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The Oral Processing of Semi-solid and Soft-solid Foods

**A thesis presented in partial fulfilment of the requirements
for the degree of
Doctor of Philosophy**

**at Massey University, Albany,
New Zealand**

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2014**

Abstract

Fluid foods are popular in modern life. They are not only enjoyable to consume and provide nutrition, but are also beneficial to special populations, such as those with dysphagia and temporomandibular joint disease or who are edentate. Food rheological properties have an important influence on food oral processing and swallowing. Tongue movement plays a vital role during oral processing of liquid, semi-solid and soft-solid foods. The purpose of this research was to investigate the boundary criteria for categorising liquid, semi-solid and soft-solid foods; identify relationships between food properties and oral processing behaviours; and characterize tongue and lower jaw behaviours during food oral processing, in particular shear stresses generated between the tongue, lower jaw and hard palate.

Constant weight samples were served to subjects who were instructed to consume them naturally, whilst movements of the tongue and lower jaw were measured via articulography and masseter and submental muscle activities were measured via electromyography. Food rheological properties (viscosity, flow curve, stretch-ability, storage modulus and loss modulus), pH and moisture content were characterized for each food sample.

The oral residence time was found to be an important oral processing behaviour, which is affected by the original food viscosity, viscoelastic properties, moisture content, and stretch-ability. Tongue movements dominate the oral processing of semi-solid and soft-solid foods instead of mastication which occurs for hard-solid food. The shear stress of the tongue and lower jaw is the main power during oral processing of semi-solid and soft-solid foods. The maximum shear stress of Greek yoghurt on tongue tip was 123 ± 31 Pa and 151 ± 59 Pa for two subjects; for custard, it was 144 ± 46 Pa and 192 ± 20 Pa. These results agree with estimated data which is currently available for the same food types. Overall, the shear stress tends to increase with increasing food viscosity.

The method developed for measuring shear stresses applied in the oral cavity during oral processing was novel and is the closest to measuring real, in – mouth, shear stresses, which has not been possible to date.

Acknowledgements

I would like to thank my supervisors, Dr Kylie Foster, Professor John Bronlund, and Dr John Grigor, for their help and encouragement during my PhD. Without their supervision this thesis would not be presented.

Thanks also to fellow staff at Massey University in Albany who have provided me with assistance and guidance during this time. Particular mention must be given to Associate Professor Marie Wong and technician Helen Matthews. I would also like to acknowledge the friendship of other students at the Albany campus who provide help in studying and in life over a few years.

This research was funded by Riddet Institute, which is greatly appreciated.

Experiments conducted in Chapter 3, Chapter 5, Chapter 6 and Chapter 7 were registered as low risk with the Massey University ethics committee. Experiments (Southern A Application 10/12) were approved by the Massey University ethics committee.

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Chapter 1: Introduction

1.1. Food oral processing

Food oral processing is a series of activities including related muscle activities, lower jaw movements, and tongue manipulations, which aims to prepare the appropriate bolus for swallowing. It is the first step within a complex digestive system. Whilst, the importance of food oral processing has been noticed by scientists for many years, most of the research has been on hard-solid foods (Hutchings & Lillford, 1988; Prinz & Lucas, 1997; Vincent & Lillford, 1991; Alfonso, Neyraud, Blanc, Peyron, & Dransfield, 2002; Hiimeae & Parmler, 1999; Kohyama, Ohtsubo, Toyoshima, & Shiozawa, 1998).

Mastication and swallowing constitutes the oral processing of solid foods. Mastication is divided into four phases: stage I transport, processing, stage II transport, and bolus formation and deglutition (Hiimeae, 2004). Hutchings and Lillford (1988) put forward a three dimensional model for the oral processing of solid and semi-solid foods, which included consideration of 1) degree of structure, 2) degree of lubrication, and 3) time. This model was the first to highlight oral residence time as an important factor.

The oral processing of semi-solid and soft-solid foods is quite distinct to that of hard-solid foods. In particular, tongue manipulation is more important than mastication during the oral processing of semi-solid and soft-solid foods. Different tongue movements have been observed during consumption of a range of these foods (Blissett, Prinz, Wulfert, Taylor, & Hort, 2007; Chen, 2009; de Wijk, Engelen, & Prinz, 2003; Hiimeae, 2004). Tongue movements also play an important role during oro-sensory perception (de Roos, 1999; de Wijk, et al., 2003; Doyen, Carey, Linforth, Marin, & Taylor, 2001; Malone, Appelqvist, Goff, Homan, & Wilkins, 1999). However, the oral processing of semi-solid and soft-solid foods is not completely understood.

The oral processing of liquids has been the least studied. This is most likely to be affected by the short oral residence time for processing liquid foods. The short oral residence time makes it difficult to observe oral behaviours, such as tongue and lower jaw movements. Conversely, swallowing of liquid foods has received more attention, as it is important for people who suffer from dysphagia and other swallowing disorders

(Cichero, 2013; Desport, Jesus, Fayemendy, De Rouvray, & Salle, 2011; Leonard, White, McKenzie, & Belafsky, 2014; Nicosia & Robbins, 2001; Smith, Jebson, & Hanson, 2014; Steele & Van Lieshout, 2008).

Oral processing is a complex process (Figure 1-1), which is highly dependent on conditions within the oral cavity (e.g. muscle activities, saliva composition and flow rate, tongue movement, and occlusion). These conditions vary greatly not only among individuals, but also within the same subject at different times of the day, for different emotions, for different foods due to feed-back mechanism on the texture and flavour perception (Aken, et al., 2007). In response to changing texture and flavour perception, food properties strongly influence oral processing (Aprea, Biasioli, Gasperi, Mark, & van Ruth, 2006; Chen, 2009; Doyennette et al., 2014; Foster et al., 2011; Lavanchy et al., 1993; Lyly et al., 2004; Mioche, 2004; Selway & Stokes, 2014).

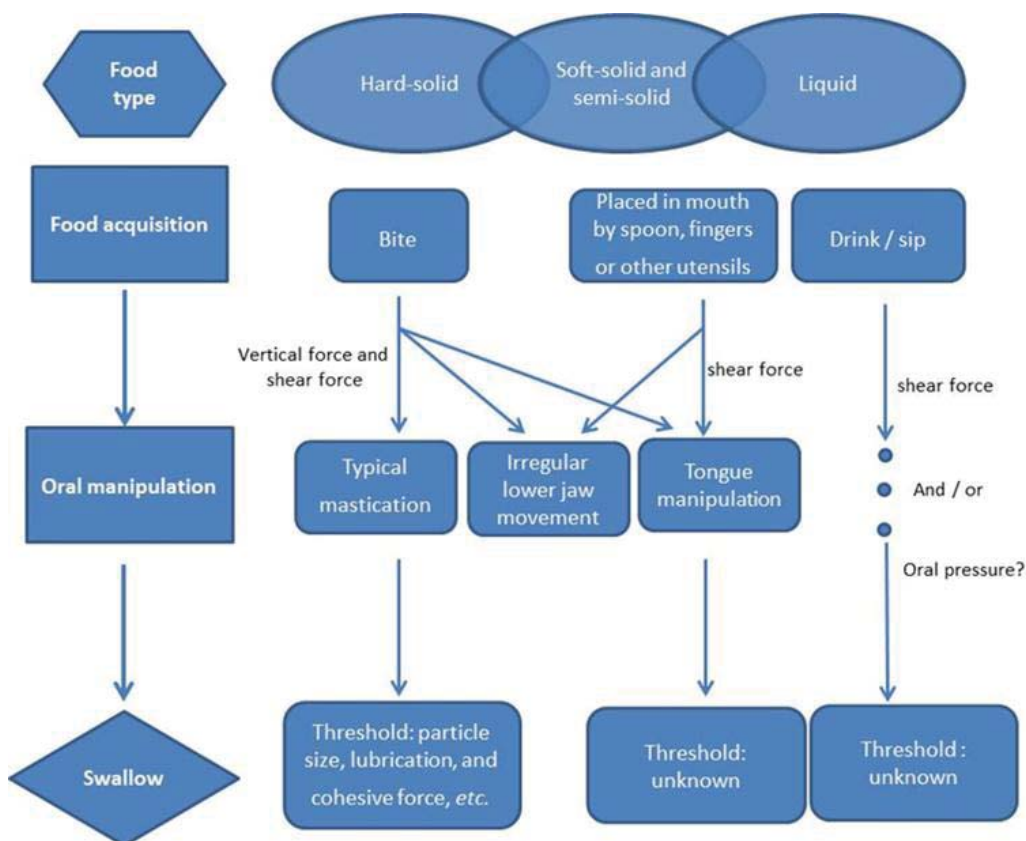


Figure 1-1: Diagrammatical representation of the general food oral processing and force for all food types.

Previous researches indicate that the oral residence time is a key parameter in food oral processing (Chen, 2009; Chen & Lolivret, 2011). However, it has neither been well

defined nor accurately measured. Two recent technologies, electromagnetic articulography and electromyography, are therefore introduced in this research to solve the problem. It also takes the advantage of both technologies to investigate tongue movements during oral processing.

It is known that food properties affect oral processing, and dynamic oral processing in turn influences food bolus formation (Hiinema & Palmer, 1999; Morell, Hernando, & Fiszman, 2014; Shiozawa et al., 2013; Young, Cheong, Hedderley, Morgenstern, & James, 2013; Yven, Bonnet, Cormier, Monier, & Mioche, 2006). Hence it is important for this research to study correlations between food properties and oral processing behaviour as well as to understand how a bolus changes during oral processing. Shear is important for the oral processing of semi-solid and soft-solid foods. This shear is produced by the tongue, teeth, cheeks and palate. The shear of the tongue tip and tongue back is also a focus of this research.

Swallowing is the last stage of oral processing regardless of food types. It is split into three phases: oral phase, pharyngeal phase and esophageal phase. Humans need at least two swallows to complete oral processing no matter how much food is taken in (Hiinema et al., 1996; Hiinema & Palmer, 1999). The mechanics governing the oral phase of swallowing are not well understood because of the complex geometry of the oral cavity and the unsteady nature of the oral process. The triggers of swallowing have not been completely revealed yet, but many scientists agree that it relates to multiple factors (such as lubrication, particle size and cohesive force) and is regulated by the central nervous system (Hutchings & Lillford, 1988; Prinz & Lucas, 1995, 1997). Recently, Chen (2009) proposed that the flow-ability of the bolus is the key factor for swallowing threshold.

1.2. Objectives for this work

This project aimed to investigate: 1) the oral processing behaviour of liquid, semi-solid and soft-solid foods, including the oral residence time (ORT) and the tongue movement during feeding; 2) the shear force in the oral cavity, especially between the tongue and palate during food oral processing. A series of experiments were designed using diverse commercial food samples (liquid, semi-solid and soft-solid foods), for which the properties of the food samples were determined.

This project had the following main objectives:

- 1) To identify and develop the most suitable methods for recording the oral processing behaviour of liquid, semi-solid and soft-solid foods (ORT and muscle activities); this includes identifying the best sensor positions on the tongue upper surface to record ORT of food samples;
- 2) To characterize the different foods based on their rheological properties and oral behaviour, and classify into different groups (liquid, semi-solid, and soft-solid foods);
- 3) To investigate the changes in bolus properties during oral processing;
- 4) To investigate the relationships between food properties and oral processing behaviour;
- 5) To measure tongue and lower jaw movements and calculate shear forces between the tongue, teeth and palate during food oral processing for a range of foods.

This research will help to: 1) contribute to the knowledge of swallowing triggers for the semi-solid and soft-solid foods; 2) provide quantitative techniques to interpret the role of the tongue during feeding; 3) elaborate the dynamic mechanism of oral processing behaviour of semi-solid and soft-solid foods.

Chapter 2: Literature Review

2.1 Introduction

The tongue is one of the most complex, active skeletal muscular organs in the body (Palmer, Hiiemae, & Liu, 1997). It is involved in a number of physical activities, such as mastication, speech, swallowing and respiration. Many studies have been conducted on mastication for which the tongue plays a critical role. The processes by which it moves and positions foods precisely are not completely known. As for oral processing of liquid and semi-solid food, few researchers have paid attention to that. However, it is well known that the tongue is more effective than teeth during consumption of those foods, especially during consumption of liquids. How the tongue dominates the whole oral processing of various foods still awaits further research.

2.2. Oral physiology

2.2.1. Teeth and jaw

Teeth are the key tool used to break down solid food into small particles and perform mastication. The anatomical structure of teeth determines that the role of teeth is to comminute (break down) food into smaller particles. Teeth are not bones, but they are the hardest structure in the human body (Bourne, 2002). From a gross anatomical viewpoint, the tooth consists of two parts: tooth crown and tooth root covered by gums (Cate, 1998). From a microscopic perspective, the tooth is composed of four major tissues: enamel, dentin, cementum, and dental pulp (Ross, Pawlina, & Kaye, 2002). All teeth are buried in the maxillary and mandible. Maxillary (upper jaw) is a part of the immovable craniofacial bone. The mandible (lower jaw) is connected to the skull by muscles and the temporomandibular joint (TMJ) at both sides of the jaw. In the TMJ joint, there is a special structure (articular disc), which is connected with the temporal bone superiorly and the mandible inferiorly. This structure reinforced laterally by the temporomandibular ligament, is the only capsular structure that runs directly between the temporal bone and the mandible (Schmolke, 1994). The structural characteristics result in the mandible being able to move to a considerable extent within an envelope of motion in three-dimensional space, for which the number of possible moving paths is infinite (Koolstra, 2002).

2.2.2. Masticatory muscles

Masticatory muscles are usually divided into elevator and depressor groups. The elevator group consists of the masseter, temporalis and the medial pterygoid muscles (referred to as mouth closing muscles). The temporalis is attached from the side of the skull to the top of the lower jaw behind the teeth and consists of vertical and horizontal muscle fibres; the masseter is attached between the cheek on the skull and the lower rear section of the lower jaw. The temporalis and masseter are located more or less superficially. The medial pterygoid is located more deeply and attached to the inside of the skull and the lower jaw. The elevator muscles are aliform shaped (Hannam & McMillan, 1994). They are suitable for the generation of large forces. The fibres are short, which limits their capacity for active shortening during contraction. At the same time, they have large physiological cross-sectional areas that allow movement of the mandibular teeth against those of the maxilla with high forces (Xu et al., 2008).

The depressor group are located in the floor of the mouth. This group consists (from superior to inferior) of the geniohyoid, the mylohyoid, and digastric muscles (known as mouth opening muscles). The geniohyoid and mylohyoid muscles connect the hyoid bone to the body of the mandible. The digastric muscle connects the mastoid process of the skull to the body of the mandible and is attached to the hyoid bone *via* a fibrous loop which goes around its intermediate tendon. The lateral pterygoid muscle completes the muscular system and connects the skull and the lower jaw. It consists of a superior and inferior head running from the mandibular neck in forward and medial directions and governs side to side movements of the jaw (Xu, Bronlund, et al., 2008). Since the two heads are considered to have different actions, they cannot be regarded exclusively as elevator or depressor muscles (Juniper, 1981). The depressor muscles and the lateral pterygoid have more or less parallel fibres and are therefore able to contract over a longer distance with less force (Koolstra, 2002). The mouth opening muscles, however, have relatively small physiological cross-sectional areas and are supported by the force of gravity; they are able to abduct to move the mandible away from the maxilla at high velocity under application of small forces.

2.2.3. Tongue

The tongue is a unique organ in mammals. It is a soft boneless skeletal muscle, which moves flexibly. Some researchers investigate tongue muscles and masticatory muscles at the same time (Kakizaki, Uchida, Yamamura, & Yamada, 2002), as they consider the two kinds of muscle as controlled by the same spot in central nervous system or as having a similar developmental origin. In fact, the developmental origin of tongue muscles is different from masticatory muscles; the nerve centre of manipulating the tongue is distinct from those for masticatory muscles, while the myogenesis depend on the developmental origin of muscles (Yamane & Tadayodshi, 2007).

The tongue is composed of intrinsic muscles and extrinsic muscles: the former lie completely within the tongue; while the latter attach the tongue to surrounding bones (Figure 2-1.). There are four pairs of intrinsic muscles within the tongue, which build the tongue shape. Superior longitudinal muscles run along the superior surface of the tongue under the mucous membrane. Inferior longitudinal muscles line both sides of the tongue, and are joined to the styloglossus muscle. The verticalis muscle lies in the middle of the tongue and joins the superior and inferior longitudinal muscles. The transversus muscle divides the tongue at the middle, and is attached to the mucous membranes that run along the sides. Intrinsic muscles alter tongue shape, such as lengthening and shortening it, curling and uncurling its tip and edges, and flattening or rounding its surface (Drake, Vogl, & Mitchell, 2005).

Extrinsic muscles originate from other structures and are inserted into the tongue's intrinsic muscles, making the tongue protrude, retract, depress and elevate. They consist of four pairs of muscles (Figure 2-2.). The genioglossus comes from the mandible; this muscle can protrude the tongue and depress the tongue centre. The hyoglossus comes from the hyoid bone, and can depress the tongue. The styloglossus is from styloid, which produces elevation and retraction motion. These three muscles are innervated by the hypoglossal nerve. The palatoglossus originates in the palatine aponeurosis, and therefore can depress the soft palate, move the palatoglossal fold towards the midline and elevate the back of the tongue. This muscle is innervated by a pharyngeal branch of the vagus nerve (Drake, et al., 2005).

Most researchers regard the tongue as a ‘muscular hydrostat’, because it has been shown that the tongue retains a constant volume when it changes shape (Kier & Smith, 1985; McClung & Goldberg, 2000; Wedeen, Reese, Napadow, & Gilbert, 2001). In other words, if the tongue alters in one dimension, there is a corresponding alteration in the other one or two dimensions. Recently, Liu *et al.* found that the tongue does not always entirely compensate for every change in one region; one dimension can alter more than the other dimension (Liu, Yamamura, Shcherbatyy, & Green, 2008), based on the constant volume of whole tongue.

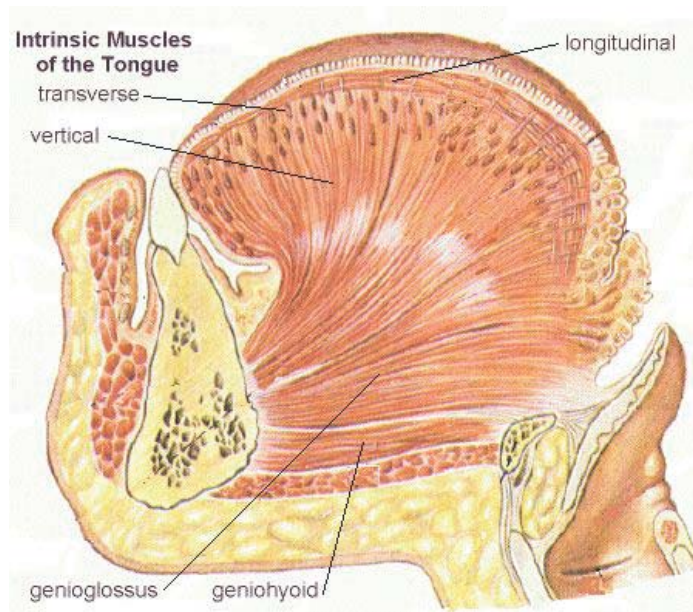


Figure 2-1. Intrinsic muscles of the tongue (Netter, F. H., 2011)

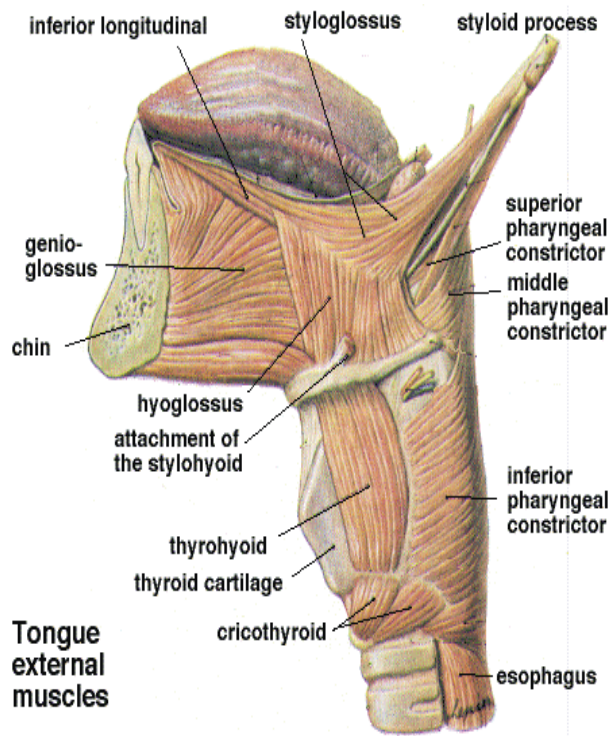


Figure 2-2. Lateral view of the tongue, with the extrinsic muscles (Netter, F. H., 2011)

Tongue action and related apparatus

The tongue is a soft and flexible structure in the mouth capable of many movements and shapes. While the tongue is immobile, it normally rests on the floor of the mouth, filling the oral cavity and presenting a fluid-like appearance with slight opening of the mouth (Ellinger, et al., 1975). During feeding, several basic tongue shapes are observed: pocket or trough-like, deep gutter-like, tongue twist (leaning sideways), and slope-like in formation (Abdelmalek, 1955). Each of these motions varies significantly. At the same time, some basic tongue actions are present during the feeding process, such as moving the tongue upwards, downwards, sideways, protrusion, retraction, and throwing. However, even the simplest functional movement cannot be performed by the tongue alone, as it is not an independent organ in the human body. It must cooperate with the hyoid and mandible, which collectively referred to as the hyolingual complex. In addition, the hard and soft palates have a close connection with the tongue during feeding. The hyoid is closely connected to the tongue by extrinsic tongue muscles and almost all tongue movements are accompanied with hyoid actions. In feeding, it moves continuously, facilitating movements of the tongue surface and processing and transporting food (Hiimae, et al., 2002). As the tongue is attached to the lower jaw, at the floor of the mouth, every functional movement is linked to mandible motion at

every stage of feeding (Palmer, et al., 1997). Some scientists have found that the cyclical movement of the soft palate and jaw motion are temporally linked, but the frequency and timing of soft palate cycles vary significantly from ingestion to swallowing during the feeding process (Matsuo, Hiiemae, & Palmer, 2005). It is assumed that the tongue and soft palate have a similar relationship. Therefore, based on tongue physiology and previous research, investigation of the role of tongue during feeding requires a consideration of other related apparatus.

2.2.4. Oral sensors

Oral sensors play a crucial role in the perception of food. Humans have five kinds of sensors, which sense five types of physical energy: chemical, mechanical, thermal, nocuous, and photoesthetic (Kolb & Whishaw, 2003). The first four kinds of sensors are present in the human mouth. The chemical receptors are sensitive to taste and odour; the mechanoreceptors mediate sensations of touch and proprioception, Meissner's corpuscles (light touch), Pacinian corpuscles (pressure) and muscle spindles are the same as those of skin and other muscles. Periodontal mechanoreceptors which are located in human dentition can detect small forces; the thermoreceptors feel the temperature of the body and objects, while nociceptors are sensitive to pain. When we eat, the tactile is the most important sensation and perception of oral food texture and tactile sensation is mainly mediated by mechanoreceptors (Engelen & Van Der Bilt, 2008).

The tongue is the region in the human body which is the most sensitive (Bourne, 2002). When we perceive food, all sensors work together, and the tongue sensors play an important role. Some specific chemical sensors (papillae or taste buds) help us to taste (sweet, salty, sour, bitter and umami) on the tongue surface (Duran & Costell, 1999; Ninomiya, 2002). There are four types of papillae on the tongue surface. Fungiform papillae are located at the tip of tongue and on both sides, and are innervated by the facial nerve. Foliate papillae are found on the tongue lateral margins, and are innervated by both the facial nerve (anterior papillae) and glossopharyngeal nerve (posterior papillae). Circumvallate papillae are present at the back of the oral part of the tongue; normally, every person only has 3-14 of this kind of papillae and they are lined in a circular-shaped row just in front of the sulcus terminalis of the tongue and innervated by the glossopharyngeal nerve. The most numerous papillae are filiform papillae, which

are very thin and mechanical; these are not included in gestation and keratinize quickly (Drake, et al., 2005). The tongue senses all tastes in every area, not one taste sensation in each specific area as Edwin Boring reported a hundred years ago.

In addition to papillae, the tongue has mainly rapidly adaptive receptors, which respond only to the application and removal of a stimulus (Trulsson & Johansson, 2002). Some researchers have found a kind of deep receptor in tongue muscle, which are most likely muscle spindles (Trulsson & Essick, 1997). Muscles spindles of mammals (and sometimes Golgi tendon organs) can sense the state of a muscle contracting against a load (Lucas, et al., 2005).

2.2.5. Saliva

Saliva is a complex, colourless, dilute natural fluid in the mouth, which has a major impact on oral processing.

2.2.5.1. Secretion of saliva

There are three main sources of saliva. The mucous-rich mucilage over the oral cavity is produced by the sublingual and many minor glands; the thin serous saliva is created by the parotid gland; the thicker saliva that forms a pool in the anterior part of the floor of the mouth is produced by the submandibular glands (Lucas, Prinz, Agrawal, & Bruce, 2002).

The density of saliva ranges from 1002 to 1012 kg/m³ (Schneyer, Schneyer, & Young, 1972), and the pH varies from 5.6 to 7.6 with a mean of 6.75. Some scientists reported a pH level of about 6.64, which varies according to the level of CO₂ in the blood (Guyton & Hall, 1996). Saliva contains over 99% water, with a variety of elements making up the remainder (Table 2-1). The salivary levels of K⁺, Ca²⁺, urea, uric acid and aldosterone are highly correlated with those existing in plasma (Dawes, 1974); however, this high degree of correlation has not been found between salivary and plasma levels of inorganic phosphate (Chicharro, Lucia, Perez, Vaquero, & Urena, 1998).

Saliva is created at all times, even if its flow rate varies from time to time, and oral conditions (e.g. dry mouth, after consumption flavoured food or psychological effects). One study found the mean saliva flow rate among a group of people at times of non-

stimulation was 26 ml/h with a range of 2.5 - 110 ml/h. The saliva flow rate increased to 46 - 249 ml/h, when the saliva flow was stimulated in the same people by giving them flavoured wax to chew (Mackie & Pangborn, 1989). However, according to the research of Dawes and Watanabe (Dawes, 1987; Watanabe & Dawes, 1988), whole saliva flow rates in humans vary from 30 ml/h at rest to 300 ml/h during chewing, and 420 ml/h in response to citric acid stimulation. At rest, the amount of the saliva in the mouth before and after swallowing is 1.1 ml and 0.8 ml respectively (Lagerlof & Dawes, 1984).

Saliva secretion has circadian rhythms; however, it can be altered by stimulation, such as gustation, mastication, vision, hearing, even talking and thinking of food, which can increase saliva flow rate. Water and chewing rate, however, have no significant influence on the salivary secretion (Mackie & Pangborn, 1990). Mastication is an important stimulus for human salivary secretion. However, the gustatory sensory stimulation was found to be more important than mechanical stimulation. In experiments among subjects at rest, chewing Parafilm and chewing natural food, the saliva flow rate was found to vary significantly (Dawes & Dong, 1995). Chewing food induced more saliva than chewing Parafilm (no flavour substance) (Mackie & Pangborn, 1990). Mackie and Pangborn (1990) also found the size of the bolus to influence saliva secretion. Dry food (less water and fat) increased the number and the time of chewing cycles, which indicates that moisture and lubrication reduces chewing time (Gaviao, Engelen, & van der Bilt, 2004). This work also results in structural changes with the addition of water. Significantly more saliva is required when people chew powdered crisp-bread than pieces of crisp-bread, because of the larger surface area. More saliva is required when chewing tough meat and dry food than tender meat and moist food (Pereira, Gaviao, & van der Bilt, 2006). Pereira *et al.* (2006) have shown that fluid addition facilitates chewing of dry foods (Melba, cake), but does not influence the chewing of fatty (cheese) and wet products (carrot) (Pereira, Gaviao, Engelen, & Van der Bilt, 2007). Citric acid has been found to elicit the largest volumes of saliva, followed by mechanical stimulation (parafilm), odour stimulation, and unstimulated saliva (Watanabe & Dawes, 1988).

The composition of saliva as a response to the four types of stimulation varies significantly. Protein concentration is the highest in unstimulated saliva, followed by saliva stimulated by odour, chewing, or citric acid. The highest buffer capacity is found

in the mechanically stimulated saliva, followed by resting and odour stimulated saliva. Mucin concentration is higher in resting than in any type of stimulated saliva (Engelen et al., 2007). Mastication increases salivary flow rate, but not the concentration of protein and α -amylase of saliva (Mackie & Pangborn, 1990). The composition of saliva is affected by the food type (Jalabert-Malbos, Mishellany-Dutour, Woda, & Peyron, 2007). Chicharro *et al.* (1998) indicates the salivary composition to be influenced by salivary flow rate during physical exercise.

Table 2-1. Composition of human whole saliva general composition (Thie, Kato, Bader, Montplaisir, & Lavigne, 2002)

Water (>99%)	H ₂ O	
Other elements (1%)	Ions (e.g. Ca ²⁺ , Na ⁺ , K ⁺ , Cl ⁻ , Mg ²⁺ , HCO ₃ ⁻ , F ⁻ , I ⁻ , Cu)	
	Proteins	Enzymes (e.g. amylase, lipase)
		Albumin
		γ -Globulin
		Mucoproteins
	Microbial agents (lysozyme, lactoferrin, lactoperoxidase)	
	Carbohydrates	Protein bound (e.g. fucose)
		Free sugars (e.g. glucose)
	Lipids and lipoproteins	
	Small organic molecules (e.g. amino acids, emocreatinine, lactate)	
	Water soluble vitamins (e.g. ascorbic acid, B group)	
Specific biochemicals: Calcitonin gene related peptide (CGRP); PGE ₂ , F ₂ and I ₂ ; Epidermal growth factor (EGF); Insulin-like growth factors I and II; Nerve growth factor; Immunoreactive 6-sulfidopeptide containing; Leukotrienes; Immunoreactive hydroxyeicosatetraenoic acid; Human β -defensins; Substance P; Melatonin; Cortisol		

Saliva glands are innervated by both sympathetic and parasympathetic nerves. Different nerve impulses result in different saliva components. The higher organic content of saliva evoked by sympathetic nerve excitation (Speirs, Herring, Cooper, Hardy, & Hind, 1974) includes an elevated level of total protein, and especially the digestive enzyme α -amylase. In addition, blood supply of the glands can affect the rate of salivary secretion.

2.2.5.2. Functions of saliva

The functions of saliva include:

1.) Protection of the oral and esophageal mucosa: Mastication enhances the production of saliva and the salivary component of the esophageal epithelial defence and, by stimulating the rate of salivary epidermal growth factor (EGF) secretion, may have a therapeutic effect in the treatment of patients with damaged esophageal mucosa (Thie et al., 2002). EGF is considered to play a main role in the esophageal protective mechanisms by maintaining the epithelial barrier and in healing of damaged mucosa. Low salivary EGF levels probably reduce the capacity of the oral mucosa to fight against injury.

2.) First stage of food digestion: A component of saliva, α -amylase, induces the first step of digestion of starch in the mouth. In vitro experiments for starch-based semi-solid foods has shown that small amounts of saliva reduce the viscosity of starch-based food as starch is broken down in the oral cavity (Prinz, Janssen, & de Wijk, 2007).

3.) Taste medium: Saliva flow can affect sensory perception (Garrett, Ekström, & Anderson, 1999). The high polarity and neutral pH of saliva can change the volatility of some flavours, especially in foods with high fat or low pH. Saliva can also modify flavour by emulsification or by breaking down starch or esters through the action of amylases and esterases (Hussein & Abdelgawad, 1983; Roberts & Acree, 1995). One study, which investigated the short-term reduction of salivary flow, found very little effect on taste perception (Christensen, Navazesh, & Brightman, 1984). It has been found, however, that the long-term reduction in saliva results in lower taste sensitivity and altered preferences (Galili, Maller, & Brightman, 1981). Therefore, saliva flow is thought to be involved in the perception of taste, flavour and food texture. Engelen *et al.* (2007) found the salivary components measured in their study varied considerably among subjects, but also within subjects as a result of different means of stimulation. Variations in salivary components were correlated with sensory perception of a number of flavours, mouth feel and after feel attributes in the semi-solids mayonnaise and custard dessert. Total protein concentration and α -amylase activity were observed to correlate most strongly with texture perception. The relationship between subject's saliva flow and subjective sensory ratings on semi-solid foods does not appear to have been investigated to date. However, scientists have found that saliva acts as a buffering system, affecting the perceived gustation (Engelen et al., 2007).

4.) Lubrication facilitates bolus formation: after a number of chewing cycles, the food fragments build up in the mouth, and can easily get lost around the mouth unless they form a cohesive bolus. During chewing, more saliva is released, which helps food particles to adhere together (Ablett, Darke, & Lillford, 1991; Hutchings & Lillford, 1988). Moistening and binding the fragments by saliva result in a coherent, slippery and viscous bolus (Jalabert-Malbos et al., 2007), which is ready to swallow.

5.) Cleaning: saliva flushes away small food particles, and assists in removing fat from the hydrophobic tongue surface (Dresselhuis, Stuart, van Aken, Schipper, & de Hoog, 2008).

6.) Antimicrobial activity: saliva contains antimicrobial agents, such as lysozyme, lactoferrin, lactoperoxidase, and immunoglobulin, which kill or restrain pathogens (Tenovuo, 1998).

7.) Protection of the dentition: saliva serves as a masticatory lubricant that assists the lubrication and polishing of tooth surface during chewing and rest (Chicharro et al., 1998).

2.2.5.3. Amylase

Amylase turns starch into carbohydrates in the mouth (Guyton, 2000 ; Hanson, Cox, Kaliviotis, & Smith, 2012). In 1833, Anselme Payen discovered and isolated amylase. It is a group of glycoside hydrolases in saliva, of which α -amylase is the most efficient. Amylase is an enzyme that breaks starch down into sugar, and is presented in human and animal saliva, where it begins the chemical process of digestion. It acts on α -1, 4-glycosidic bonds. The pancreas also produces amylase (α - amylase) to break down dietary starch into di- and trisaccharides which are converted by other enzymes into glucose to supply the body with energy. The α -amylases are calcium metalloenzymes, and cannot act in the absence of calcium.

By acting at random locations along the starch chain, α -amylase breaks down long-chain carbohydrates, ultimately producing maltotriose and maltose from amylose, or maltose, glucose and limited dextrin from amylopectin. In human physiology, both the salivary and pancreatic amylases are α -amylases. The optimum pH conditions for α -amylase are 5.6 - 6.9. Starch digestion is initiated by α -amylase in the oral cavity. The

starch is reduced in its ability to bind water, which induces a lower viscosity of the product. In this way, α -amylase influences the sensation of melting in semi-solids.

The secretion of α -amylases in saliva not only depends on the type of food (Jalabert-Malbos, et al., 2007), but is also determined by a different nerve impulse. Proctor and his co-workers found that the parasympathetic nerve impulse produced saliva with relatively low amylase levels but induced a substantial increase in serum amylase concentration. However, sympathetic nerve stimulation resulted in a high amylase concentration of saliva but little or no change in serum amylase activity (Proctor, Asking, & Garrett, 1989). For α -amylase activity, there were no significant variations among saliva obtained by different types of stimulation; nevertheless, the activity in mechanically stimulated saliva looked higher than in odour stimulated saliva, but was not significant (Engelen, et al., 2007).

2.3. Overview of oral processing

Oral processing is the first step of food digestion and consists of: acquisition, mastication, clearance and swallowing. In every part the tongue plays a vital role. Processing of solid food in the mouth can be divided into: transport to the cheek teeth, selection for crushing, chewing, pre-swallow and swallowing (Heath, 2002). However, semi-solid and liquid food manipulation in the mouth is different from solid food and not as well understood.

Semi-solid foods do not have regular chewing cycles like solid food during oral processing. The oral processing is briefer and more irregular than for solid food and liquid food, especially the food transport from the front teeth to the oropharynx. For some semi-solid foods, it is not necessary to use the teeth to fracture the food.

According to different types of semi-solid food, the oral movements vary significantly: sometimes a simple movement, at other times lifting the tongue against the palate and smearing the food over the hard palate in a complex pattern; and sometimes involving roughly chewing food for couple of cycles. Oral movements during processing of semi-solid foods have been found to be related to sensory ratings of liking, creaminess and roughness (de Wijk, Polet, Bult, & Prinz, 2008). Oral processing of semi-solid food is also affected by temperature, shear, dilution and chemical break-down by α -amylase as soon as it is ingested into oral cavity (Prinz, Janssen, & de Wijk, 2007).

Oral processing of liquid food is much simpler than for solid food. The fluid is divided into a suitable bolus by the tongue, cheeks and hard palate after ingestion; then propelled across to the pharyngeal surface of the tongue and into the hypopharynx, finally entering the esophagus (Dodds, Stewart, & Logemann, 1990; Dua, Ren, Bardan, Xie, & Shaker, 1997; Hiemae & Palmer, 1999).

Whatever the food type, tongue movements play a significant role in oral processing, and must be studied to understand oral processing in greater depth.

2.3.1. Food acquisition

There is no general definition of food acquisition. Acquisition is a cognitive process of acquiring acceptable food. It can start before food purchase and end at the beginning of mastication. In this review, it is defined as the placement of food in the oral cavity or the first bite.

For solid food, the first bite is a crucial factor during food acquisition. Some researchers studied the first bite in rabbits, and divided it into opening, fast closing, and slow closing: 3 distinct phases (Schwartz, Enomoto, Valiquette, & Lund, 1989).

Bite force and bite speed are two important features of the first bite. The former consists of two elements: an anticipating one and a peripherally induced one. The anticipating force starts well before the fracture of the food; then the peripherally induced biting force follows about 23 ms later (van der Bilt, Engelen, Pereira, van der Glas, & Abbink, 2005). The force applied on the first bite is related to food geometry (Peyron, Maskawi, Woda, Tanguay, & Lund, 1997), food texture and mechanical properties (Mioche & Peyron, 1995). The bite speed is dominated by food mechanical properties and individual oral physiology (Mioche & Peyron, 1995). Meullenet et al. (Meullenet, Finney, & Gaud, 2002) found the difference among individuals to be greater than between foods for biting speed. Normally, the bite force of semisolid food is much smaller than solid food in the same individual, and liquid does not require biting.

Acquisition is known to be affected by mouth size, bite size and several food properties.

2.3.1.1. Mouth size and bite size

Oral processing is influenced by two sorts of factors: extrinsic factors and intrinsic factors. Food size, hardness or rheological behaviour (elasticity, plasticity or brittleness) are extrinsic factors which can vary masticatory parameters. Age, gender or dental health are common intrinsic factors which are known to influence oral processing (Woda, Mishellany, & Peyron, 2006).

Mouth size has traditionally been calculated as the volume of one mouthful of water (Lawless, Bender, Oman, & Pelletier, 2003). Previous studies showed that a normal female and male adult can take about 25.2 ± 8.1 g and 30.5 ± 10.1 g water as one mouthful, respectively (Medicis & Hiimae, 1998). However, the amount of food, which can be taken is not only dependent on individual mouth size, but also on physical food properties, as people do not need to have a mouthful of food during feeding. Generally, the volume of food for each mouthful decreases from liquid to soft solid and further to hard solid food (Medicis & Hiimae, 1998). Similarly, for natural portion sizes, it is assumed to decrease from liquid to semisolid and solid food. Steele and Van Lieshout (2004a) investigated human consumption of various viscosities of liquid and semi-solid foods, and found subjects took significantly smaller volumes per sip for thicker and heavier liquids within apple-flavoured and non-flavoured liquids. The frequency of sequential swallowing (per second) decreased with increasing bolus viscosity. Other scientists (de Wijk, Zijlstra, Mars, de Graaf, & Prinz, 2008), however, found that if the bite effort is eliminated, the difference of bite size between semisolid (dairy) and liquid disappeared. Along with the change of bite size, the vertical amplitude of mandibular movements changes as well (Lucas, Luke, Voon, Chew, & Ow, 1986; Peyron, et al., 1997; Woda, et al., 2006).

2.3.1.2. Appearance properties

Size, shape, volume, density and porosity are the first impression for a consumer; they are external characteristics of the food (Sahin, 2006). Before eating, initially consumers perceive and estimate these properties, and then make a decision on how to consume the food. Good appearance can provide more hedonic value during feeding, and affect the first portion size (Burger, Cornier, Ingebrigtsen, & Johnson, 2011; Eertmans, Baeyens, & Van den Bergh, 2001; Sorensen, Moller, Flint, Martens, & Raben, 2003).

2.3.1.3. Textural properties

Food textural properties are a group of physical characteristics of the food structure; they are sensed mainly by the feeling of touch, are correlated to the deformation, disintegration, and flow of the food under a force, and are measured objectively by functions of mass, time, and distance (Bourne, 2002).

All textural properties affect feeding behaviour somewhat. The initial food consistency determines the number of chewing cycles before the first swallow and overall sequence duration (Hiemae et al., 1996). Hardness is used frequently to describe solid food characteristics. Guraya and Toledo (1988) defined hardness as the perceived force required to break the food sample into several pieces during the first bite by the molars (Bourne, 2002). But this definition is not comprehensive; in the other words, hardness is a loose term. Whatever the definition is, this characteristic affects food ingestion (Palmer, et al., 1997).

Research has found that when the food is taken to the mouth, the individual will use bigger bite force to cut it if the food is evaluated to be hard (Woda, et al., 2006).

2.3.2. Food oral processing

Food oral processing is a series of activities in oral cavity to prepare the appropriate bolus for swallowing. Oral processing behaviour is divided into three parts according to different food types. They are discussed in separate subsections.

2.3.2.1. Oral processing of liquid food

Liquid processing is different from solid food due to it having very different physical properties. The most distinguished feature of liquid is flow; the oral processing is faster and easier than solid foods, as it requires a different oropharyngeal control from solid foods (Hiemae, 2004; Hiemae & Palmer, 1999). The tongue and palate contribute more than others in the oral processing of liquid. While the aliquot of liquid is organized in the oral cavity, the tongue rises toward the hard palate anteriorly and begins to push the liquid posteriorly toward the larynx; the posterior oral cavity is sealed between the soft palate and tongue back (Dua, et al., 1997). When the individual is ready to swallow or -subconsciously swallow, the sealed posterior oral cavity

abruptly opens, and the bolus is passed rapidly through the open larynx and into the pharynx, then propelled into the esophagus by a combination of tongue and pharyngeal movements (Dodds, Logemann, & Stewart, 1990).

The oral processing time of liquid food is faster than solid food. Small changes in food properties such as viscosity, fat content, and particle size affect oral processing behaviour (de Wijk, Polet, et al., 2008). Therefore, various liquid foods should have different processing times and behaviours in different individuals. However, the available literature on liquid foods is limited.

2.3.2.2. Oral processing of semi-solid and soft-solid foods

Scientists define solid food and liquid food as two extremes of one continuum, with semi-solid food (semi-liquid food) in the middle (Bourne, 2003). As yet, there is no generally agreed definition of semi-solid foods, as it is not always possible to determine whether a material is behaving as a liquid or a solid. Semi-solid food is related to the rate of deformation when stress is applied. Therefore, many semi-solid foods display viscous and/or elastic properties (McKenna, 2003). From previous studies, it is well known that semi-solid foods include some emulsions, and food emulsions demonstrate a great range of rheological characteristics. Thus, the oral manipulation and swallowing of semi-solid food is quite different from solid food (Hiemae & Palmer, 2003). For semi-solid food generally only the tongue is used to compress food on the hard palate and spread it. The mashed food is propelled or pushed into the pharynx by the tongue in the stage II transport cycles. A bolus accumulates in the oropharynx during multiple transport cycles (oropharyngeal aggregation time, which may last up to about 10 or 12 seconds in healthy individuals). Subsequently, the swallowing process is more like a liquid: the tongue surface sweeps the remaining food from the oral cavity into the pharynx (squeeze-back), and the pharyngeal surface of the tongue pushes backward to propel food through the pharynx (tongue base retraction) (Hiemae & Palmer, 1999, 2003).

Chen and associates conducted a series of experiments to study oral processing in relation to the food properties of a full range of liquid, semi-solid and solid foods. They tested food bolus properties during oral processing, focusing on the swallowing phase. Regarding solid foods, Chen, Karlsson, and Povey (2005) marked the acoustic ranking

of six different biscuits, and their results from instrumental assessment were consistent with results from sensory panel tests. Regarding liquid and semi-solid foods, such as lab-constituted liquid or gel and commercial foods, Chen and Moschakis (2006) discovered the heat-set whey protein gel had a smoother surface with salt addition than without salt addition. They further concluded that the pressure drop and cavitation of a suddenly stretched fluid could be critical in influencing perception of food stickiness in another study (Chen, Feng, Gonzalez, & Pugnali, 2008). The viscoelasticity of biopolymer fluids composed of casein and waxy maize starch was a factor influencing the stretching of biopolymer fluids, which was quantified by stretch-ability (Chan et al., 2009). Chen and Lolivret (2011) used eighteen commercial fluid foods and ten lab-constituted foods (liquid and semi-solid foods) to investigate the importance of food bolus rheological properties on swallowing. They found that the bolus rheology, especially its extensional stretch-ability, had the critical influence on the ease of swallowing. Chen and Stokes (2012) found that tribology was another key aspect to understand food oral processing, texture and mouthfeel, because it involved fluids' rheological properties as well as the surface properties of interacting substrates in relative motion. In addition, Alsanei and Chen (2014) found a positive correlation between the maximum tongue pressure and the maximum consistency of bolus that the subject swallowed for those who had lower tongue pressure generation capacity (< 40 kPa).

Chen (2007) also reviewed the surface texture as an important sensory perception factor for consumers. After that, Chen and Lolivret (2011) explained the relationship between sensory perception and food physical properties. Recently, Chen and Eaton (2012) confirmed that creaminess was not a key sensory property but an integrated sensory experience.

In summary, Chen's studies demonstrated that the oral processing of semi-solid foods is impacted by food properties, especially food rheological properties and tribology in the oral cavity. He also related food properties to human sensory perception during oral processing of semi-solid foods, which provides important information for food development.

Besides food properties, oral sensitivity, tongue movements, temperature, saliva composition and oral physiology are also important to the perception of semi-solid food

(Engelen & Van Der Bilt, 2008). Furthermore, all these factors impact the oral processing of semisolid food.

Shear in oral cavity

Shear is the key factor in food rheology. It is considered to be the main force of oral processing of semi-solid foods. Shear is a force that one plane exerts on a neighbouring plane per unit area of contact, and which causes a deformation in a direction related to the direction of the applied force (International Food Information, 2009). Shear forces are applied during food processing, both in vitro and in human oral cavity, such as mixing, extrusion or pressing, and mastication. Shear forces affect the texture of final product or ready-to-swallow bolus.

Shear stress is the stress component applied tangentially to the plane on which the force acts. It is expressed in units of force per unit area. Shear stress is a force vector that possesses both magnitude and direction (Bourne, 1982a). Shear related parameters are used to predict or describe the texture property of semi-solid foods (Terpstra et al., 2005; Terpstra et al., 2009). Terpstra et al. (2005, 2009) investigated the relationship between orally perceived thickness and calculated shear stress on the tongue for two types of viscous semi-solid food: mayonnaise and custard. They found a linear relationship between calculated shear stress and thickness within a limited range of shear stresses (mayonnaise < 150Pa; custard < 30Pa). This result is similar to the work of Kokini (Elejalde & Kokini, 1992; Kokini, Kadane, & Cussler, 1977). Outside these limited ranges, the linear relationship broke down and the perceived thickness levelled off with shear stress for both mayonnaise and custard (Terpstra, et al., 2005).

Shear rate is an important parameter to assess food rheological properties in the mouth. It is the velocity gradient established in a fluid as a result of an applied shear stress (Bourne, 1982b). In food processing, the effective shear rate is representative of oral deformation (Cutler, Morris, & Taylor, 1983; Houska et al., 1998; Shama & Sherman, 1973; Terpstra, et al., 2005). Various researchers have tried to determine it and their studies can be classified into two main types: large-deformation (steady-shear) measurements which were used prior to 1982; and small deformation (dynamic) viscosity measurements (Stanley & Taylor, 1993). During oral processing, a force is applied by the tongue and teeth, causing shear stress and food break-up. The shear rate

operating in the mouth during eating is not constant (Shama & Sherman, 1973) and varies over several orders of magnitude depending on the food. The shear rates in the mouth for various foods range from 10 to 500 s⁻¹ (Elejalde & Kokini, 1992); for milk, the shear rate was 416 s⁻¹. Shearing results in little difference in liquid model systems. The shearing effect is especially high for a solid food that has to be broken up for the release of flavour compounds (Roberts & Acree, 1995).

Shear strength is another term to describe the oral shearing in oral processing. It is the maximum shear stress which a material can withstand (Kramer & Szczesniak, 1973). However, shear rate and shear stress are more commonly used terms.

2.3.2.3. Oral processing of solid food

Mastication is the typical activity during oral processing of solid food. Mastication includes chewing, grinding, or crushing with the teeth and preparing for swallowing and digestion. It is a process which precedes swallowing (Bourne, 2002). Mastication is a reaction to solid foods and some soft-solid foods, and is not necessary for certain soft semi-solid foods, mastication is not necessary. Drinking, sucking or acquisition by spoon is more usual for liquid and some semi-solid and soft-solid foods.

Overview of human mastication

The main role of human mastication is to convert a piece of food into a bolus suitable for swallowing (Hutchings & Lillford, 1988; Prinz & Lucas, 1997; Vincent & Lillford, 1991).

Humans perform 1 - 1.9 masticatory cycles per second during eating (Luschei & Goldberg, 1981). Generally, the process of mastication can be divided into four stages: Stage I transport, Processing, Stage II transport, and bolus formation and deglutition. In Stage I transport, the ingested food is moved from the incisal area to the post-canine teeth. During the processing stage, food is fractured into smaller pieces and particles; this is followed by stage II transport, in which comminuted food is moved through fauces for bolus formation. The last stage of mastication is bolus formation and deglutition (Hiimae, 2004). It has been found that the magnitude and duration of mastication are significantly larger in the late stage of chewing (8 strokes before initial swallowing) than in the early stage (Hiimae, 2004). The masticatory frequency has

been found to be the most important parameter for the assessment of an individual's masticatory function (Woda, et al., 2006), as it does not vary within an individual for a given food. Masticatory frequency does show inter-individual variability, large differences between males and females, and changes in mouthful size or the rheological characteristics of natural food (Woda, Foster, Mishellany, & Peyron, 2005). However, Alfonso *et al.* (2002) found that masticatory frequency differed only slightly compared to the various chewing patterns during mastication. Kohyama *et al.* (1998) observed the mastication of 6 kinds of cooked rice using different methodologies. They found that inter-individual differences in mastication behaviour were greatest in the early stages of mastication, and these differences decreased during subsequent mastication. The proposed explanation for this decrease was that the physical properties of the rice samples became more similar as oral processing progressed.

During oral processing, the properties of food change as it is continually subjected to cutting, grinding, pressing, mixing and kneading by the teeth and tongue (Kohyama, et al., 1998). This in turn affects evaluation in the oral cavity. For instance, hard and irregular particles are easier to distinguish compared to softer and regular particles during oral processing (Engelen, Van der Bilt, Schipper, & Bosman, 2005). These hard and irregular particles will be selected and chewed longer, until consistent food bolus is formed. If these particles are hard to make into an acceptable bolus, they will be spat out. With food bolus property changing, the oral evaluation will change.

Before evaluation, a part of food must be chosen to be assessed, this is known as selection. Food is fragmented during mastication and this can be considered as the result of two processes: selection and breakage (Lucas & Luke, 1983) for solid foods. In this view, every cycle begins with the selection process during chewing, which means the food particles have a chance of being placed on the teeth occluding surface and being fractured. The selection process is undertaken depending on a number of factors, the action of the tongue and the cheeks is the vital factor, but the tooth shape, the total occlusal area of the molar teeth, and the particle size and number are also important for selection process (Vanderglas, Vanderbilt, Olthoff, & Bosman, 1987).

Vanderglas *et al.* (1987) proposed a mathematical equation to describe the selection chances of the artificial food cubes and blocks. The experimental selection chances over one chew $S_{x(1)}$ increased as a power function of the edge size of the particles X_E , hence:

$$S_{x(1)} = v \cdot X_E^w \quad (1)$$

in which v , is the selection chance for $X_E = 1\text{mm}$, and w is constant, and $0 \leq S_{x(1)} \leq 1$ (Vanderglas, et al., 1987). But the selection chances of other foods have not been determined yet.

The breakage function is the measurement of the distribution of fragments of broken particles formed by every chew, relative to the size of the parent particle. The breakage function depends on the mechanical properties of foods (Lucas, et al., 2002).

Kohyama *et al.* (2003) found that the masticatory parameters (number of chewing strokes, mastication time, EMG duration, EMG amplitude and so on) did not correlate with the physical properties of food measured for small deformation. The breaking properties of food had relatively little influence on the entire stages of human mastication (Sasaki, & Hayakawa, 2008).

2.3.3. Subject factors influencing oral processing

Dentitions, age, preference, and gender are known to affect masticatory parameters, including the number of chewing cycles, total EMG activity during a sequence, sequence duration, masticatory frequency, vertical and lateral amplitudes of the mandibular movement.

The number of teeth, loss and restoration post-canine, and the number of occlusal contact areas affect mastication performance (Zhao & Monahan, 2007). Muscle force and the number of teeth are more important than other factors (Kohyama, Mioche, & Bourdiol, 2003; Lucas, 2007; Fontijn-Tekamp, van der Bilt, et al., 2004). Age and gender only influence the number of chewing cycles and the total EMG activity during the oral processing of solid foods (Woda et al., 2005). The tongue function is also affected by age (Hirai, Tanaka, Koshino & Yajima, 1991; Steele & Van Lieshout, 2004a; McAuliffe, Ward, & Murdoch, et al., 2005; McAuliffe, et al., 2008). Preference is a subjective factor. The different preference may be due to consumers finding different food samples are easier to manage in the oral cavity (Brown & Braxton, 1998). For example, the bitter taste decreases the number of chewing cycles (Neyraud, Peyron, Vieira, & Dransfield, 2005), which indicates less preference for consumers.

2.3.4. Food factors influencing oral processing

The human masticatory system is highly responsive to changes in food texture (Lucas, et al., 2002). Food texture has minimal effect on Stage I Transport of mastication and swallowing. But significant differences occur during the processing stage and the time taken for complete bolus formation once the first part of triturated food passes through the fauces (Hiemae, 2004).

De Wijk *et al.* (2006) used four different viscosity and sweetness semi-solid foods to quantify oral movements using an ultrasonic imaging method. Tested foods were made of milk and carboxy-methyl cellulose. They found that oral movements were affected by the sweetness, viscosity and the attributes of food which is being rated. The effect tended to be specific during different periods. During the bulk phase, high sweetness foods stimulated more oral movements than low sweetness foods, and the effects were limited to the anterior part of the tongue. During the swallow phase, specific oral movements expanded to the middle, posterior and horizontal parts of the tongue. Oral movements also increased with food viscosity and sweetness when sweetness was rated. Attributes (thickness, sweetness, creaminess and bitterness) with relatively high perceived intensities induced relatively few oral movements, and were assessed quickly. This study demonstrates that oral movements are determined by food properties and food attributes.

Various terms are used to describe food texture properties; the most commonly used terms are explained below.

Stickiness

A seminal definition of stickiness is the force sensed in removing material that adhered to the mouth (generally the palate) during a normal eating process (Szczesniak, 1963). As the development of food technology, the definition is more objective compared to the first one. The stickiness is focus on the measurable adherence force between different contacting oral surfaces, such as the tendency of a food to adhere to the contacting surfaces, especially the palate, teeth and tongue during mastication (Jowitt, 1974); or the degree of adherence (pasta) to the teeth during mastication (Brown, Dauchel, & Wakeling, 1996); or the energy of separating two contacting surfaces (Gay, 2002). Sticky food is advised to be avoided by dentists, as normally consumers cannot

accurately estimate the retention of food on teeth (Kashket, Vanhoute, Lopez, & Stocks, 1991).

Stickiness is an easily perceived texture feature, but quite hard to measure quantitatively. Some methods to measure this parameter include probe tack method, atomic force microscopy and chemical force microscopy (Chen, Feng, Gonzalez, & Pugnaroni, 2008). Chen *et al.* (2008) applied a probe tensile separation method to quantify the characteristic of fluid foods stickiness and determine its correlation to consumer's sensory perception. They used twelve commercial fluid foods, with different levels of perceived stickiness, e.g. custard, honey, yoghurt, condensed milk and so on. Seven foods were selected to conduct sensory analysis based on quantitative tensile strength, which were classified as high, medium, low and a little sticky. They believed that pressure drop and cavitation of a suddenly stretched fluid could be vital in influencing consumers' sensory perception of food stickiness. They also found a linear relationship between the maximum tensile force and the work till the maximum force against the mean sensory score.

Sensory stickiness has been hypothesized to derive from the viscoelastic and adhesive properties of a food. The type of surface is not an important factor in determining differences in sensory stickiness between food samples (Dunnewind, Janssen, Van Vliet, & Weenen, 2004). De Wijk *et al.* (2003) found positive correlations between sensory stickiness and the starch, fat and carrageenan levels in custard desserts. Sensory stickiness was also found to be affected most by the starch level, followed by the carrageenan and fat levels (Dunnewind, et al., 2004). Some other factors contribute to the perception of food stickiness, such as adhesiveness, chewiness, viscosity, and moisture content (Caldwell, 1970). Kohyama *et al.* (1998) investigated masticatory behaviour using cooked rice with different amylose contents. They found the masticatory behaviour was more related to the adhesiveness and stickiness of rice as measured by a texturometer than to the hardness. Richardson *et al.* (1989) reported that the assessments of sliminess, thickness and stickiness were all directly correlated with dynamic viscosity at a frequency of 50 rad.s^{-1} .

Stickiness usually involves adhesive and cohesive forces. Hosoney and Smewing (1999) found that in most food systems, the adhesion force is a combination of an adhesive force and a cohesive force. If a food material is perceived to be sticky then the adhesive

force is high and the cohesive force is low. At the beginning of mastication, food is just transferred to the molars and broken into a few pieces, and the adhesion and cohesion have not been completely presented; but from the middle to late stages, adhesion has a greater influence on mastication (Kohyama, *et al.*, 2008).

Food particles or emulsion droplets stick not only to themselves, but also to the oral mucosa. Vital factors that determine whether they aggregate or stick around the mouth include the work of adhesion in food-food and food-mucosal interfaces, the surface tension of fluid in the mouth and the viscosity. The frictional resistance that removes food particles from the mucosa by tongue is another related factor (Lucas, Prinz, Agrawal, & Bruce, 2004).

Adhesion and cohesiveness

The practical adhesion of one material (A) to another (B) is defined based on two criteria: 1) the adhesion of A to B is a relative figure of merit indicating the tendency of A to stick or bind to B based on an observation or measurement that can be qualitative; 2) the precise meaning of the term is completely dependent on the measurement technique applied, and the experimental and environmental conditions when the measurement was made. Thus, qualitatively, it might be said that A has good adhesion to B because A was never observed to separate from B under a variety of common conditions (Lacombe, 2006). In this general definition, the adhesion is clearly measurable. Aguilera and Stanley considered that adhesion is a subject both of polymer and surface science. The main property of a good adhesive in the food technology field is its capability to wet and spread over the surface of the pieces to be stuck together (Aguilera & Stanley, 1999).

So far, most researchers have measured adhesiveness of processed foods by applying probe tests and calculating the negative area of a force-time curve, either in Texture Profile Analysis (TPA) tests, with a double cycle, or in single-cycle trials. With the increasing precision and variety of modern instrumentation, TPA is a very useful tool for determining instrumental texture parameters. On the other hand, it is clear that not all foods possess adhesiveness; hence it is not worth measuring adhesiveness in all cases (Fizman & Damasio, 2000).

Cohesiveness is a mechanical textural attribute. It comes from cohesive forces – chemically, it is the action or property of particles sticking together, being mutually attractive. Adhesiveness involves sticking to another surface. No comprehensive and objective definition has been agreed upon, but two common conceptions of sensory cohesiveness, are often utilized. The first one is the degree to which the sample deforms before rupturing when biting with the molars (Muñoz, Szczesniak, Einstein, & Schwartz, 1992). This definition is useful for the initial bite of solid foods. The sensory technique used for measuring the attribute is to place sample between molar teeth, compress and evaluate the amount of deformation before rupture sample (Muñoz, *et al.*, 1992). The second definition of cohesiveness is usually referred to as cohesiveness of mass, this is the degree to which the bolus holds together after food mastication (Bramescio & Setser, 1990; Muñoz, *et al.*, 1992). This is useful for semisolid foods or for solid foods that have been chewed. However, neither of them is unsuitable for liquid food.

Cohesiveness is an important attribute for a variety of foods, such as meats, baked goods, and low fat foods, *etc.* Moderately cohesive foods are easy to manipulate in the mouth and tend to hold together during swallowing. Extremely cohesive foods require more work to break down, and foods with very low cohesiveness easily break apart and can become stuck in the throat due to low cohesive force. Videoradiography studies show good cohesiveness of the bolus while swallowing (Gleeson, 1999). Both sensory evaluation and instrumental measurement of cohesiveness have shown good correlation before swallowing (Kaufmann, 2006). A cohesive mixture is formed in the food bolus from liquid-coated particles that cohere by viscous adhesion. Thus, the food bolus can move smoothly down the pharynx during deglutition (Lucas, *et al.*, 1986; Prinz & Lucas, 1995). Therefore, cohesiveness is of considerable importance for patients with dysphagia or swallowing problems in order to choose appropriate food (Desobry-Bandon & Vickers, 1998).

Fat content, particle size, and rheological properties are the primary factors impacting on cohesiveness (Afoakwa, Paterson, Fowler, & Vieira, 2008; Van Hekken, Tunick, Malin, & Holsinger, 2007). Sensory research has demonstrated that higher fat contents produce increased perceptions of cohesiveness and other texture attributes, even ease of swallow (Ordóñez, Rovira, & Jaime, 2001; Szczesniak, 1963). Afoakwa *et al.* (2008) found that larger particles result in decreased perceptions of cohesiveness, but produce a

fattier after feel and a higher perception of particles in typical dark chocolate (total fat was 25% - 35%).

As cohesiveness is an important factor for oral processing and swallowing of semi-solid soft-solid and hard-solid foods, several instrumental prediction methods have been conducted on cohesiveness measurement; but none of them is accurate and widely agreed. This may be because analysed samples are not uniformly distributed on a sensory cohesiveness scale and that the instrumental methods used can crush samples, but there is no saliva addition. However, the sensory evaluation technique of cohesiveness concerns the rupture of the sample (Di Monaco, Cavella, & Masi, 2008).

Flow / viscosity and elasticity

For liquid and semisolid foods the flow behaviour is normally measured in terms of viscosity (η) which is the ratio of shear stress (τ) to shear rate ($\dot{\gamma}$) (Stanley & Taylor, 1993). Most fluid and semisolid foods show non-Newtonian viscoelastic behaviour and exhibit both viscous and elastic properties (Bistany & Kokini, 1983). Yield stress is a typical parameter for fluids, since it is a threshold shear stress. The applied stress must overcome the yield stress to start flow, it is a non-Newtonian fluids effect, and Newtonian fluids will always flow when a stress is applied.

Viscosity is the internal friction of a fluid or its tendency to resist flow. For Newtonian fluids, the viscosity does not depend on the shear rate, but for non-Newtonian fluids it depends on the shear rate (Rao, 2007). In 1979, Szczesniak reported that viscosity related sensory terms such as thin, thick and viscous appeared to compose the most important mouthfeel sensation in the sensory assessment of food texture, which confirmed that flow properties play a dominant role in the assessment of food texture (Szczesniak, 1979). Generally, foods are complex materials which exhibit both viscosity and elasticity in their mechanical behaviour; so that when the firmness of food is assessed subjectively it may not be clear whether the viscosity or elasticity is being judged, because they are the objective quantities for characterizing the different mechanical dimensions of a material (Sone, 1972).

Food viscosity is affected by temperature (Bourne, 2002; Rao, 1977), concentration, molecular weight of solute, and suspended matter (Bourne, 2002).

Food viscosity and flow behaviour are impacted by temperature (Rao, 1977), simultaneously, the amount of ingested food affects the temperature in the involved area, since more fluid foods will be taken into the constant oral cavity in larger volumes than that of thicker foods. And viscosity also influences the retention time before swallowing (Takahashi & Nakazawa, 1991), and the duration of food processing in mouth during preparation for swallowing (Lee, Takahashi, & Pruitt, 1992).

Christensen and Casper (1987) found that the pure oral assessment was less sensitive to physical differences in viscosity than that of combined oral and non-oral assessments, such as visual observation and touching. Dynamic viscosity measurements at 50 rad.s^{-1} have been found to closely correlate with the EMG activities of the muscles that control tongue movement (Dea, Eves, Kilcast, & Morris, 1989).

However, food bolus properties are not constant; they are modified dynamically during mastication.

Flavour

Flavour is mainly released into the oral cavity from food. The non-volatile tastes are detected by the receptors on the tongue — taste buds, while the volatile components are received by olfactory receptors in the nose. Saliva and mastication accelerates the rate of flavour release in the oral cavity (Brown, et al., 1996).

Except gustatory perception, olfactory contribute a lot to flavour, because the flavour largely decreases while pinching the nose during eating. Retronasal aroma, the odour sensation experienced during food consumption, is caused by flavour molecules travelling from the mouth to the nasal cavity via the nasopharynx. Orthonasal aroma, however, occurs during sniffing as odorants enter the nasal cavity through the external nares. Retronasal aroma is affected by salivation, chewing, and temperature change of the food after it enters the mouth (Roberts & Acree, 1995). Odorants are absorbed into the nasal mucosa and afterward gradually desorbed depending on the physicochemical character of the compounds. The whole process is even more complex, because after food material is swallowed, a film containing saliva and residuals of the food with odorants will be formed at the oral and pharyngeal mucosa, contributing to the processes of desorption and absorption (Rabe, Krings, Banavara, & Berger, 2002).

Several factors influence flavour perception. Mastication is the most influential factor; it alters the flavour by accelerating food transport (Burdach & Doty, 1987), increasing the exposed surface area, and reducing the diffusion path from a solid matrix to the vapour phase (Roberts & Acree, 1995). Apart from mastication, temperature change causes food to melt or soften and affects flavour perception. In addition, the degree of flavour release in the mouth is related to the duration of oral processing (Buettner & Schieberle, 2000). Not only the total amount of released odorants but also the flavour profile in general was affected (Rabe, et al., 2002). It is unclear whether food flavour significantly affects masticatory patterns. Alfonso *et al.* (2002) found that masticatory patterns were not affected by bitter flavour. They investigated the effects of bitter flavour on masticatory patterns (several useful parameters for objectively evaluating chewing function) by using acceptable viscoelastic gels containing 0, 40, 70 or 100µm quinine. They found masticatory patterns were not affected by the concentration of quinine in the gels and no feedback from taste to the motor control of mastication.

In solid foods, release of volatiles from the food into the saliva is through mechanisms of dissolution, melting, or hydration of the food mixture. And the non-volatile flavour release is related to the surface of the fragmented food particles and saliva flow. In liquid foods, emulsification and droplet size, saliva flow and breath affect flavour release and perception. Liquid is processed faster in the oral cavity, after swallowing a proportion of the flavour-enriched liquid remains in the mouth, as a thin film coating the oral cavity. The thickness of this coating and the quantity of flavour remaining in the mouth will depend on the viscosity of the film. Further dilution by saliva may alter the relative release rates of the volatiles and the aftertaste (Dattatreya, Kamath, & Bhat, 2002). The majority of flavour components are hydrophobic, therefore, they prefer to partition into the lipid rather than the aqueous or gas phase. In emulsions, the presence of protein at the oil/water interface induces a significant effect on flavour release and flavour perception of hydrophobic flavour compounds (Guichard, 2002). In oral processing, odorant compounds will be less released from liquids within initial ingestion, which contribute to the exponential character of the initial release flavour (Rabe, et al., 2002). For starch based semisolid foods, hydrocolloid and amylose form complexes with aroma compounds (Guichard, 2002). Cayot *et al.* (1998) studied starch-based food matrices, the results did not show the connection with amylose content nor the viscosity of the creams, either. Fat is another important influencing factor of

semisolid foods flavour. Fat influence the flavour of foods through the effects on flavour perception, flavour stability, and flavour generation. The addition of fat induces significant retention of hydrophobic flavour compounds and results in noticeable effects on flavour perception. Variation in the fat content modifies the overall perception of flavour. The melting point of the fats influences the solubility of aromas and flavour release (Guichard, 2002).

2.3.5. Swallowing and oral clearance

The final stage of oral processing is clearance and swallowing. Swallowing varies between individuals, but generally it has three characteristic swallowing patterns: interposed swallow, terminal swallow, and spontaneous swallow (Okada, Honma, Nomura, & Yamada, 2007). Interposed swallow occurs between the occlusal phase and opening phase within rhythmic chewing cycle. The duration of chewing cycle involving interposed swallow is significant longer than normal chewing cycles (Okada, et al., 2007). Terminal swallow ends the masticatory sequence, and always follow preswallowing cycles which is often termed clearance (Hiemae, et al., 1996; Okada, et al., 2007; Palmer, et al., 1997). Clearance cycles are incomplete, irregular, and involve low-amplitude of jaw movement (Okada, et al., 2007). Normally, spontaneous swallow refers to the saliva swallowed naturally in unconsciousness (Kelly, Huckabee, & Cooke, 2006; Shaker et al., 1992).

The precise triggers for swallowing are still incompletely understood. Some scientists consider it to depend on two separated thresholds: food particle size and particle lubrication (van der Bilt, et al., 2005). While others believe cohesion and plasticity may be important (Peyron, Mishellany, & Woda, 2004).

Swallowing is easier for liquid and semisolid foods than solid foods, especially liquid food which can flow to swallow. For semisolid foods, viscosity and other rheological properties impact the swallowing process.

2.3.5.1. Processing of clearance and swallowing

Clearance is a period of irregular mastication behaviour with more complicated tongue movements before swallowing. The aim is to collect the appropriate particles and

prepare to swallow. Hiimeae *et al.* (1996) found clearance to be a characteristic of human mastication which has not been described in other mammals.

Swallowing is a process, passing food from the mouth to the pharynx, then into the pharyngeal and esophageal (Lowe, 1980). The process of oropharyngeal swallowing activates 26 muscle groups within a very short period of time (Buettner, Beer, Hannig, & Settles, 2001). Hiimeae and Palmer (Hiimeae & Palmer, 1999) defined the hypopharyngeal transit time (HTT) as swallowing. HTT is from the moment that the leading edge of the bolus begins to move across the hypopharynx until the trailing edge enters the esophagus, reaching the level of the vocal cords.

Abdelmalek (1955) separated swallowing from mastication and depicted it as three stages in terms of tongue movements: 1) 'closure' stage, the tip of the tongue raised and pressed against the front teeth and hard palate, so as to close off the mouth and pharynx. 2) 'Slide preparation' stage, the hyoid bone pulled upwards and anteriorly sharply, the tongue sloped downwards and backwards, presenting a smooth slope leading from the mouth to the oropharynx. 3) 'Pressure' stage, the bolus is forced to the pharynx by pressure between the tongue and palate. The tongue participates in the oral stage and pharyngeal stage of the swallowing process. A progressive backwards squeezing of the tongue against the hard palate and the contracting constrictor muscles propels the food bolus backwards (Lowe, 1980). A biphasic deformation of the tongue surface was observed with the initiation of the swallow: a) anterior displacement, which is to modify the tongue shape and position to best enclose the bolus. b) posterior displacement and modification of the tongue, which propels the bolus from the oral cavity to pharynx (Gilbert, Daftary, Campbell, & Weisskoff, 1998). Schwestkapolly *et al.* (Schwestkapolly, Engelke, & Hoch, 1995a) observed tongue movements during swallowing with and without an orthodontic appliance using an Articulograph (AG100). They found that the rest and work position of the tongue and the pattern of tongue movement were different. Orthodontic appliance caused the tongue to have a more posterior position, and an increase in vertical and a decrease in the sagittal components of the movement pattern.

In liquid swallowing, tongue movements exhibit a stereotypical sequence, the tongue blade (tip) leads the sequence followed by the tongue body, then by tongue dorsum and finally by the mandible. The second most common sequence observed has been the

tongue body leading the sequence, and then followed by tongue dorsum, mandible and tongue blade (Steele & Van Lieshout, 2008). Jack et al. (1995) studied tongue movement during consumption of liquid, semi-solid and jelly using electropalatography, they characterized the tongue movement into three phases during oral processing: approach, full-contact and release. The release phase corresponded to swallowing, the tongue rapidly went downward in the initial part of release phase, and then decreased in the later stage of this phase. In higher frequency swallowing, fewer variations were observed in the coordination of the tongue and mandible, in other words, the movements of the tongue and mandible tended to be coordinated by a more stereotypical pattern (Steele & Van Lieshout, 2008). In semi-solid swallowing, the tongue movement has not been well understood. De Wijk *et al.* (2008) found that oral movements (jaw and tongue movements) varied significantly with the type of semi-solid food and with the type of attribute. Individual subjects displayed a highly personal behaviour (de Wijk, Polet, et al., 2008). It is hypothesized in this study that the swallowing of semi-solid foods is divided into three groups: liquid pattern, solid pattern and mixed pattern.

2.4. Tongue functionality during feeding

The tongue is the most active element in feeding, it can move approximately 30 times a minute (Szczesniak, 1963), even though the average length of this soft tissue is 10cm at most from the oropharynx to the tongue tip.

The tongue and mandible coordinate movement and innervate the mastication process. In the oral processing of solid food, jaw and teeth complete the ingestion phase, then the tongue transports the ingested food to the molars for mastication, afterwards processed food is moved to the pharynx. At the same time, food retention, sorting and mixing actions take place with the assistance of the cheeks and teeth. Sensory evaluation of food is another important tongue functionality. This function does not only rely on all kinds of sensors on the tongue, but also depends on the tongue movement. If the tongue movement is restricted, subjects get the lowest attribute ratings, when the tongue movements increase in complexity, subjects get gradually increasing attribute ratings, which indicates all flavour and mouth feel attributes require at least some tongue movement (Engelen & Van Der Bilt, 2008). Food attributes are a series of texture parameters; attribute ratings mean the consumer is asked to rate how much he/she likes

the appearance, flavour or texture of a product, or specific sensory characteristics (Peryam & Girardot, 1952; Popper, Rosenstock, Schraidt, & Kroll, 2004).

2.4.1. Food transport

When food is ingested, the tongue moves food forwards, then backwards to carry food to the mouth, then compresses the food against the hard palate and transports it to the occlusal surface of the premolar and molar teeth (Chen, 2009). This movement is to evaluate the required size of the bite of food. In stage I transport, the tongue tip moves upwards and backwards against the anterior hard palate to evaluate the food texture (Okada, et al., 2007). After ingestion, food is moved to the post-canines by a pull-back tongue movement (Stage I transport), a rapid retraction without the tongue shape changing. The duration of this process varies according to initial food consistency. Stage II transport of masticated food through the larynx to the oropharyngeal surface of the tongue occurs intermittently during jaw motion cycles. The main movement during this stage is squeeze-back, which depends on tongue–palate contact (Hiemae & Palmer, 1999).

The tongue mainly controls food placement on the occlusal plane by rotation, tilting and pushing. Three types of processing cycles are found: 1.) unilateral; 2.) bilateral and 3.) Shift. Tongue-pushing and cheek-pushing are important activities to transport food during the end of stage I transport and the intercuspal phase. Jaw movement is more vertical during cheek-pushing than in tongue-pushing. Segregation and aggregation of food is also correlated with tongue movements (Mioche, Hiemae, & Palmer, 2002). Saitoh et al. (2007) examined the effect of chewing on the relationship between bolus transport and swallow initiation by lateral projection videofluorography. They found that chewing and initial consistency can alter this relationship. The transport of liquids to the hypopharynx is highly depends on gravity, while the transport of chewed solid food to the valleculae is active, and depends mainly on tongue-palate contact. Chewing appears to reduce the effectiveness of the posterior tongue-palate seal, allowing food to spill into the pharynx. Chewing behaviour may also affect the timing of food transport and swallow initiation. An articulograph data reveals that patterns of tongue movements are primarily vertical rather than sagittal (Blissett, Prinz, Wulfert, Taylor, & Hort, 2007; Goozee, Murdoch, Theodoros, & Stokes, 2000; Schwestkapolly, et al., 1995a; Steele & Van Lieshout, 2004a, 2004b). An intensive change of the pattern is found at the

posterior tongue dorsum, where sagittal components are decreased and vertical components are increased. In addition, the direction of the moving orbits of the tongue tip and the reference point on the mandible runs more parallel (Schwestkapolly, et al., 1995a).

Abdelmalek (1955) investigated chewing in subjects who had lost teeth. He described mastication as comprised of five stages: 1) the 'preparatory' stage, in which the tongue dorsum prepares to become trough-like to collect food; 2) The 'throwing-stage', in which the tongue twists over on one side rapidly, and the dorsum faces the lingual surface of the teeth, so that it can throw food onto the surface of the lower molar teeth; 3) The 'guarding' stage, in which the tongue keeps a twisted position and the dorsum presses the medial side of the grinding teeth to prevent food falling down to the occlusal plane; 4) The 'sorting-out' stage, in which the buccinator muscle pushes the food into the buccal cavity and on to the tongue, and the tongue prepares to return to the position of rest, then moves rapidly and jerkily to help sort out the large particles on to the middle trough-like part of the tongue, after that the large particles can be replaced on the occlusal surface of the teeth to continue processing; 5) The stage of 'bolus formation', part of which overlaps with the sorting stage. The tongue makes alternate side to side churning movements to mix the crushed food with saliva and prepare to swallow. In this model, tongue movement is the key factor to define every processing stage during mastication and swallowing.

2.4.2. Food retention

Intraoral food retention has two meanings. One is that food is retained on the soft tissue and hard dental tissue. After swallowing, this is often referred to as oral coating (Caldwell, 1968). The other is that food is kept at the base of the oral cavity, which consists of the occlusal surface, the lingual side of the teeth and the tongue surface during oral processing (Abdelmalek, 1955; Kashket, et al., 1991; Xu, Lewis, Bronlund, & Morgenstern, 2008). The majority of food is retained on the tongue during feeding; a small fraction is kept on the teeth and other tissue in the oral cavity (Abdelmalek, 1955; Kashket, et al., 1991).

Before food is introduced to the mouth, the tongue dorsum goes upwards and prepares to become trough-like in shape in order to collect food. After food ingestion, food

samples stay stably on the tongue surface until they are transported to the premolars. The tongue is able to position and align food (Prinz & Lucas, 2000). Apart from placing food samples on the teeth, the tongue twists and its dorsum presses on the medial side of the molar teeth to prevent the food samples or fragments slipping medially into the buccal cavity (Abdelmalek, 1955). The tongue and the buccinator muscle of the relevant side act together to keep the food between the molar teeth, and prevent its escape, while cutting and comminuting food. This function is not completely understood, but a number of food properties are thought to affect it, such as stickiness, crumbliness, viscosity and so on (Caldwell, 1968).

Oral coating is one form of food retention in the oral cavity. Previous studies found that this form of food retention is related to food texture, amount of ingested food and salivary flow rate (Caldwell, 1968). Adhesion is considered the most important physical property related to the intraoral food retention (Caldwell, 1970). When people chew food, sticky food can be squeezed between the teeth and into fissures will be retained there for a longer period (Caldwell, 1970) and different types of food are cleared at different rates (Kashket, et al., 1991). Kashket, *et al.* (1991) studied twenty-one commercial foods to determine the food stickiness rating and tooth retention of each food. They found that the amount of food retained increased proportionally with the amount of food ingested and the weight of retained food particles decreased progressively with the time of food consumption for all tested foods. Salivary flow rate is related to the speed of food clearance in the oral cavity, and salivary amylase may be important in loosening the adhesive bond of starches to intraoral surfaces (Caldwell, 1970). The solubility of food may affect food clearance or retention as much as adhesiveness (Caldwell, 1970).

A number of studies found that foods with a high starch content have slow salivary clearance rates, while which are rich in sucrose foods have initially high salivary carbohydrate levels and rapid clearance rates (Bibby, Mundorff, Zero, & Almekinder, 1986; Edgar, Bibby, Mundorff, & Rowley, 1975). Kashket, *et al.* (1991) found the initial retention appears to vary inversely with most food clearance rates. In recent years, scientists have used infrared spectroscopy (de Jongh, Janssen, & Weenen, 2006; De Jongh & Janssen, 2007), sensory panels (Prinz, Huntjens, & de Wijk, 2006; Wijk, Kapper, Borsboom, & Prinz, 2009) and instrumental turbidity of rinse water to measure

oral coatings for semi-solid foods. The results have indicated that oral coating is very useful for food sensation, especially for after-feel sensation. Different semi-solid foods have various oral coating locations and clearance rates. The oral coating of starch-based semi-solid foods is impacted by saliva due to the reaction of amylase. The turbidity of rinse water is strongly correlated with food viscosity and fat content (Prinz, et al., 2006).

2.4.3. Food sorting and food mixing

Food sorting occurs after the completion of a series of chewing movements. The upper and lower molar teeth are separated from each other, while the buccinator muscle drives the cheek medially so that it bulges between the teeth and pushes the falling food into the buccal cavity and on to the tongue, which is preparing to regain its rest position on the floor of the oral cavity (Abdelmalek, 1955). Then, the tongue moves rapidly and jerkily again. This kind of fast movement may help to sort out the larger particles of food (which still need comminuting) on to the middle trough-like part of the tongue, and then place them between the teeth, while sufficiently comminuted particles are placed more laterally on the tongue sides (Abdelmalek, 1955). These movements are repeated until all food particles are comminuted.

Simultaneously, the tongue mixes food particles and saliva together to make a cohesive bolus, which is suitable to swallow. While forming a bolus, the tongue makes alternate side to side mixing movements; these are referred to as throwing or rolling and folding movements (Prinz & Heath, 2000). Rolling movements are when the tongue rotates the food around its long axis; this operation is performed by the tongue primarily. Folding food along its long axis is mostly performed by the teeth (Chen, 2009), in preparation to crush food into smaller particles. However, not all foods require sorting and mixing. Imai *et al.* (1995) identified two phases during chewing peanuts using ultrasonography: sorting, which is irregular, and bolus formation, which is stable and rhythmic in vertical motion. However, some test foods (semi-solid foods - pudding and banana) only had one phase (bolus formation), as they can be swallowed without chewing.

After sorting and mixing, food bolus are move to pharynx for swallowing. Multiple swallows were observed within sequences while feeding, it was inferred that two processes must be occurring concurrently during the chewing cycles preceding a

swallow: first, inadequately triturated food continues to be processed; second, adequately triturated food is collected for bolus formation. The tongue has been assumed to be greatly responsible for these segregation and aggregation activities (Hiimeae & Palmer, 1999).

2.4.4. Food evaluation

Food evaluation does not start in the mouth. People begin to have food sensory impressions from the marketplace where visual, odour and tactile senses, and perhaps taste are used to select food. Most people use their senses of sight, smell, taste, touch and hearing to measure the sensory characteristics and acceptability of food. Sensory factors are the major determinant of people's subsequent purchasing behaviour (Watts, Ylimaki, Jeffery, & Elias, 1989). The tongue and soft tissue in the oral cavity contain many sensory receptors as discussed in Section 2.2.4.

These chemical receptors, mechanical receptors, rapidly adapting sensors and deep sensors can not only perceive saltiness, sweetness, bitterness and sourness, but also detect the surface and texture properties of food and particles. While food is being manipulated, food evaluation is dynamically proceeding and a message is sent to the central nervous system to decide what to do next.

Tongue movement is also important for food evaluation. Perception of flavour and mouth feel attributes is assisted by tongue movement. Engelen *et al.* (2008) found that if the tongue movement is restricted, subjects receive the lowest attribute ratings, when tongue's movements increase complexity, subjects receive gradually increasing attribute ratings.

2.5. Neural Control

2.5.1. Central nervous system (CNS) control

Mastication is regarded as an unconscious and automatic behaviour. It is regulated by a central pattern generator (CPG) in the hindbrain (Dellow & Lund, 1971; Hiimeae, 2004; Lucas, et al., 2004; Lund, 1991; Nakamura & Katakura, 1995). The CPG needs external triggers. Once the motor output starts, it produces a fixed movement with a constant rhythm (Lucas, et al., 2004).

The mastication CPG is subdivided into two neuronal groups by function: one group generates masticatory rhythm, which means giving a time signal to alter the rhythm of jaw closing and jaw opening; the other group generates a spatio-temporal pattern of the activities of the jaw, tongue and facial muscles (Nakamura & Katakura, 1995). The former neuronal group regulates the cyclical movements of feeding: each cycle has closed and open phases in humans. Each open and closed phase includes antero-posterior and medio-lateral elements (Hiimeae, 2004). It is assumed that the heart of the CPG is located between the Vth and VIIth nuclei in adults. Part of the brainstem between the rostral poles of the trigeminal (NVmot) and facial motor nuclei (NVII) can produce rhythmical movements in the jaw muscles even when separated from the rest of the brain (Kogo, Funk, & Chandler, 1996; Nakamura, Katakura, Nakajima, & Liu, 2004).

A series of studies were carried out to determine the role of the facial primary motor area (MI) in the cerebral cortex with different oral behaviour environments. Facial MI was found to play an important role in elemental and learned motor behaviours and in certain aspects of chewing and swallowing (Sessle et al., 2007).

The CPG receives inputs from higher centres of the brain, especially from the inferior-lateral region of the sensorimotor cortex and from sensory receptors. Mechanoreceptors in the lips, oral mucosa, muscles, and in the periodontal ligaments around the teeth roots have particularly powerful effects on movement parameters. Besides controlling motoneurons to regulate the jaw, tongue and facial muscles, the CPG also modulates reflex circuits, and these brainstem circuits are believed to participate in the control of human speech. During mastication some reflexes are suppressed, while the amplitude of others is regulated in phase with mastication. The ipsilateral and contralateral cortical representations of the tongue are under analogous inhibitory and facilitatory control, possibly by the same intracortical network (Muellbacher, Boroojerdi, Ziemann, & Hallett, 2001).

Sakamoto *et al.* (2008) conducted a systematic review of research into the activated regions in the tongue secondary somatosensory cortex presentation (SII) following stimulation of the tongue. They found that the tongue areas are considered to occupy a small region in SII with insufficient spatial separation to differentiate anterior from posterior areas using magnetoencephalography, which has a higher spatial resolution

than EEG. They found that the tongue primary somatosensory cortex (SI) lay more laterally and anteriorly than the hand or foot SI. And the location of the tongue SI in the contralateral hemisphere was significantly different from that of the tongue SII. SII has been speculated to serve a higher level of cognitive function in somatosensory processing (Sakamoto, Nakata, & Kakigi, 2008).

The CPG was proposed to control mastication and swallowing several decades ago (Baessler, 1986; Selverston, 1980). Recently, it was proposed that the CPG for mastication controls soft palate motion during mastication and oral food transport, but not swallowing (Matsuo, et al., 2005). Another study found that subjects can consciously inhibit food to the valleculae in stage II transport during mastication and decide when to swallow. Individual decisions can alter the position of a food bolus in the oral cavity at swallow onset (Palmer, Hiimeae, Matsuo, & Haishima, 2006). This study also indicated that mastication and swallowing are located in different brain areas. From another viewpoint, it also indicated that mastication is not completely unconsciously controlled; individual decisions do affect mastication, especially in food transport and bolus formation.

The final motor pattern is determined by the coordinated activity of all motoneurons in the Vth, VIIth and XIIth nuclei that are fired within each cycle of mastication. There are interactions among CPGs controlling them, between mastication and swallowing, swallowing and respiration, but not between mastication and respiration (Lund & Kolta, 2006).

2.5.2. Peripheral nerve control

2.5.2.1. Tongue innervations

The peripheral nerve control of the tongue is quite complex involving several cranial nerves. First of all, most muscles of the tongue are innervated by the hypoglossal nerve (cranial nerve XII); only the palatoglossal muscle is innervated by the pharyngeal plexus, a branch of the Vagus nerve (cranial nerve X) (Gest & Schlesinger, 1995). Secondly, sensory innervation of the tongue is divided into taste sensation and general sensation. For the anterior two-thirds of the tongue, which are referred to as the oral part, general sensations and taste sensations are carried via different nerves. Somatic sensations travel from the tongue through the lingual nerve — a main branch of the

mandibular nerve, which emerges from the trigeminal nerve (cranial nerve V). General sensation from the areas of the oral mucosa and the gingiva of the lower teeth is also delivered by this nerve, while the taste sensation of the oral part of the tongue is carried to the facial nerve (cranial nerve VII) through the chorda tympani (Ross, 2007). The posterior third of the tongue is the pharyngeal part, which is innervated simply, as the taste sensation and general sensation are both carried by the glossopharyngeal nerve (Gest & Schlesinger, 1995) (Figure 2-3.).

2.5.2.2. Peripheral feedback

Based on peripheral nerve control, all kinds of sensory receptors in the oral cavity collect sensory information and send them to the central nervous system (CNS) through peripheral nerves (Martini, 1988), which impact and adjust the CNS control during oral processing (Bailey, Rice, & Fuglevand, 2007; Chicharro, et al., 1998). In this process four kinds of papillae, rapid adapting receptors and deep receptors collect all taste and general sensations and deliver peripheral feedback to affect masticatory behaviour (Brown, Langley, Martin, & Macfie, 1994; Lassauzay, Peyron, Albuissou, Dransfield, & Woda, 2000).

Many studies have shown that peripheral feedback does exist. Foster *et al.* (2006) hypothesised a dual theory: firstly, a cortical-brain stem preprogrammed mechanism to adapt the shape of the jaw movements to the rheological properties of the food; secondly, a brain stem mechanism with mainly sensory feedback from the mouth to adapt muscle force to food hardness. Lowe (1980) found that local anesthesia had been applied to oral tissue and the temporomandibular joint (TMJ), rhythmic coordinated masticatory movements did not change in humans, but the tongue was often injured; this indicates that tongue protective reflexes are disrupted when the peripheral sensory feedback is blocked. The tongue protective function during mastication has been attributed to the lingual nerve in humans (Lowe, 1980).

The feedback includes signals about the physical properties of food which change progressively during mastication producing a concomitant change in the muscle work and cycle speed (Brown, et al., 1994; Lassauzay, et al., 2000).

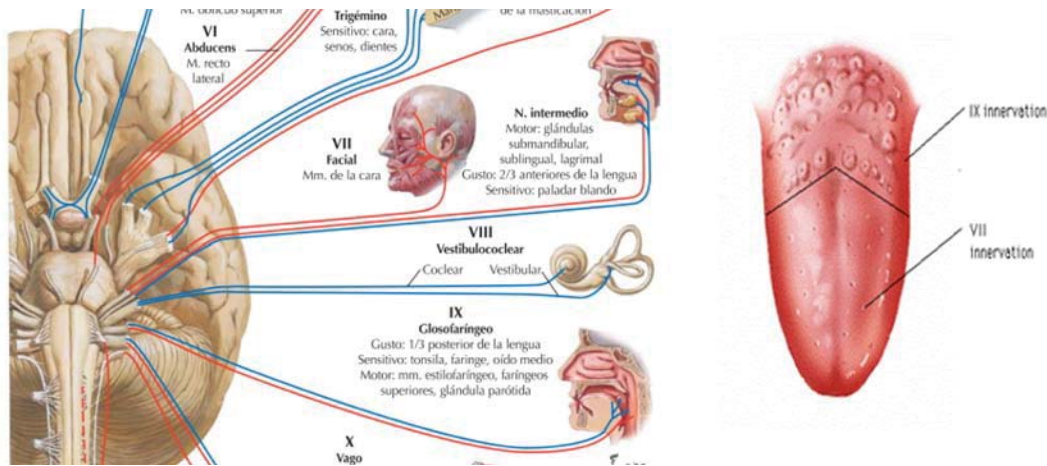


Figure 2-3. Left: Tongue innervations by cranial nerves. Right: Mapping of areas sensory innervation on the tongue (Colbert, B. J., Ankney, J. J., Lee, K. T., 2010)

2.5.2.3. Blocking tongue function

In animal experiments, researchers have found that periodontal pressure receptors and muscle spindles provide positive feedback to jaw-closing muscles during mastication (Bilt, Engelen, Pereira, Glas, & Abbink, 2006). However, human topical anaesthesia experiments have shown that rhythmic chewing activity can still be evoked in the cortex, after elimination of superficial sensory feedback from peripheral receptors. This means that neither periodontal input nor muscle spindle input is essential for basic rhythmic mastication activity (van der Bilt, et al., 2005). Possibly, rhythmic chewing activity after topical anaesthesia could be attributed to deficient anaesthesia.

In experiments in which topical anaesthesia was applied to tongue dorsum and palate, no significant difference was found in size perception of food particles (Engelen, van der Bilt, & Bosman, 2004). Engelen, et al. (2005) found that oral perception of the size of small spheres was underestimated, the sizes of large spheres were overestimated, and that topical anaesthesia also reduced spatial acuity (such as two-point discrimination). It was assumed that two-point discrimination only stimulates the superficial receptors which can be blocked by anaesthetic, while perception of spheres or irregular particles might stimulate more deep receptors, which are important to mastication performance and swallowing (Engelen, et al., 2004). All these experiments only blocked the superficial receptors in the oral cavity, as the method used was invasive. However, some interesting findings emerged from studies with participants with hemiplegia. Those with hemiplegia of the right side cannot chew on the left unparalysed side, though the left side mandibular muscles are still healthy, because the muscles of the right half of the

tongue cannot throw food to the left side of teeth. People with cancer of the tongue experience a similar impairment; they only masticate on the affected side after recovery from operation (Abdelmalek, 1955).

2.6. Oral processing measurement techniques

Several techniques have been used to measure muscle activities, jaw, head and tongue movements during oral processing.

2.6.1. Functional MRI (magnetic resonance imaging)

Functional MRI (fMRI) is a type of specialized MRI scan and one of the most recently developed forms of neuroimaging instruments. It measures the haemodynamic response related to neural activity in the brain or spinal cord of humans or other animals. In mastication research, fMRI has been used to investigate the variation in the blood-oxygenation-level-dependent (BOLD) signals in both hemispheres before chewing and after chewing, and variations in BOLD during tongue protrusion, leftward and rightward tongue movement (Shinagawa et al., 2004). Echo-planar imaging (EPI) is one of the most efficient forms of MRI. It has the fastest acquisition method (100ms/slice), but limited spatial resolution. It has the capacity to image lingual soft tissue in 3 spatial dimensions during physiological movement (Gilbert, et al., 1998).

MRI has low invasiveness and radiation exposure, and relatively wide availability. But the limitation of this technique for feeding research is that the subject has to be lying down, which can affect bolus handling in the oral cavity before swallowing initiation and the time of pharyngeal transit. The other limitation is it cannot clearly show intramural anatomy and mechanics, particularly the relationship between the intrinsic and the extrinsic musculature of the tongue (Gilbert, et al., 1998). It is also relatively costly.

2.6.2. EMG activity

Electromyography (EMG) is a technique used to measure and record the electrical activity in muscles (Jonas, 2005). When muscles are active, they produce an electrical current which is usually proportional to the level of muscle activity (Shiel, 2009). EMG is often used in case of muscular dystrophy, inflammation of muscles, pinched nerves,

and peripheral nerve damage, to detect abnormal electrical activity of muscles or isolate the level of nerve irritation or injury (Jonas, 2005). EMG has also been used in mastication and swallowing research (Casas, Kenny, & Macmillan, 2003; Foster, et al., 2006; Gonzalez, Sifre, Benedito, & Nogues, 2002; Kohyama, et al., 1998; Neyraud, et al., 2005; Pereira, et al., 2006; Taniguchi, Tsukada, Ootaki, Yamada, & Inoue, 2008). Two kinds of electrodes are often used: surface or needle electrodes. Needle electrodes have better muscle selectivity, but are invasive (Huang, Chen, & Chung, 2004).

Studies of mastication which employed EMG have found that the masseter and styloglossus are active in the jaw-closing phase, which perform tongue protrusion. The digastric and genioglossus are active in the jaw-opening phase, which perform tongue retraction (Kakizaki, et al., 2002). In the jaw-closing phase, digastric short burst (DSB) and genioglossus short burst (GgSB) have often been observed in EMG, and often accompanied by an inhibitory period of relevant antagonistic muscles in rabbits. These are thought to be induced by a peripheral sensor input, reflex response (Kakizaki, et al., 2002).

EMG is an effective way to detect the electrical activity of muscles, but does not show the movement of the muscle directly. Surface electrodes which are commonly used are also subject to disturbance and variability due to placement on the skin.

2.6.3. Electromagnetic Articulography (EMA)

The earliest procedure of articulography was carried out by Sonoda in 1974. The technology was developed further until in 1982, the first 2-dimensional Electromagnetic Articulography (EMA) appeared. In 1988 Carstens Medizinelektronik developed the first commercial EMA, AG100. This evolved through several stages into the AG500, which captured 5-dimensional images (three Cartesian coordinates: x, y, and z; and two angular coordinates: azimuth and elevation). This instrument was invented to investigate the movement of articulators inside the oral cavity during speech, but it has also been used to study feeding and swallowing.

In speech research, EMA is used to observe tongue action, especially the action of the tongue tip, tongue body and tongue dorsum during speaking (Cheng, Murdoch, Goozee, & Scott, 2007; Kuruvilla, Murdoch, & Goozee, 2007; Marino et al., 2002). Linguists have used several methods to position sensors on the surface of the tongue to trace

tongue movement in a sealed mouth. Similarly, in feeding studies, EMA is used to investigate lingual movements during oral processing. The receiver coils (sensors) have usually been fixed to the tongue blade, tongue body and tongue dorsum, but the distance from the anatomic tongue tip could be different in different research (Goozee, et al., 2000; Simonsen, Moen, & Cowen, 2008; Tabain & Perrier, 2007). In 2004, Steel and Van Lieshout used an articulograph AG100, to study swallowing (Steele & Van Lieshout, 2004b). In a later study, they observed the dynamics of lingual-mandibular coordination during liquid swallowing, but they fixed receiver coils to various locations on the tongue surface (Steele & Van Lieshout, 2008). Schwesdkapolly et al. (1995b) observed tongue movements while biting and swallowing using EMA.

Earlier EMA studies used the more limited AG100 or AG200 device (Cheng, Goozee, & Murdoch, 2005; Cheng, Murdoch, Goozee, & Scott, 2007; Fagel & Clemens, 2004; Murdoch, Goozee, Theodoros, & Stokes, 2000; Steele & Van Lieshout, 2004; Tabain & Perrier, 2007). In these earlier models, the receiver coils had to be fixed on the midsagittal line of the tongue surface, and their axes had to be perpendicular to the midsagittal plane, parallel with the axes of the transmitter coils. Therefore, only the data in the midsagittal plane could be collected during articulators' movement. These problems were resolved with the AG500 which can collect more dynamic data, not only from the midsagittal plane in the oral cavity, but also from other locations (Blissett, Prinz, Wulfert, Taylor, & Hort, 2007; Wang, Nash, Pullan, Kieser, & Rohrle, 2013). Consequently, it is possible to collect further data of tongue movements during oral processing and observe more tongue functions during feeding.

AG500 collects data of distance from the centre of cube, and the distance between the coils must be greater than 0.8cm (Carstens, 2006). One important limitation is the coils and wires may restrict chewing behaviour.

2.6.4. Videofluorography (VFG)

VFG is a new generation of cineradiography, which requires much lower radiation levels and has become a standard radiological diagnostic tool (Hiimae & Palmer, 2003). It has been widely adopted in studies of mastication and swallowing in recent years (Heath, 2001; Hiimae, 2004; Hiimae & Palmer, 1999; Hiimae et al., 2002; Mioche, et al., 2002; Okada, et al., 2007; Palmer, et al., 1997; Palmer, et al., 2006). For

mastication behaviour, it does not permit fine-scale analysis of tongue fleshpoint movement (Beck & Gayler, 1990). VFG has been used to measure tongue and jaw movement (Palmer, et al., 1997), and investigate patterns of food movement and breakdown in the coronal plane (Mioche, et al., 2002). Using this method, the observer can easily see dynamic images from the video, and directly determine the contour of movement pattern. But this technique still has some defects: specific food position cannot be identified because of the shadow between food and the teeth/tongue (Mioche, et al., 2002); two dimensional data collection means that it is impossible to monitor lateral movement during feeding; and only limited data can be collected from subjects in order to minimise exposure to radiation.

2.6.5. Ultrasonograph

Ultrasonic echo-sonography appeared in the 1950's and began to be widely applied in the medical field and research. Recently, more and more studies have been conducted using ultrasonography during feeding, especially for the study of tongue movement (Blissett, et al., 2007; de Wijk, et al., 2006; Imai, et al., 1995). The ultrasonograph has two imaging types: B-mode images, which show a 2 dimensional recording of the slice through the oral cavity; and M-mode images, which depict the movements of the tongue during chewing, as a function of time. In M-mode, a single column of pixel is abstracted from each frame of the B-mode image and plotted sequentially. The resulting plot allows movement to be seen (de Wijk, et al., 2006). Normally, the probe is positioned laterally underneath the chin to record the movement of a coronal section through the tongue (Blissett, et al., 2007). To quantify the tongue movement, the 'marker' pellet technique can be used in ultrasonographic research as well.

It can image soft tissue in real time and the imaging has a rate of data capture of up to 30 frames / s. It is also non-invasive and cheaper than MRI. Ultrasonography has no physical interference, so does not restrict tongue movements at all. The major disadvantage of ultrasonography is that it cannot record the information of specific lingual fleshpoints, such as the data between the tongue surface and vocal tract, and its resolution is limited. Therefore, most researchers do not use it as the only way to study the whole oral process, but combine with other techniques. However, latest and more complex ultrasound techniques can elicit data and produce 3D models of the tongue surface (Hiimeae & Palmer, 2003).

2.6.6. Tongue pressure measurement

During mastication, swallowing and speech, the pressure in the oral cavity changes dynamically.

Kieser et al. (2008) applied a new method to measure the pressure in the mouth during swallowing. They used 8 miniature pressure transducers fixed on the chrome-cobalt palatal appliance to measure pressure between tongue and lip, the lateral tongue margin and cheeks, and tongue pressure on the midline of the palate. They found some unexpected pressure changes in the mouth, recording negative pressure in the mouth during swallowing, not only at rest. The tongue pressure on the midline of the hard palate increased anteromedially, and then fell rapidly toward the back of the mouth before a wave of increased pressure propelled the bolus toward the back of the palate (Kieser et al., 2008). In an earlier study, it had been found that tongue pressure on the hard palate was generated anteromedially, then followed by a wave of pressure anterolaterally, midmedially, posterolaterally, and posteromedially (Hori, Ono, & Nokubi, 2006; Ono, Hori, & Nokubi, 2004). Casas *et al.* (2003) combined three techniques (EMG, dynamic ultrasound imaging and the miniature pressure transducer) to study the oral processing during chewing of solid food. They found that the intervals between peak pressure recorded at each pressure transducer and peak jaw-closing activity for each masticatory cycle were not significantly different and displayed large statistical variation.

2.7. Rheological measurement

Rheological properties of food are a dominant factor during oral processing, especially for liquid and semisolid foods (Chen, 2009; Janssen, Terpstra, De Wijk, & Prinz, 2007; van Aken, Vingerhoeds, & de Hoog, 2007).

Normally, viscosity measurements are taken under laminar flow conditions. Under conditions of turbulent flow of Newtonian fluids, the measured viscosity will be higher. In general, non-Newtonian fluid foods have laminar flow due to the high viscosity (Morrison, 2001; Rao, 2007). It is hard to determine whether food flow is turbulent or laminar during oral processing. However, it is considered that Newtonian fluids have laminar flow if they are swallowed directly (i.e. with- no extra tongue movement except

bolus transport to the pharynx). All types of foods have turbulent flow if the tongue makes complicated movements during oral processing of foods.

Viscosity is measured by a viscometer. There are various viscometers to fit different foods. Rotational viscometers and concentric cylinder viscometers are the most frequently used instruments. For the former, shear rate is derived from the rotational speed of a cylinder or a cone. For the concentric cylinder viscometer, a cylinder is placed concentrically inside a cup containing a selected volume of the test fluid. The plate and cone geometry is another common tool, but it is unsuitable for dispersions containing large solids. The use of a concentric cylinder and cone-plate geometries in combination with low-inertia rheometers is suitable for studying time-dependent viscous and viscoelastic properties of foods (Rao, 2007). Beside these, parallel disk geometry is suitable for steady, laminar and isothermal flow fluids; a mixer viscometer is often used to measure suspensions of solid matter in a continuous food medium and other complex foods; a vane can also be used to measure certain rheological parameters, such as viscosity, yield stress, shear and so on; pressure-driven flow viscometers (usually Capillary viscometers) are not well suited for studying time-dependent rheological behaviour due to the difficulty of obtaining reliable values of time-dependent wall stresses. At present, viscometers are available for use in combination with a computer, with which shear rate-shear stress data and other rheological parameters can be calculated by software. However, for different foods, such as Newtonian fluids, non-Newtonian fluids, Power law fluids, melting food (chocolates) and so on, corresponding equations and methods are used to calculate data.

Viscoelastic behaviour of many foods has been studied by means of dynamic shear, creep-compliance, and stress relaxation techniques (Rao, 2007). It is conventional to use different symbols for the various rheological parameters in different types of deformation: shear, bulk, or simple extension. The following symbols are used for the 3 types of deformation (Ferry, 1980) (Table 2-2).

Small amplitude oscillatory shear (SAOS) - also known as dynamic rheological experiment - can be used to determine viscoelastic properties of foods. In an SAOS experiment, a sinusoidal oscillating stress or strain with a frequency ω is applied to the material and the phase difference between the oscillating stress and strain as well as the amplitude ratio are measured (Rao, 2007). SAOS experiments provide a suitable means

for monitoring the gelation process of many biopolymers and for obtaining an insight into gel/food structure. Once the linear viscoelastic region is established, three types of dynamic rheological tests can be used to obtain useful properties of viscoelastic foods, such as gels, and of gelation and melting: 1) Frequency sweep studies, in which G' and G'' are determined as a function of frequency at a fixed temperature; 2) temperature sweep studies, in which G' and G'' are determined as a function of temperature at fixed frequency; 3) time sweep study, in which G' and G'' are determined as a function of time at fixed frequency and temperature (known as a gel cure experiment) (Grosso & Rao, 1998). A Thermal Scanning Rigidity Monitor (TSRM) is used to determine viscoelastic properties of foods (Wu, Lanier, & Hamann, 1985). A Vibrating Sphere Rheometer can be used to obtain magnitudes of G' and G'' at a specific frequency, but it has only a limited range of oscillation frequencies (Hansen, Hosney, & Faubion, 1990).

Table 2-2. Viscoelastic parameters from shear, simple extension, and bulk compression (Rao, 2007)

Parameter	Shear	Simple extension	Bulk compression
Stress relaxation modulus	$G(t)$	$E(t)$	$K(t)$
Creep compliance	$J(t)$	$D(t)$	$B(t)$
Storage modulus	$G'(\omega)$	$E'(\omega)$	$K'(\omega)$
Loss modulus	$G''(\omega)$	$E''(\omega)$	$K''(\omega)$
Complex modulus	$G^*(\omega)$	$E^*(\omega)$	$K^*(\omega)$
Dynamic viscosity	$\eta'(\omega)$	$\eta'_e(\omega)$	$\eta'_v(\omega)$
Complex viscosity	$\eta^*(\omega)$	$\eta^*_e(\omega)$	$\eta^*_v(\omega)$

ω is the frequency of oscillation; time $t = \omega^{-1}$.

2.8. Conclusions from the literature

This review provided an overview of human oral processing of solid, semi-solid and liquid foods. It summarised what happens in the oral cavity after food ingestion and what factors impact oral processing behaviour. It is clear that the tongue plays an important role in all aspects of the process.

From this review, it is clear that oral processing behaviour varies during the consumption of different types of food. The properties of food, such as stickiness, hardness, flavour, viscosity, adhesion and cohesion affect oral processing behaviour. Although some work has been carried out on the oral processing of liquid and semisolid foods, no research has been found that characterises how the food properties affect oral

processing time, mixing, saliva incorporation and shear applied. Similarly there is no clear characterisation of the properties (e.g. a critical yield stress) required in the food to alter the mastication process during oral processing. The difficulty of measurement of some of these processes in the mouth is one reason for gaps in existing knowledge. This review, however, identified a number of techniques that could be used to investigate this further.

Chapter 3: Development of methodologies for recording oral processing behaviours during consumption of liquid, semi-solid and soft-solid foods

3.1. Introduction

The main objective for this research was to explore a series of practical methods to accurately measure human oral processing behaviours during feeding. It includes the determination of the observation points in the oral cavity, oral residence time definition and measurement and the determination of the appropriate muscles for muscle activity investigation. An articulograph (EMA, AG500) and an electromyograph (EMG) were used for the development of the methodology.

EMA has been used to investigate the oral processing of liquid and semi-solid foods (Blissett, Prinz, Wulfert, Taylor, & Hort, 2007) over the past decade. Swallowing of semi-solid and solid foods has been well studied using various devices including EMA and EMG (Section 2.3.5). However, the entire process of consuming liquid, semi-solid and soft-solid foods (from acquisition to swallowing) is not well understood. Questions such as how to define and measure food oral residence time, how the tongue moves during oral processing and what drives food bolus formation and transportation still need to be answered. New methods are required to investigate this further.

An electromagnetic articulograph AG500 (EMA, Carstens Medizinelektronik) is a speech movement recording device. It can also be used for recording tongue movement, including the movements of the tongue tip, tongue body and tongue dorsum (Cheng, Murdoch, Goozee, & Scott, 2007; Kuruvilla, Murdoch, & Goozee, 2007; Marino et al., 2005; Steele & Van Lieshout, 2004a).

EMA records the location of the sensors which are attached to the tongue or any other position in the mouth in three dimensions with a high accuracy as they move within a magnetic field (200Hz). The result is calculated by a spatial measurement system and visualized as a graph of traces illustrating the position and orientation of the attached sensors. However, it is difficult for EMA to study oral processing of some soft-solid foods and hard-solid foods, because the wires and sensors restrict the movement of the tongue and lower jaw in the oral cavity. Only a limited number of liquid and semi-solid

foods have been tested using an EMA. These include apple juice, water, chocolate milk, milk (Steele & Van Lieshout, 2004a, 2004b), and a gum Arabic-based confectionery (Blissett, 2007).

Previous studies have recorded the tongue movement at three points: the tongue tip, middle of the tongue upper surface (tongue body) and back of the tongue upper surface (tongue back or tongue dorsum). These points have been found to be the most active areas during speech and feeding (Goozee, et al., 2000; Simonsen, Moen, & Cowen, 2008; Tabain & Perrier, 2007).

EMG has been used in mastication and swallowing research for about 50 years. In food science, EMG is used mainly to measure muscle activities during oral processing of solid foods. Studies of mastication which employed EMG have found that the masseter and styloglossus are active in the jaw-closing phase and perform tongue protrusion. The digastric and genioglossus are active in the jaw-opening phase and perform tongue retraction (Kakizaki, et al., 2002). EMG is an effective way to detect the electrical activity of muscles however it does not show the movement of the muscle directly. Surface electrodes are commonly used but are subject to disturbance and variability due to placement on the skin.

The objectives of this chapter were to:

- 1) Determine appropriate positions for EMA sensors on the upper tongue surface;
- 2) Develop a method for accurately and simply recording the oral residence time (ORT) during the oral processing of liquid and semi/soft-solid foods;
- 3) Select suitable food samples for use in further investigations.

3.2. Determination of the sensor coil positions on the upper tongue surface

The purpose of this work was to determine positions for EMA sensors that will allow measurement of oral residence time and investigation of tongue and lower jaw movement.

3.2.1. Materials and methods

Participant

Having given informed consent, one female subject took part in this preliminary experiment. The subject had a natural dental condition, no neurological impairment, neuromuscular complaints, dysphagia, or dysphonia. She was not taking any medicine which could influence oral movements and saliva secretion (Appendix A1). The study sessions were conducted in an isolated and quiet laboratory room within the Institute of Food, Nutrition and Human Health, Massey University, Auckland. This work was approved by the university ethics committee (Massey University Human Ethics Committee: Southern A Application 10/12).

Food samples

Two commercial foods (roasted peanuts, from the bulk bins at a local supermarket; plain yoghurt, Fresh n' Fruity), and tap water were used as food samples in this study. One medium sized roast peanut, a teaspoonful of yoghurt and 10 ml tap water were each presented on a disposable tea spoon (yoghurt and peanut), or 30 ml plastic container (tap water). Each food sample was tested in triplicate and random order.

Sensor positions

Six sensor coils were secured to the tongue upper surface as shown in Figure 3-1, where: sensor "a" was near the tongue tip (1 cm away from the real tongue tip); sensor "b" and "c" were on the left and right sides of the tongue; sensor "d", named tongue body, was in the centre of the tongue, between sensor "b" and "c"; sensor "e" was on the back of the tongue; and sensor "f" was on the tongue tip, which was the cross point of mid-sagittal line of the upper surface and the lower surface of the tongue. The movement of both sides of the upper tongue surface (sensors b and c) during feeding has not been investigated previously.

Reference sensors were placed on the upper incisor and behind the left and right ears above the bones. These enabled the subtraction of head movements when analysing the data.

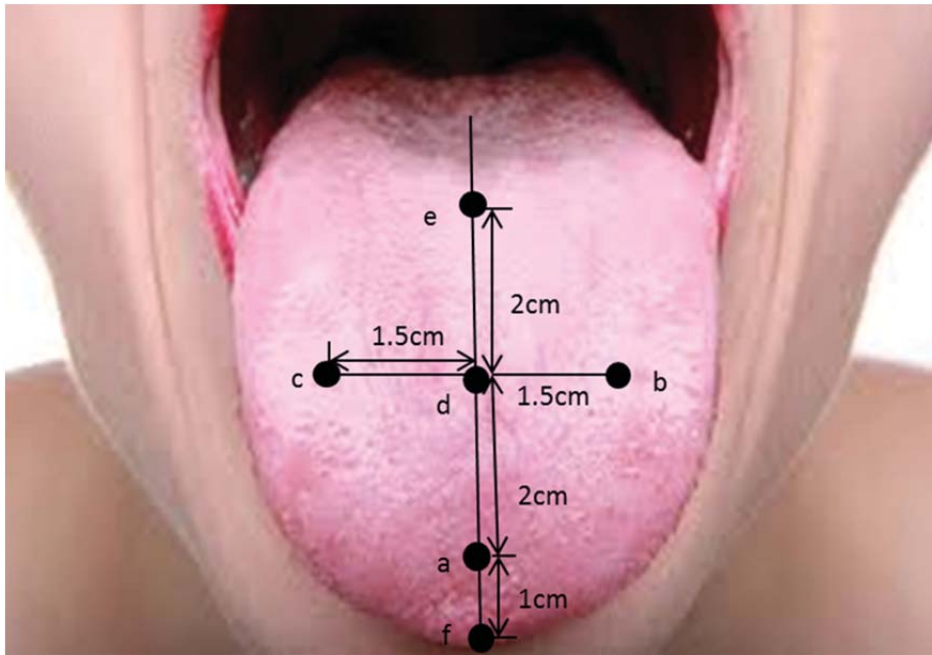


Figure 3-1. Locations for attaching sensor coils to the tongue: a) Near tongue tip; b) Tongue left; c) Tongue right; d) Tongue body; e) Tongue dorsum; f) Tongue tip.

The subject stood in the centre of the articulograph magnetic cube during the experiment. A cosmetic pencil and a ruler were used to measure and mark the positions of the sensor coils on the tongue upper surface when the tongue was at rest position. Prior to gluing sensors, the tongue upper surface was dried carefully and thoroughly using filter paper, especially at the marked area of the sensor coils. Latex (plasty-late) coated sensor coils were secured to the tongue upper surface and teeth using adhesive (Cyano-Vaneer Fast, Hager & Werken) and tweezers. Tweezers and sensor coils were disinfected in a 75% alcohol solution for at least four hours before and after use. The two reference sensor coils positioned behind the ears were secured using tape. In total, nine sensors were attached to the tongue, teeth and behind the ears. An earth line was clipped on the subject's left wrist.

Method

The subject faced towards the positive half of the anterior-posterior axes (X axis) in the centre of the EMA cube (see Figure 3-2). Nine food samples (3 each of roasted peanuts, yoghurt and water) were presented to the participant in random order. Each sample was placed next to the lower lip and then into the mouth. At this point the subject was instructed to start oral processing and recordings commenced. After swallowing,

recordings were stopped and the subject rinsed her mouth three times using tap water in order to avoid carryover to the next sample.

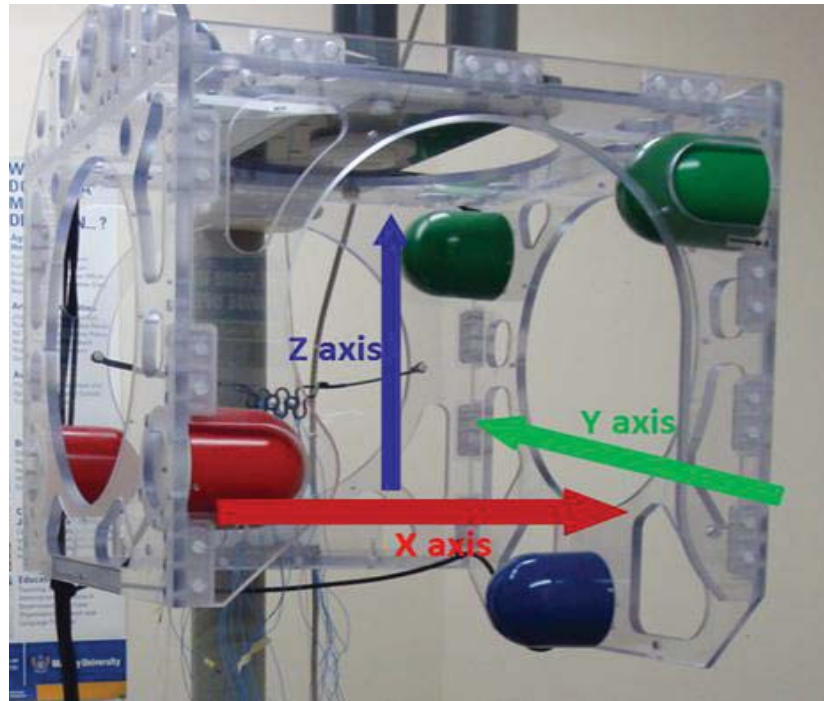


Figure 3-2. EMA AG500 magnetic cube. Three arrows show 3 dimensions in the tube: X axis is anterior-posterior dimension, Y axis is lateral dimension, and Z axis is vertical dimension. The magnetic field is generated by 6 transmitters arranged inside the cube.

Data Analysis

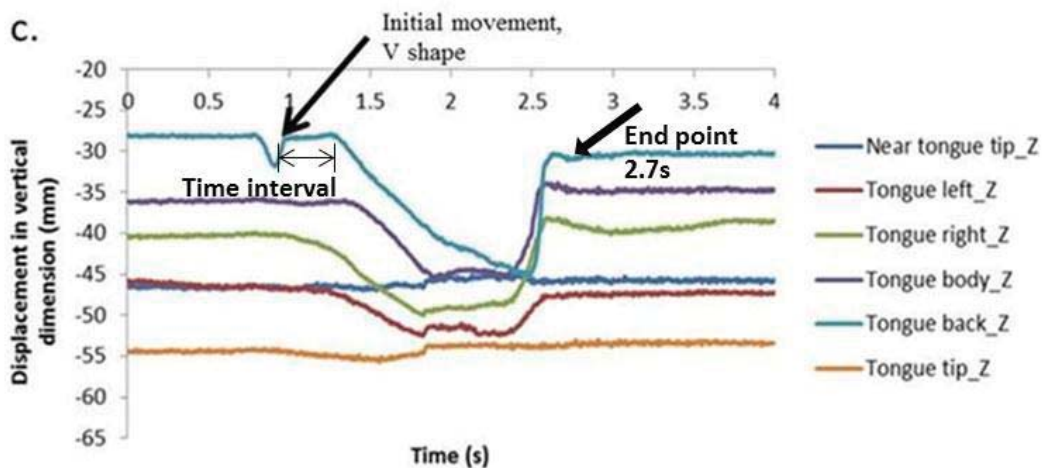
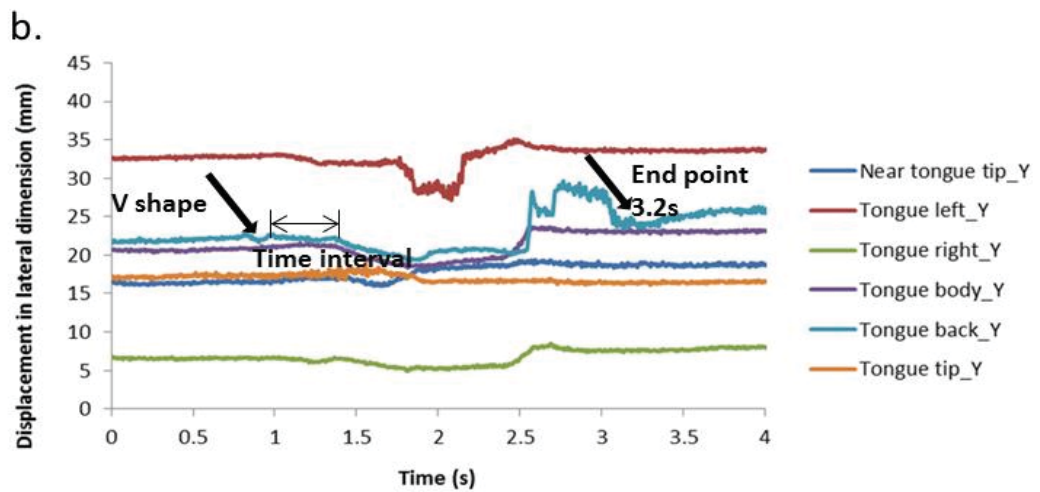
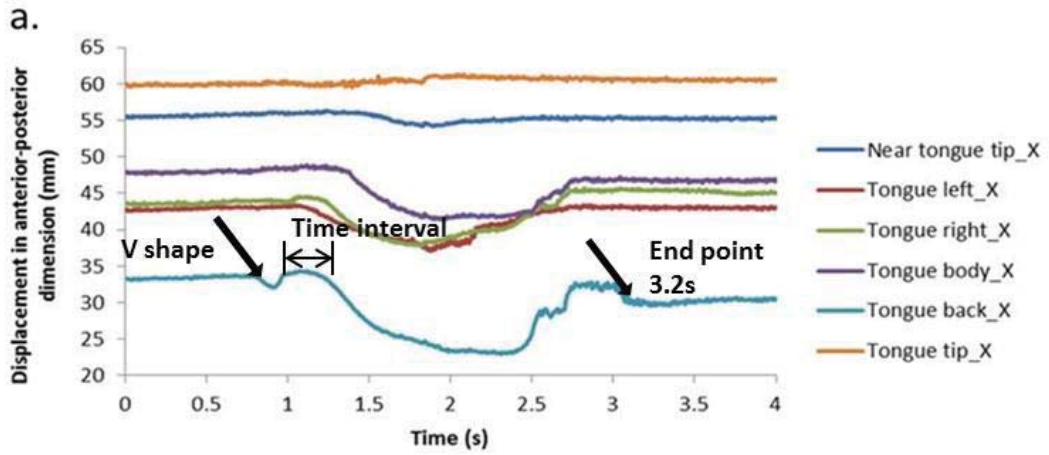
The original data from the EMA is the strength of the signal detected by the sensors within the magnetic field, where the strength of signal is inversely related to the distance from the centre of the EMA cube (where the signal is the strongest). This data was then converted to a distance from the centre of the cube using the CalcPos software. The head movements were later subtracted from the distance data using the NormPos software provided by Carstens.

3.2.2. Results and discussion

Sensor coil displacements in anterior-posterior, lateral and vertical dimensions (X, Y, and Z axis) were recorded, which represented the behaviour of the tongue area under each sensor coil. Figure 3-3 (a, b and c) shows the sensor coils displacement – time plots in three dimensions (X, Y and Z axis) during consumption of one sip of tap water.

Figure 3-3 showed the earliest movement started at the tongue back, which was like a small V shape in all three dimensions. This initial movement is believed to be caused by closure of the oropharynx (the tongue goes backwards and pauses) protecting the subject from choking while drinking fluid (Matsuo & Palmer, 2008; McFarland & Lund, 1995). After that, the tongue left, tongue right and tongue body starts moving backwards one after the other (Figure 3-3a and 3c). The tongue back starts moving again with the tongue right almost at the same time. For this one subject, consuming water, the tongue back has the greatest displacement in all three dimensions, which is related to swallowing behaviour. The tongue tip and near tongue tip do not move greatly, especially the former, during consumption of a thin liquid.

The small V shape movement on the tongue back was used as the start point of the oral residence time measurement. This point was selected as it is the real start of food processing, and is easier to distinguish than the movements of the tongue left, tongue right and tongue body due to the greater slope on the X and Z axes. The final movement during the oral processing of tap water is between the middle and back of the tongue, about 3 to 5 cm away from the tongue tip on the mid-sagittal line. Figure 3-3c (Z axis) shows the clear end point of the oral processing is at about 2.7 s, but on the X and Y axes, the end point is at about 3.2 s, as the tongue back is still moving along the X and Y axes. These outcomes indicate that the data on the Z axis may have been more accurate if the subject had been instructed to remain stationary after swallowing.



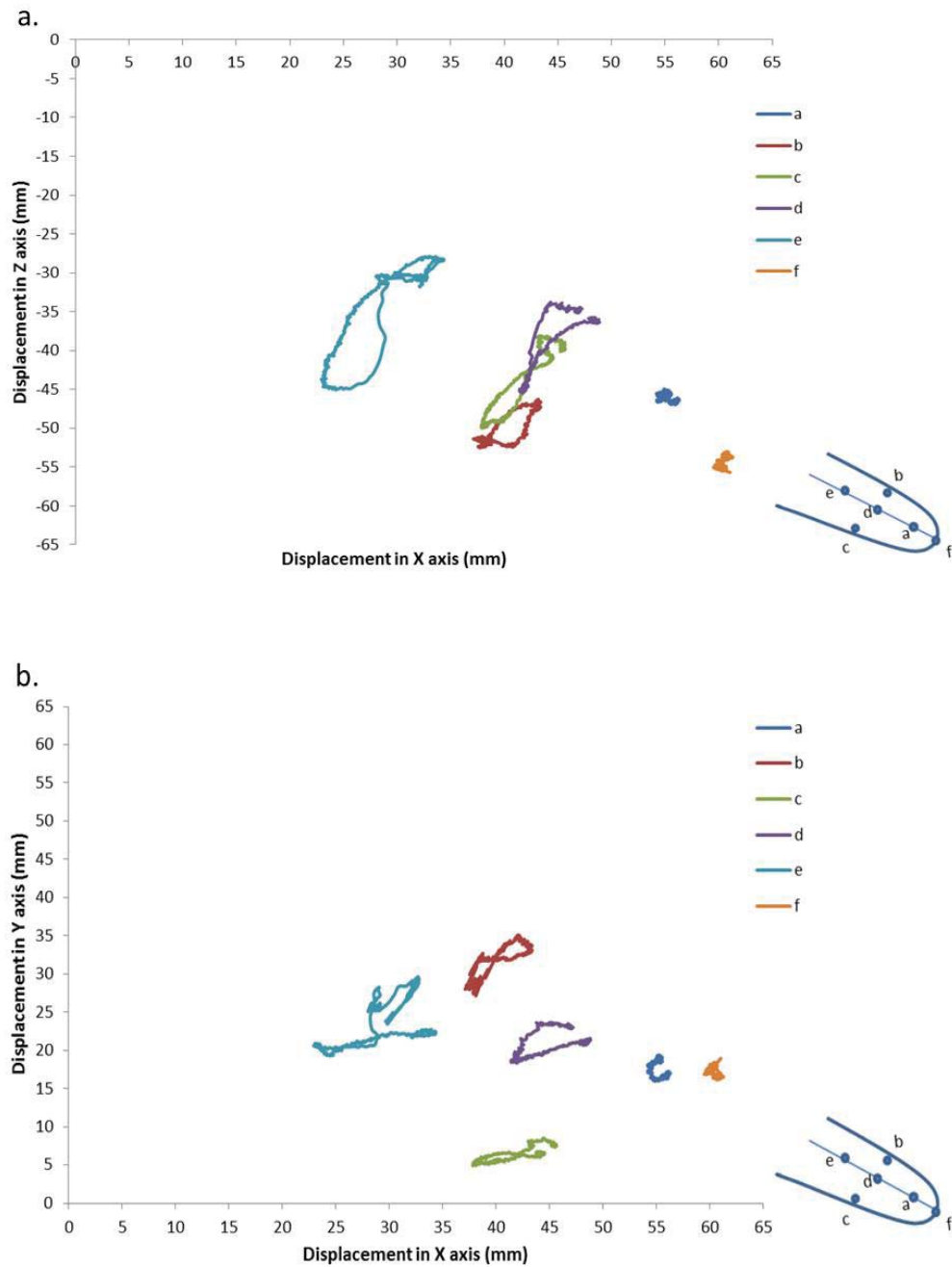
Figures 3-3a, b, and c. Sensor coils movement in three dimensions: a) anterior-posterior dimension (X axis), b) lateral dimension (Y axis), c) vertical dimension (Z axis) during consumption of one sip of tap water. The black arrow points to an initial v shaped movement before oral processing. $\left\langle \right\rangle$ indicates the time interval between food ingestion and the start of oral processing.

There is a time interval between food ingestion and oral processing only on the tongue back during consumption of water (Figure 3-3a, b and c). The time interval is a short pause after the earliest movement. The graphics show that the oral residence time of drinking tap water is very short. The total oral time from opening the mouth to finishing swallowing of tap water is about 1.76 (using the vertical dimension, Z axis as the recording axis) or 2.10 s (using the anterior-posterior dimension, X axis as the recording axis) for this sample. In the lateral dimension for this subject, this time is not as clear as in the other two dimensions, as the amplitude of movement is smaller.

During the oral processing of water, the tongue carries water backwards and downwards directly, and then swallows. Afterwards, the tongue tends to stretch back to the rest position. There are not many other oral movements. However, the tongue does not go back to the original place exactly, shown by the base lines not returning to the same level before and after oral processing. This observation may be attributed to: 1) the features of the tongue, it is soft and flexible and regarded as a ‘muscular hydrostat’, therefore, when the tongue alters in one dimension there is a corresponding alteration in the other one or two dimensions, but the alterations are not always identical (Liu, Yamamura, Shcherbatyy, & Green, 2008); 2) the tongue does not relax completely, because it is preparing for the next ingestion; and 3) some residue was left in the oral cavity, which made the oral conditions different.

According to the experimental protocol, the subject was asked to consume samples as naturally as possible, and was instructed not to pause during consumption. If a subject was waiting for a sample, the subject was free to place the tongue differently.

Figure 3-4a and b show the trajectory of sensor coils in EMA during consumption of tap water in 2 dimensions. The trajectories of the tongue tip and near tongue tip are short and near the initial positions of these sensors. The trajectory of the tongue back (dorsum) is the longest, and it is composed of a small loop (above) and a bigger loop (below). The bigger loop is considered to be caused by the swallowing movement.

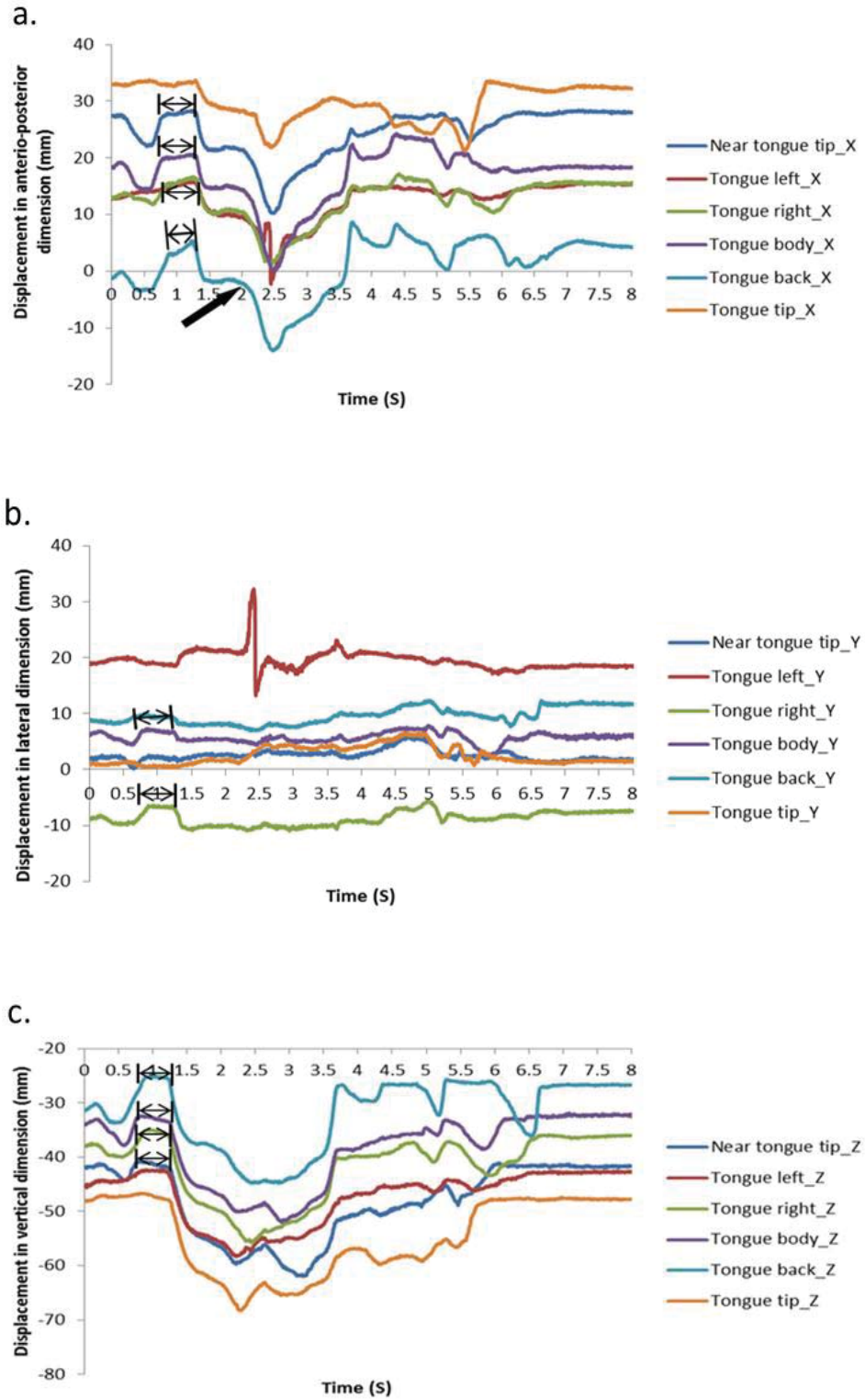


Figures 3-4a and b. Traces of sensor coils in EMA during consumption of tap water. Graphic a shows X-Z plane (anterior-posterior and vertical dimensions); graphic b shows X-Y plane (lateral and vertical dimensions). Sensor a, b, c, d, e and f represent near tongue tip (blue), tongue left (red), tongue right (green), tongue body (purple), tongue back (light blue), tongue tip (orange).

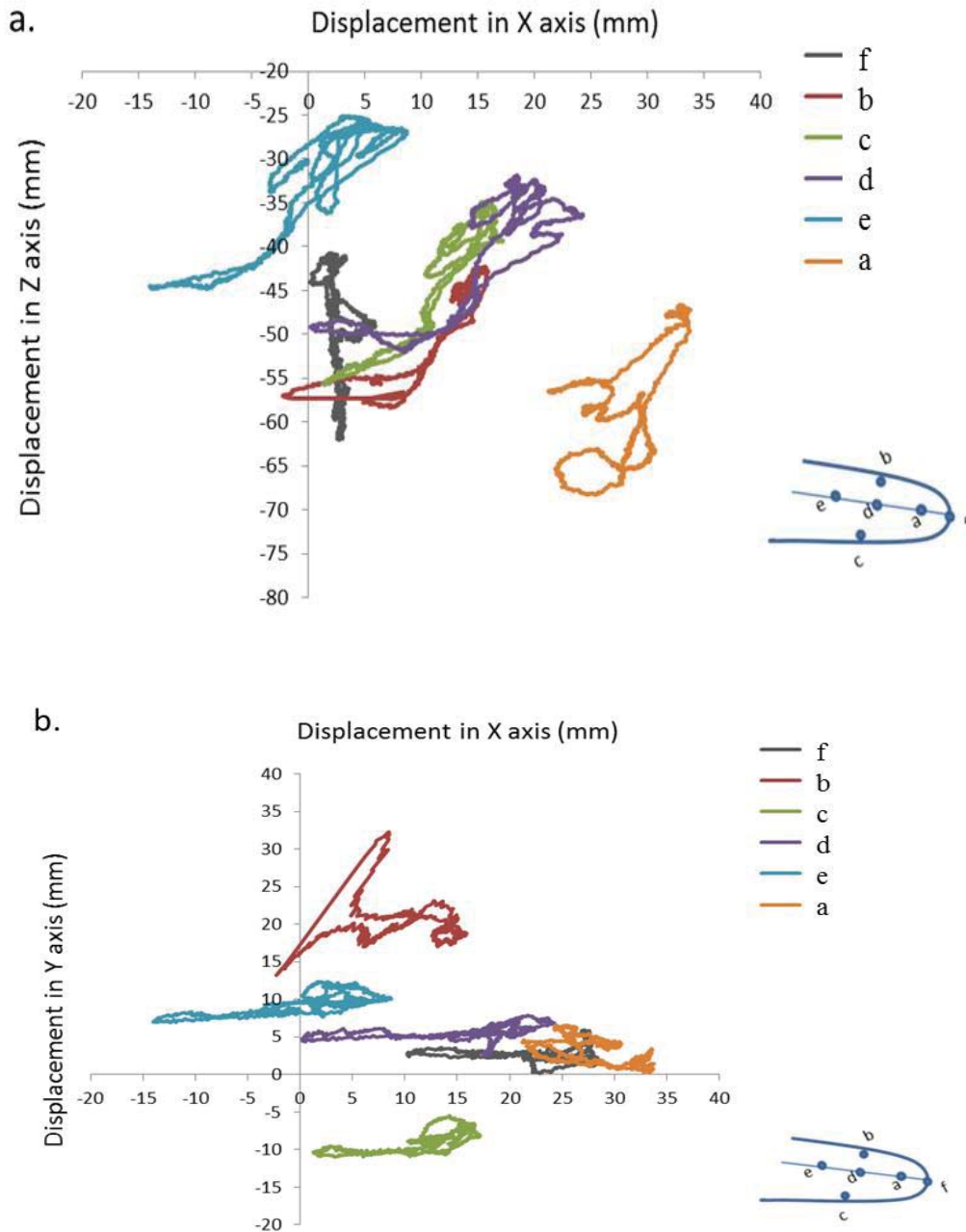
Figure 3-5 plots the movement of the sensor coils on three axes during consumption of yoghurt. There is a clear difference between this case and the consumption of tap water. A distinct time interval was found between food ingestion and the oral processing behaviour on the X, Y, and Z axes. This is a natural delay between food ingestion and

oral processing (indicated by $\leftarrow\rightarrow$ in Figure 3-5). The time interval was about 0.24 - 0.67 s as estimated from different dimensions and different positions. This interval only appeared in the vertical dimension during consumption of tap water (the flat phase after the V shape in Figure 3-3c). The start of mouth opening and end of swallowing were not clear enough to determine the oral residence time, because of the uneven base line and the time interval. Therefore, a better method was required to record a clearer start and end of oral processing. During oral processing of tap water and yoghurt, the tongue movement in the anterior-posterior dimension and vertical dimension are greater and more active than in the lateral dimension. But in the lateral dimension, a sharper spike appears which indicates a rapid tongue movement in the lateral dimension after food ingestion. This movement is likely to be food transfer from the mid-sagittal line or right side to the occluding surfaces (teeth) on the left side by the tongue. As it is not necessary for liquid to be transported to the teeth, there is no such sharp spike while orally processing tap water.

During consumption of tap water and yoghurt, sensor coils on the tongue left, tongue right, tongue body and tongue back have similar movement tendencies on the X and Y axis. The displacement of the tongue tip and near tongue tip is greater during consumption of yoghurt than tap water, which will be discussed further in Chapter 6.



Figures 3-5 a, b, and c. Sensor coils movement on X axis, Y axis and Z axis during consumption of one teaspoon of yoghurt. The black arrow shows the commencement of swallowing.



Figures 3-6 a and b. Traces of sensor coils in EMA during consumption of yoghurt. Graphic a shows X-Z plane; graphic b shows X-Y plane. Sensor coils position was the same as Figure 3-1(right bottom of the graph). Sensor a, b, c, d, e, and f represent tongue tip (orange), tongue left (red), tongue right (green), tongue body (purple), tongue back (blue), near tongue tip (grey).

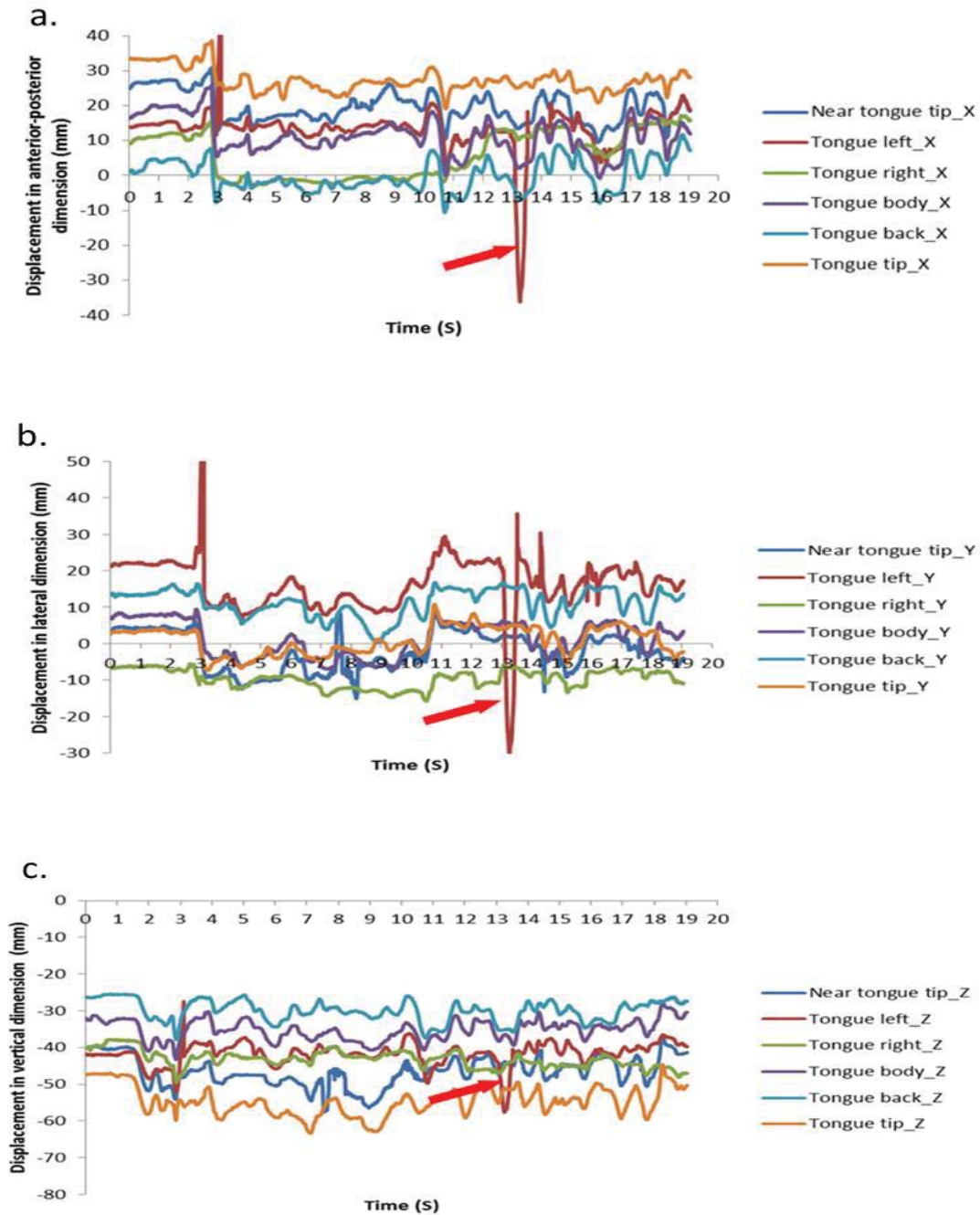
Figure 3-6a and b show the trajectory of EMA sensor coils during consumption of yoghurt in 2 dimensions. The trajectories of the tongue tip and near tongue tip are more complex and longer in this case than those seen during the consumption of tap water. The trajectory of the tongue back (dorsum) looks longer than the trajectories of other

sensors in the X - Z plane (Figure 3-6a), but the trajectories of all 6 sensors are equally complex in the X - Y plane.

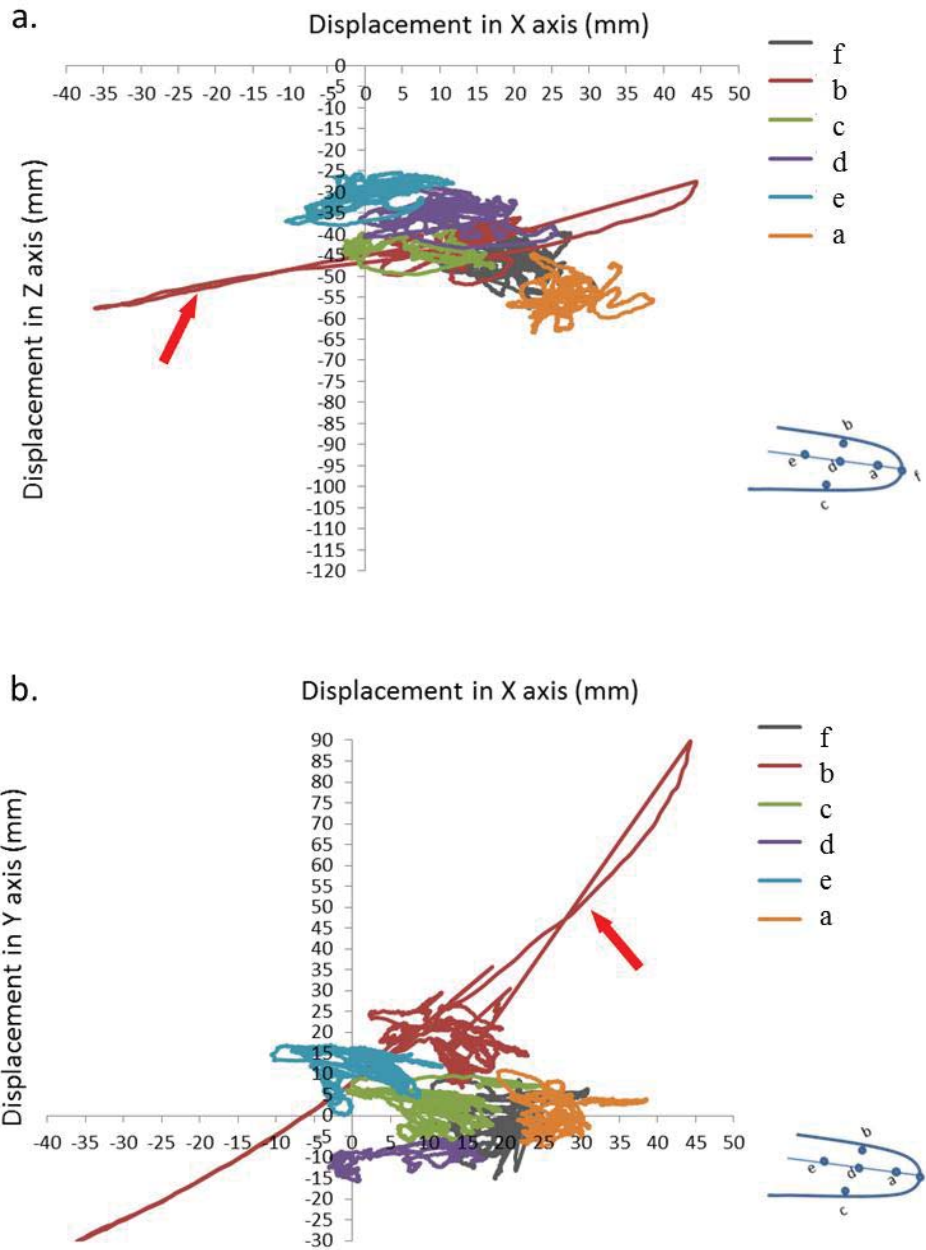
Sensor coils were fixed on different positions in the mid-sagittal line and both edges of the tongue surface in several trials. These trials were carried out to explore new sensor coil positions. For example, the sensor coil position of tongue back were trialled at 4cm, 4.5cm and 5cm away from the real tongue tip in the mid-sagittal line; the position of tongue body were trialled at 2cm, 2.5cm and 3cm away from the real tongue tip in the mid-sagittal line. The sensor coil positions on both tongue edges were trialled at 2 cm and 1.5 cm away from the mid-sagittal line, 3.5 cm away from the tongue tip in side-sagittal line on both sides. The results showed that the sensor coils on both tongue edges have similar movements to the sensor coils on the tongue body and/or tongue tip (Figure 3-3 and 3-5). Therefore, the sensor coils on both edges of tongue upper surface were removed, which also had the advantage of reducing the wire restriction in the mouth. The tongue back and tongue body positions at 5cm (away from the real tongue tip) and 3cm demonstrated the most active and greatest displacements in all trials; therefore, these positions were selected as the best choices (the tongue back and tongue body) in this study.

Figure 3-7 shows the movement of sensor coils on the tongue surface during consumption of roasted peanut. The figures indicate that the subject took the first bite during the first mouth closing and there is no natural delay before starting oral processing. The displacement of the first bite is greater than the following chewing cycles on the X and Y axes. After a few chewing cycles, the sensor coil on the tongue left detached (the red arrow in Figure 3-7), as the sensor coil shows a sharp spike, and the movement of that sensor coil is different from before. The subject was aware of the sensor coil having dropped off. The same trial was repeated to test the stability of the sensor coil gluing on the tongue upper surface during consumption of solids. Tests indicated that the restriction of sensor coils and wires impacted chewing activity in the oral cavity. The hard food or food particles move past the sensor coils and wires, restrict chewing activity and cause the sensor coils to detach and the wires are at a high risk of being cut by the teeth. The articulograph AG500 is not suitable for studying tongue movements during oral processing of hard solid foods. Thus, experimental food samples can only comprise liquid, semi-solid and soft solid foods.

The tongue body, tongue edges, tongue back and near tongue tip went backwards and downwards after food ingestion. The lateral movement was infrequent and small in amplitude during consumption of water and yoghurt, but it was much more prominent during consumption of roasted peanut, as the tongue was moving particles back to occluding surface (Shinagawa et al., 2004).



Figures 3-7a, b and c. Sensor coils movements are shown on X axis, Y axis and Z axis during consumption of one roasted peanut. The red arrow indicates the tongue left sensor coil detached from the tongue upper surface.



Figures 3-8a and b. Traces of sensor coils in EMA during consumption of one roasted peanut. The red arrow shows the sensor coil detached from the tongue upper surface. Graphic a shows X-Z plane, graphic b shows X-Y plane. The annotation of sensor a, b, c, d, e, and f are as same as Figure 3-6.

Figure 3-8 shows the tongue moves actively during consumption of roasted peanut. The trajectories of 6 sensors are equally complex. There is no significant swallowing sign in the trajectory plots.

Figure 3-4 also shows the sensor coils did not go back to exactly the original positions, although they were very close. This causes a problem in that it is hard to ensure that all

sensor coils are placed in exactly the same positions each time on the same person, even when positions are marked on the tongue at rest position.

As it can be seen in Figure 3-6, consuming yoghurt made the tongue movement trajectory more complex than drinking tap water. Both Figure 3-3 and Figure 3-5 show that the tongue had a brief pause after sample ingestion, which is considered to be a protection from thin food flowing to the lower pharynx to prevent choking, and also as a preparation for oral processing. After the detected pause, it starts the transportation and oral processing, but the process is not as fast as drinking water, especially at the beginning phase and the end phase. At the beginning of oral processing, the tongue moves backwards and downwards slowly, and is likely involved in the movements to press and squash foods on the hard palate. During oral processing of yoghurt, the tongue stays in the downwards and backwards position longer than during the consumption of water. This could relate to the food's rheological properties, such as viscosity. The backward movement of the tongue is slowed down by more complicated movements, such as repeated smaller amplitude backwards, downwards and lateral movements. These movements are described as swiping and gently pressing yoghurt on the hard palate using the tongue. The trajectory of sensor coils on the tongue front part is similar to the tongue body, tongue back and tongue edges during consumption of yoghurt. During consumption of water, the tongue front part moves only slightly. This indicates that oral processing behaviour is affected by food type. Food rheological properties are believed to contribute to this effect (Chen, 2009; Chen, Feng, Gonzalez, & Pugnali, 2008).

The trajectories of sensor coils are much more complicated during consumption of roasted peanut (Figure 3-8) compared to yoghurt. Chewing cycles and intermediary swallows made the trajectory more complicated. The red track indicates that the sensor coil on the tongue left position dropped off during oral processing. Several replicates with peanuts demonstrated that the EMA was not suitable to record the tongue movement during oral processing of hard solid food. Therefore, hard solid food was not investigated further in this study.

3.2.3. Conclusions

The preliminary experiment results show that: 1) Mouth opening is not always an accurate starting point for calculating the oral residence time, because the tested food has not been loaded on the tongue surface. For some semi-solid foods, a time interval appears between food ingestion and the start of oral movements. In this study, the time interval is considered to be a part of oral processing and therefore must be included in the oral residence time measurement. The end point of the oral residence time also needs to be defined more clearly. 2) The sensor coils on both tongue edges have similar movements as the tongue tip and tongue body in the anterior-posterior and vertical dimensions. In the lateral dimension, they do not appear to be large movements except for the occasional transfer of food from the tongue or one side of the mouth to the other side. Therefore, these two sensor coils were not used in further experiments in order to give the participant more freedom of movement. 3) EMA AG500 is not suitable for studying the tongue movements during the oral processing of hard solid food.

3.3. Determination of the oral residence time

3.3.1. Determination of the oral residence time using jaw and tongue movements

3.3.1.1. Introduction

Oral residence time (ORT) was defined by Chen and Lolivret (2011) as the period from the time of ingestion until when the subject gave the sign of having completed swallowing. It included food ingestion (from mouth opening to the food being loaded onto the tongue upper surface), oral processing and swallowing. However, the ORT should only record the time when food is loaded and processed in the oral cavity. During food ingestion, the mouth is opened and the food sample is loaded on the tongue surface, but the oral processing movement has not started yet. For thin liquids, the food ingestion (drinking or sucking) time and ORT are both short; for semi-solids and soft-solids, the food ingestion (using utensil or biting) time is longer than for thin liquids. As a consequence the food ingestion time may affect interpretation of the ORT to different extents depending on the food and how it is acquired. Therefore, the food ingestion time

was excluded from the oral residence time in this study. Consequently, the definition of the ORT is different from previous research.

The preliminary experiments and previous studies showed that the ORT of food samples can be measured using EMA (Blissett, et al., 2007). Accurately measuring and defining the ORT using the tongue and jaw movements was the focus of this section.

The objectives of this experiment were to:

- 1) Define the start and end points of oral processing to enable a more accurate determination of the ORT;
- 2) Modify sensor coils positions in the oral cavity to explore more observation points;
- 3) Screen food samples for further experiments.

3.3.1.2. Materials and methods

Participants

Two subjects took part in these experiments. The screening criteria and consent procedures are the same as described in Section 3.2.1.

Food samples

Five food samples were used (Table 3-1). These were chosen because the flavour and texture were acceptable for the subject to consume in one teaspoonful and they did not require classic chewing behaviour.

Food samples were left at room temperature for at least 1.5 hours before serving. Disposable tea spoons were used to carry food to the mouth. The top surface was flattened using the back of a knife blade to ensure constant volume. Each food sample was randomly presented in triplicate. The disposable spoons were weighed before and after oral processing and the amount of residue left on the spoon was calculated.

Table 3-1. Commercial food samples

Food sample	Brand	Company	Serving method
Standard milk (whole fat)	Anchor (blue top)	Fonterra	Ready to serve
Hazelnut spread	Nutella	Ferrero	Ready to serve
Cream cheese	Kraft brand, Original Philadelphia cream cheese	Kraft Foods Group Inc.	Ready to serve
Plum jam	Craig's, Black Doris Plum fruit jam	Wattie's	Ready to serve
Greek yoghurt	Yoplus (natural yoghurt)	Yoplait	Ready to serve.

Method

The method used here was the same as in Section 3.2.1 except that the positions of sensors were different. This work was approved by the local ethics committee (Massey University Human Ethics Committee: Southern A Application 10/12). One sensor was placed on the near tongue tip position (same as in Session 3.2.1.); the second sensor was placed on the tongue base (the tongue lower surface in mid-sagittal line and 2 cm away from the real tongue tip, and in front of the frenulum) (Figure 3-9). This position was not used in previous research. The third sensor was placed on the lower incisor, which moves with the lower jaw and is used to track lower jaw movements. It can also be used to indicate the occurrence of chewing activity. Two reference sensors were fixed, one on the upper incisor and the other behind the left ear (on bone).

The subject sat in the EMA cube; five sensors were secured on the positions described above. The subject was instructed to move the food sample to the lower lip and then put into the mouth after being instructed to begin. The subjects kept their tongue and jaw still for at least 3 seconds (count from 1 to 5s) rather than starting oral processing immediately after food ingestion (Figure 3-9 and Figure 3-10, time b). When oral processing was completed, the subjects kept the tongue and jaws still for another 3 seconds. At this point, recordings were stopped, the mouth was rinsed three times and the subject prepared for the next food sample. The action of keeping the tongue and jaws still was designed to separate the food ingestion (Figure 3-9 and 3-10) time from the start of oral processing and to determine the end point of oral processing clearly to enable the ORT to be calculated.

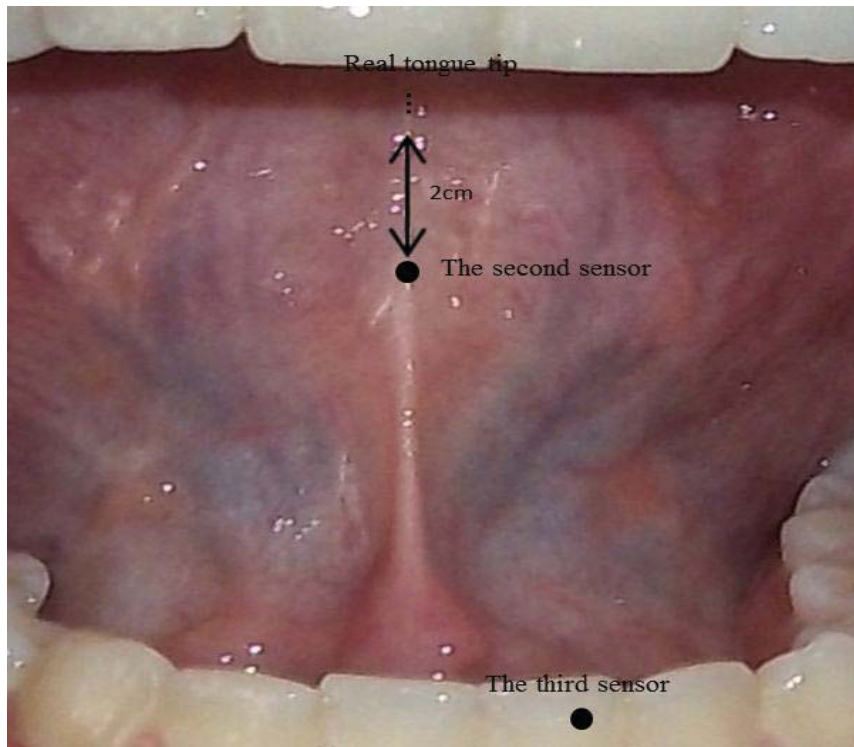


Figure 3-9. The positions of the second and third sensors in the oral cavity

3.3.1.3. Results and discussions

The EMA data (Figures 3-10, 11 and 12) shows that keeping the tongue and jaw still for a few seconds allows the food ingestion time to be separated from the oral movement. The pause at the terminal swallow also makes the end point of oral processing clearer than before (Figure 3-5). In addition, a separate oral movement appears after terminal swallowing (blue arrow in Figure 3-11), which indicates another clearance movement occurs after swallowing. Normally, two or more swallows appear during oral processing (Hiimeae et al., 1996; Okada, Honma, Nomura, & Yamada, 2007; Palmer, Hiimeae, & Liu, 1997) which presents difficulties in determining the end point of oral processing. In this experiment the end time is defined as when the subject finishes the terminal swallow and subsequent tongue and jaw movement cease. The subject was told that all oral movement should stop after the terminal swallow, no matter how much of the food sample remains in the oral cavity. The start of oral processing is very clear in the EMA graphs, so it is defined as the time when the tongue starts oral movement after the food sample is loaded on to the tongue surface.

EMA traces also show that the sensor coil on the tongue base only experienced a small displacement (within 5 mm on the Z-axis). The tongue base remained almost flat, even

during consumption of highly viscous foods such as Nutella (Figure 3-10). The start time and end time are not as easy to determine from the tongue base movements. So far, the most appropriate positions for the sensor coils placement in the oral cavity have been determined to be the near tongue tip, tongue body, tongue back (Section 3.2.) and lower incisor.

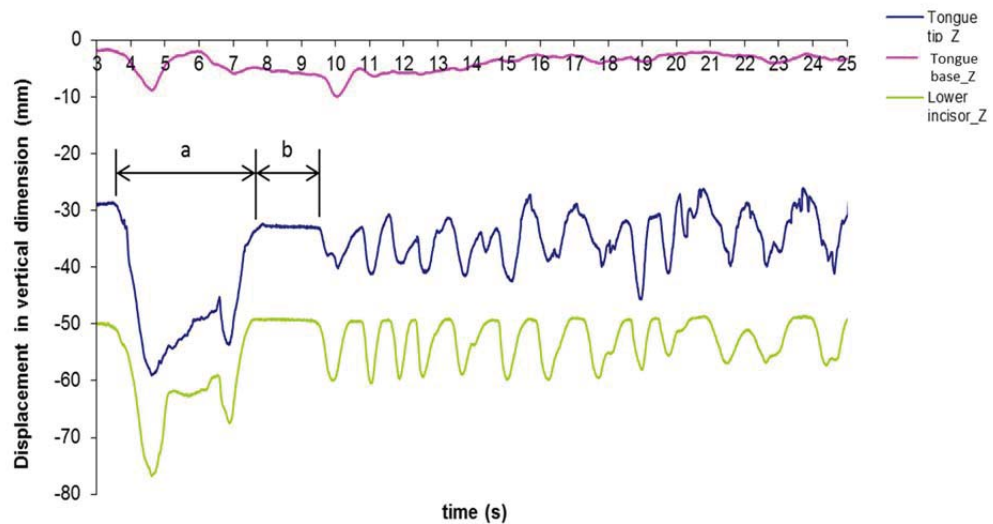


Figure 3-10. The movement of sensors on tongue tip, tongue base and lower incisor on Z axis during consumption of Nutella. The time a is food ingestion time, b is the time the tongue and jaws keep still. This figure does not show the end time of oral processing.

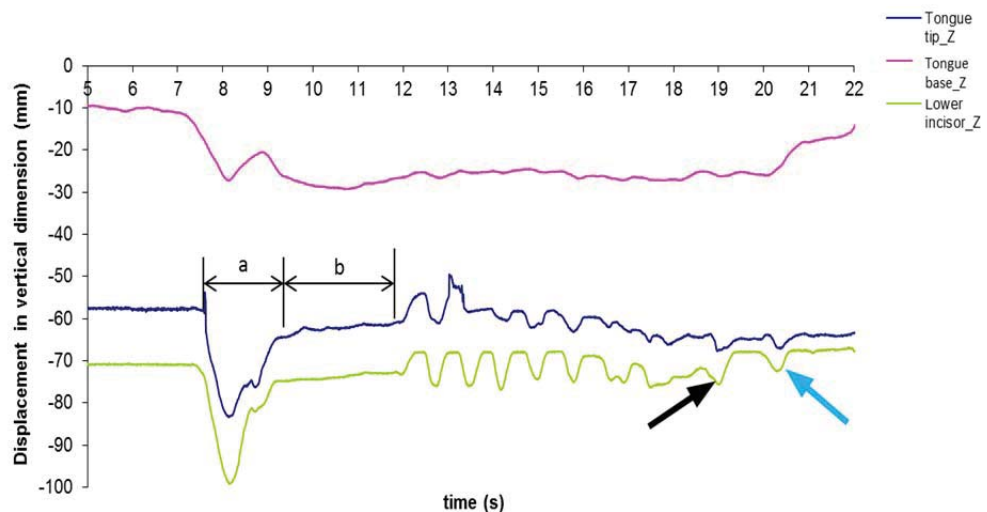


Figure 3-11. The movement of sensors on tongue tip, tongue base and lower incisor on Z axis during consumption of plum jam. The time a is food ingestion, and b is the time the tongue and jaws keep still. The black arrow indicates the terminal swallowing after clearance; the blue arrow shows another oral movement after terminal swallowing and pause.

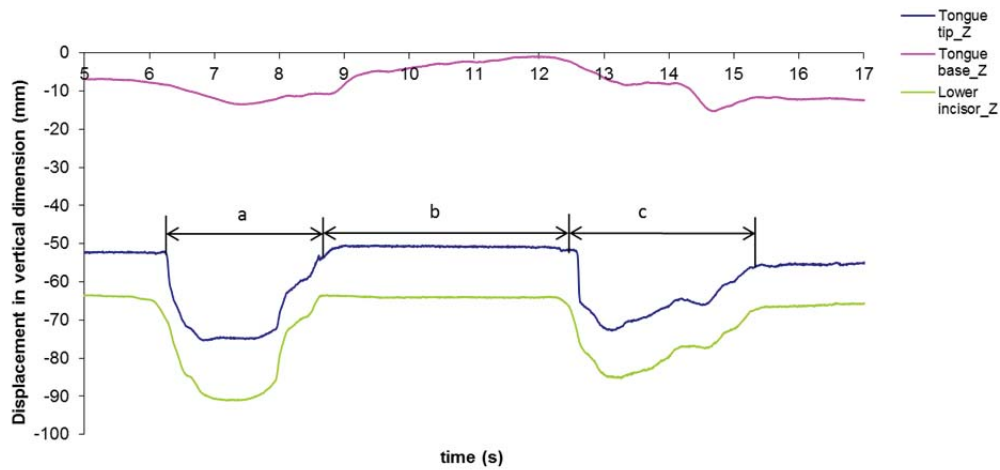


Figure 3-12. The movement of sensors on tongue tip, tongue base and lower incisor on Z axis during consumption of standard milk. The time a is food ingestion, and b is the time the tongue and jaws keep still. The time c indicates swallowing time and movement.

The mean mass of residual food on the spoon increased with the viscosity and stickiness (refer to Section 4.2.3.) of the sample. For example, hazelnut spread (Nutella) had a much higher residue percentage than standard milk. This is likely to have been the result of a stronger adhesive force between the stickier food and the spoon, which led to more residue on the spoon than less stickier foods. Therefore, the mass of the ingested food tended to decrease with increased food stickiness.

Table 3-2. Mass of one teaspoon food samples

Food sample	Mean mass of one teaspoon of food (g) ± SD	Mean mass of residual food on spoon (g) ±SD	Mean mass of food ingested (g) ±SD	Percentage of residue (%)
Standard milk	5.44±0.07	0.12±0.02	5.31±0.08	2.21±0.28
Hazelnut spread	5.56±0.04	0.42±0.03	5.15±0.05	7.55±0.40
Cream cheese	5.73±0.04	0.39±0.02	5.34±0.03	6.81±0.32
Plum jam	5.59±0.10	0.33±0.04	5.25±0.07	5.90±0.50
Greek yoghurt	7.80±0.69	0.31±0.04	7.49±0.72	3.96±0.13

The mass range of one teaspoon of food sample used in the experiment was from 5.44 g to 5.73 g, except yoghurt whose mass was higher. The range of corresponding residue on the spoon after food ingestion was from 0.12 ± 0.02 g to 0.42 ± 0.03 g, and the average value of five samples residue on spoon was 0.31 ± 0.10 g. The mass range of ingested food was from 5.15 ± 0.05 g to 7.49 ± 0.72 g, and the average value was 5.71 ± 0.89 g. There is a large difference in natural bite sizes or sips among different foods (de

Wijk, Zijlstra, Mars, de Graaf, & Prinz, 2008; Hiemae et al., 1996; Lawless, Bender, Oman, & Pelletier, 2003; Medicis & Hiemae, 1998). This portion size was found to be comfortable for the subjects to have as a serve for these five food samples. The average percentage of residue in the spoon was 4.61%. The portion size of food samples to be served in future experiments was therefore determined to be 5.30 g on a disposable teaspoon.

3.3.1.4. Conclusions

A method for determining the ORT was developed. The start point was defined as the time when the tongue starts oral movement after the food sample was loaded on to the tongue surface. The end point was defined as the time when clearance and the main swallow had finished, and all oral movement had stopped. The food sample size for future work was determined to be 5.30 g.

A series of experiments demonstrated that the best sensor positions on the tongue upper surface are: tongue tip, tongue body and tongue back. The best reference sensors are upper incisor and behind both ears.

3.3.2. Determination of the oral residence time using muscle activities

3.3.2.1. Introduction

EMG has been widely used to investigate muscle activities (Section 2.6.2) and is regarded as accurate for investigating facial muscle activities (Hugger, Hugger, & Schindler, 2008; Wozniak, Piatkowska, Lipski, & Mehr, 2013).

The masseter and styloglossus muscles are active when the lower jaw closes and the tongue protrudes. The digastric and genioglossus muscles contribute to jaw opening and tongue retraction (Kakizaki, Uchida, Yamamura, & Yamada, 2002). Two anterior digastric muscles are in the submental triangle. The hyoid bone is the bottom line of the submental triangle and the right and left anterior bellies of the digastric muscles are the lateral sides. The floor of this triangle is formed by the two mylohyoid muscles (Moore, 1925-; Drake, 1950-) (Figure 3-13). Swallowing is closely tied with tongue retraction. Therefore, masseter muscles and digastric muscles are often used to study mastication and swallowing using EMG (Ashida, Iwamori, Kawakami, Miyaoka, & Murayama, 2007; Ishihara et al., 2011; McKeown, Torpey, & Gehm, 2002). Oral movement

comprises not only mastication, but all oral activity involving the tongue and lower jaw movements. Theoretically, masseter muscles and submental muscles (anterior digastric muscles) are suitable to investigate oral movements for liquid, semi-solid and soft solid foods. In addition, these muscles are easy to locate and fix electrodes to.

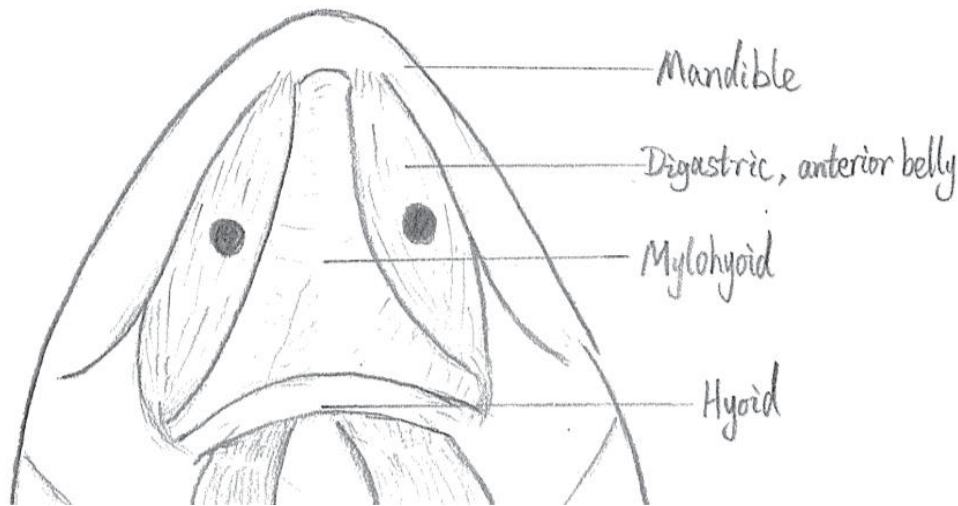


Figure 3-13. The submental triangle area. Black dots show the position of electrodes on submental muscle.

The objectives for this work were to:

- 1) Find positions on the face or neck to accurately determine the ORT using EMG;
- 2) Collect muscle activity data during the oral processing of different foods.

3.3.2.2. Materials and methods

The same two subjects from Section 3.3.1.2 also participated in this experiment. The screening criteria and consent were as described in Section 3.2.1. The subjects were guided to scrub the skin of the masseter, submental muscles or temporalis, Adam's apple, hyoid bone and the collar bones with a rough paper towel, which was wetted with alcohol spray (CV - TRONIC, German). Commercial food products were purchased from a local supermarket: cashew nuts, standard milk, Nutella, plum jam, Greek yoghurt and cream cheese (Table 3-1). One medium size cashew nut and one teaspoon of standard milk, Nutella, plum jam, Greek yogurt and cream cheese were served to the subjects. This experiment has been approved by the Massey University ethics

committee (Massey University Human Ethics Committee: Southern A Application 10/12).

The EMG activity was recorded by a PowerLab/4SP unit (ML750, ADInstruments Pty Ltd, Australia). The bipolar surface electrode was a disposable Ag/AgCl electrode (model MLA1010B, ADInstruments Pty Ltd, Australia). This unit has four-channel inputs, which are band-pass-filtered (10-500Hz). The bio-amplifier setting was: voltage range 2mV, high pass 10Hz, low pass 200Hz, notch 50Hz, and speed rate 1000/s. The signal was filtered (0.5–1,000 Hz) and amplified to 1,000 times of the original using a bio-amplifier. The collected signal was rectified using RMS in Chart5 software, which calculated the square root of the mean of squares (RMS) of the data points in the selection or returned to the absolute value at the active point.

The muscle activities during oral movements were recorded on the subject's preferred chewing side, because previous EMG research found that the amplitude of the activities on the preferred chewing side is greater during oral processing of solid foods (Vinyard, Williams, Wall, Johnson, & Hylander, 2005). The right side was the preferred chewing side for these two subjects. The subjects sat in the chair in their normal feeding position. The room temperature was 20°C. Electrodes were fixed on the right masseter muscle and both sides of the submental muscle (under chin, front belly of digastric muscle, Figure 3-13). These electrodes were attached non-invasively on the subjects' skin and did not restrict the oral movement during feeding. The subjects consumed food samples in a random order. The procedure was as described as in Section 3.3.1.2. Food samples were processed on the subjects' preferred chewing side (right side).

The ORT and the activity of oral movement related muscles were determined from rectified EMG RMS charts.

The ORT was defined as the time from when the food sample was loaded on the upper tongue surface to when the clearance and terminal swallowing had finished (Section 3.3.1.3.). When recording ORT using EMG, the same experimental procedure and the same ORT definition were used for ease of comparison of the two methods in the same conditions.

The RMS plot was numerated from the original EMG trace; data points were selected every 0.02 seconds from the original EMG trace to make the RMS plot. The RMS plot

only has positive value, and gives better view of muscle activity than the original EMG trace. The ORT time was determined from RMS plot according to the ORT definition and the pauses before and after oral processing movement.

3.3.2.3. Results and discussion

Determination of the position of EMG electrodes

In order to get reliable EMG recordings, the EMG electrodes need to be placed in positions where: 1) an adequate intensity of muscle activity during oral processing of semi-solid and liquid foods can be recorded; 2) the traces are reproducible.

Many trials were conducted to select appropriate electrode positions around the facial area. The masseter, temporalis, submental muscle, Adam's apple, and hyoid bone are related to chewing and swallowing activity; therefore, they were chosen to be tested in these trials. The EMG traces of these muscles or positions (subject A) were shown respectively in Figures (Figure 3-14 to Figure 3-19) during oral processing of cashew nut, standard milk, hazel nut spread (Nutella), cream cheese, plum jam and Greek yoghurt. The EMG traces of subject B are shown in appendix (A2).

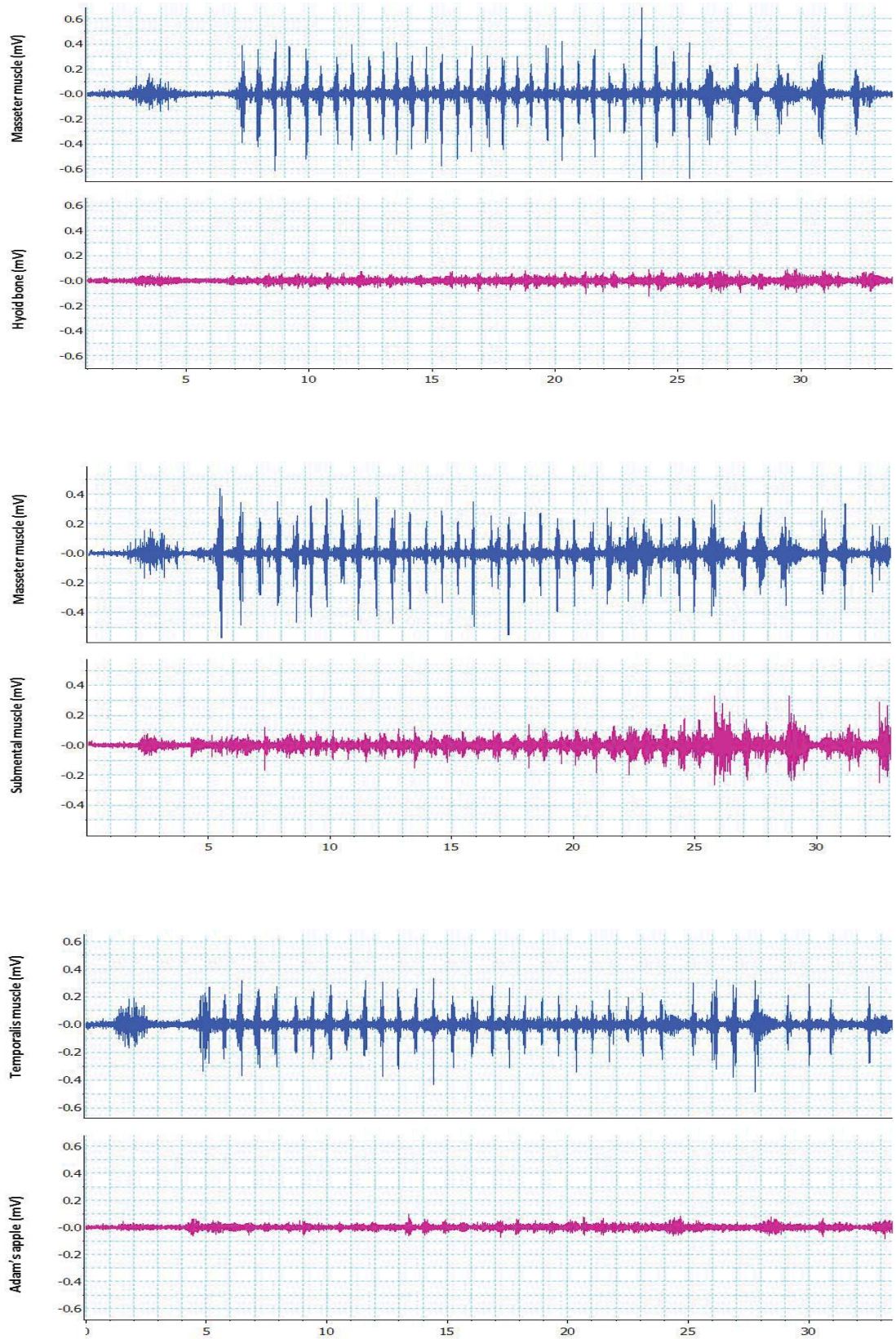


Figure 3-14. The EMG traces of right masseter, submental muscle, temporalis, hyoid bone, and Adam's apple during consumption of 1 cashew nut for subject A in 3 sessions.

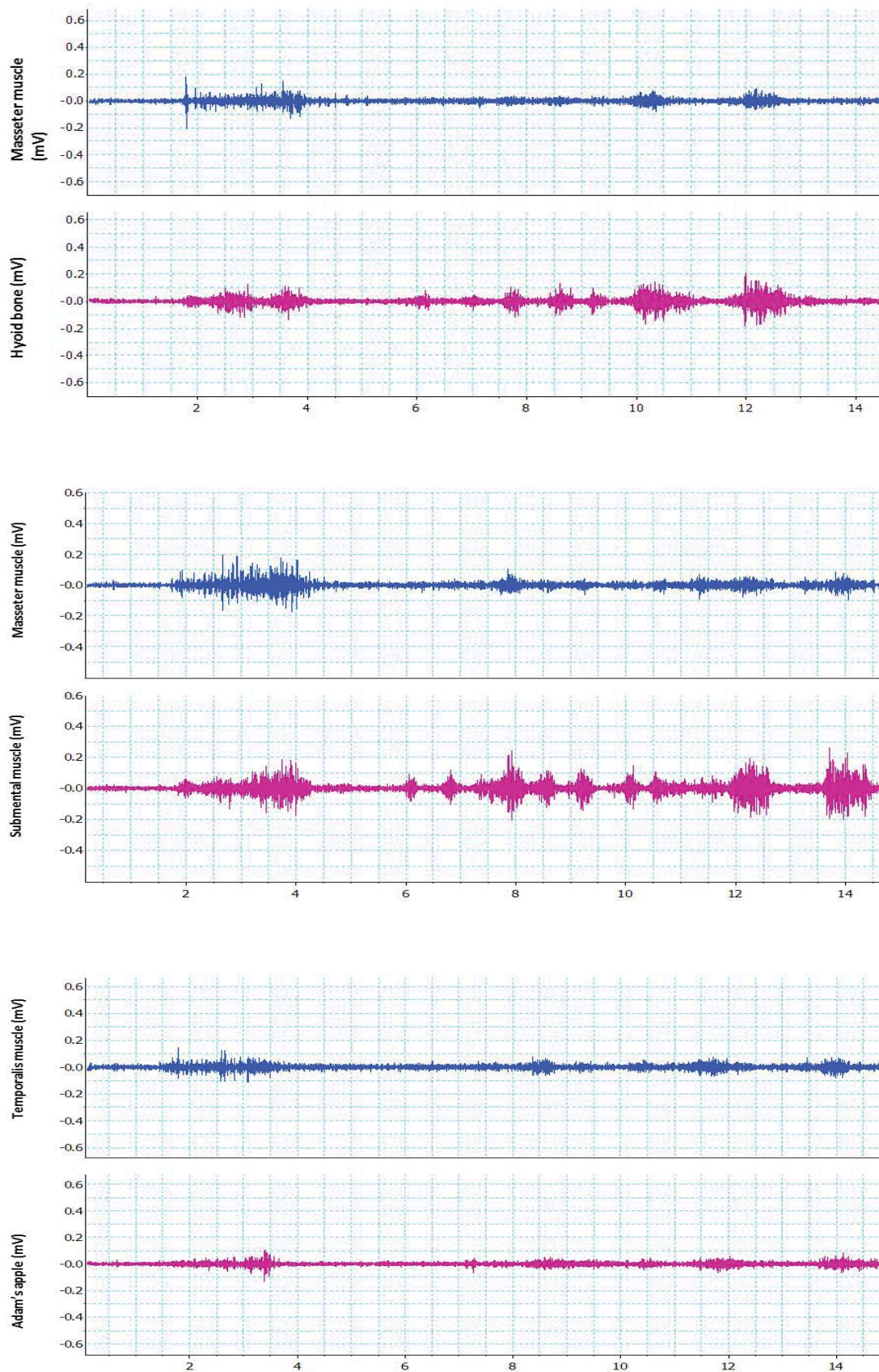


Figure 3-15. The EMG traces of right masseter, submental muscle, temporalis, hyoid bone, and Adam's apple during consumption of Greek yoghurt for subject A in 3 sessions.

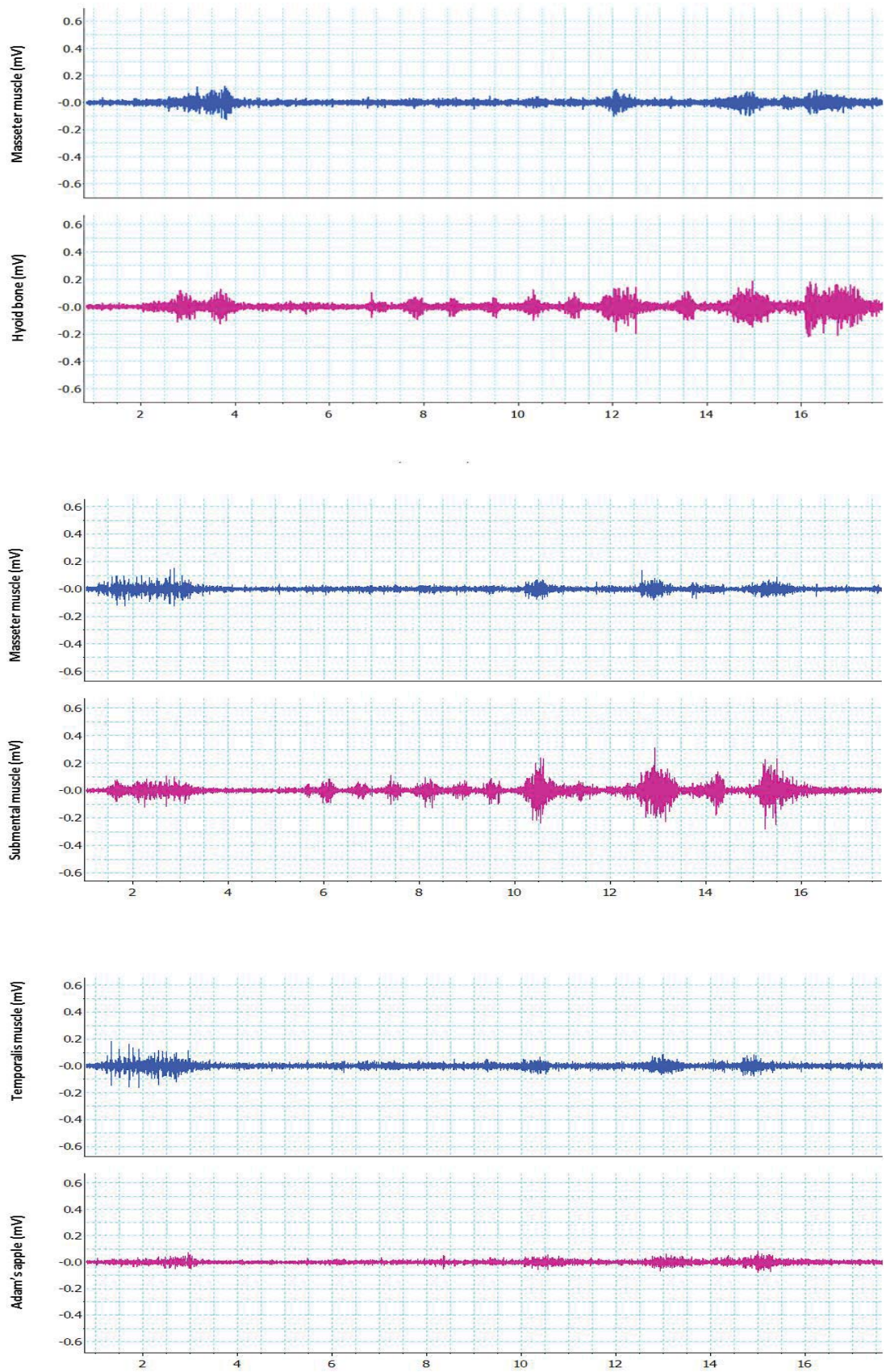


Figure 3-16. The EMG traces of right masseter, submental muscle, temporalis, hyoid bone, and Adam's apple during consumption of plum jam for subject A in 3 sessions.

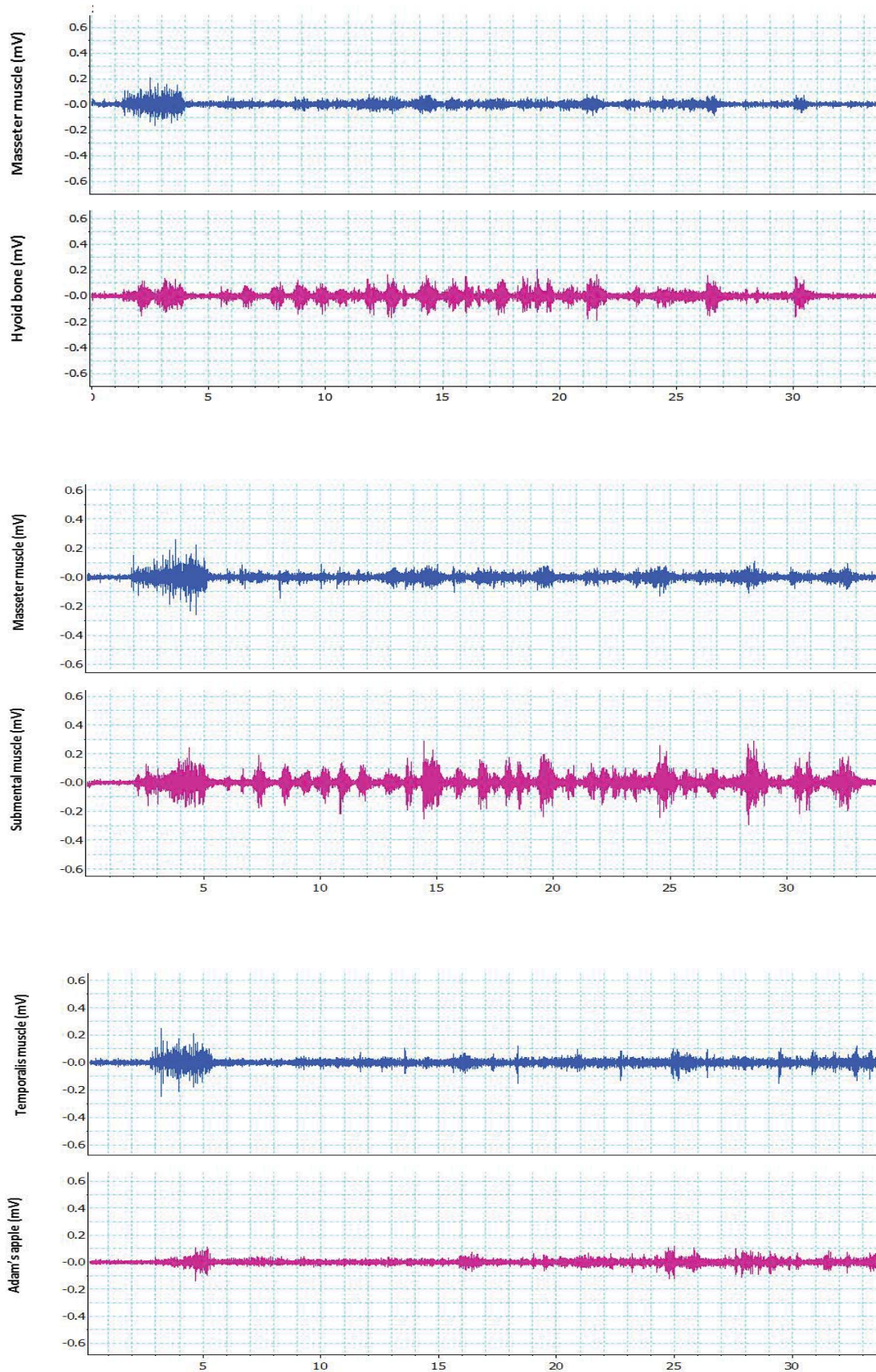


Figure 3-17. The EMG traces of right masseter, submental muscle, temporalis, hyoid bone, and Adam's apple during consumption of Nutella for subject A in 3 sessions.

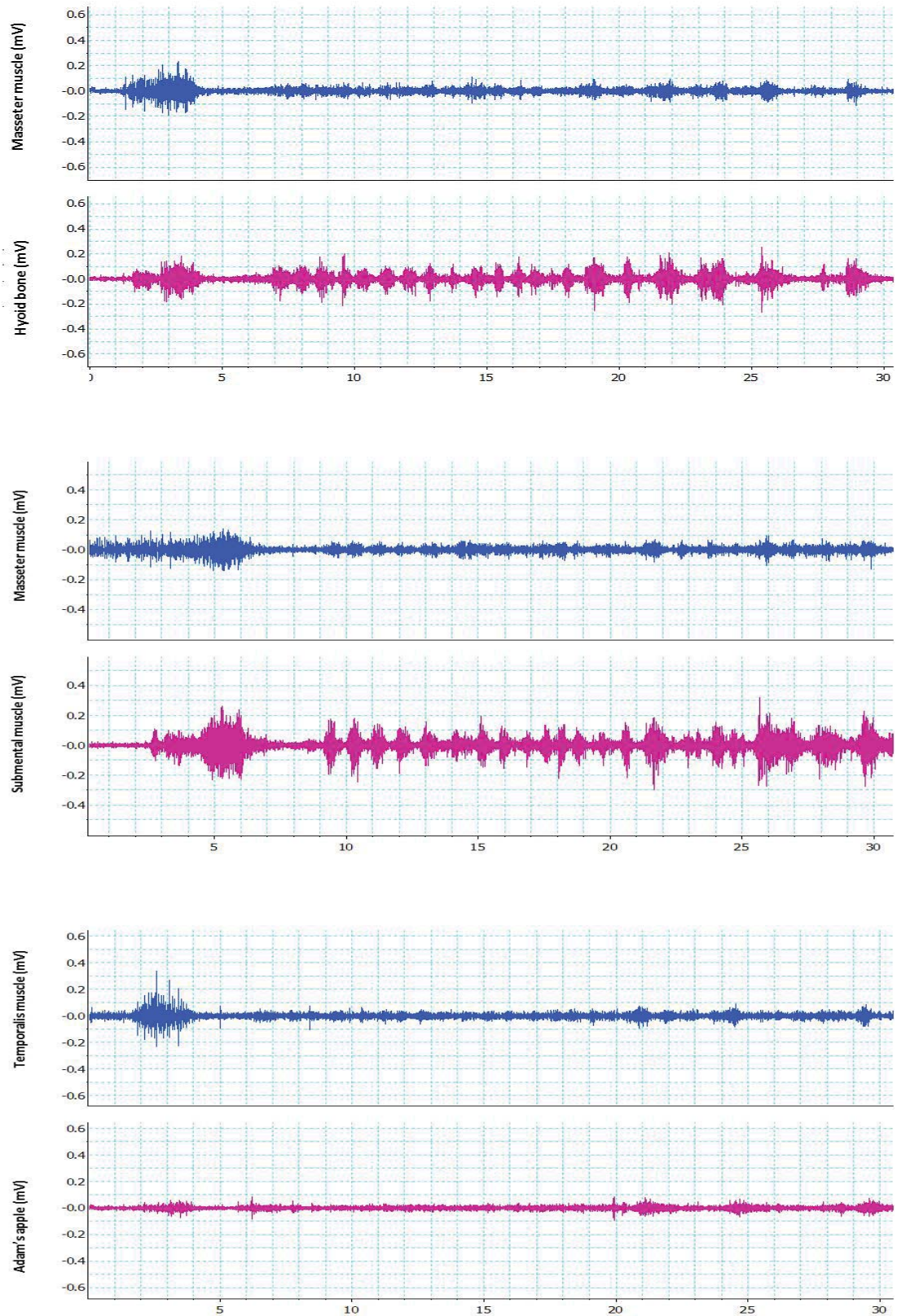


Figure 3-18. The EMG traces of right masseter, submental muscle, temporalis, hyoid bone, and Adam's apple during consumption of cream cheese for subject A in 3 sessions.

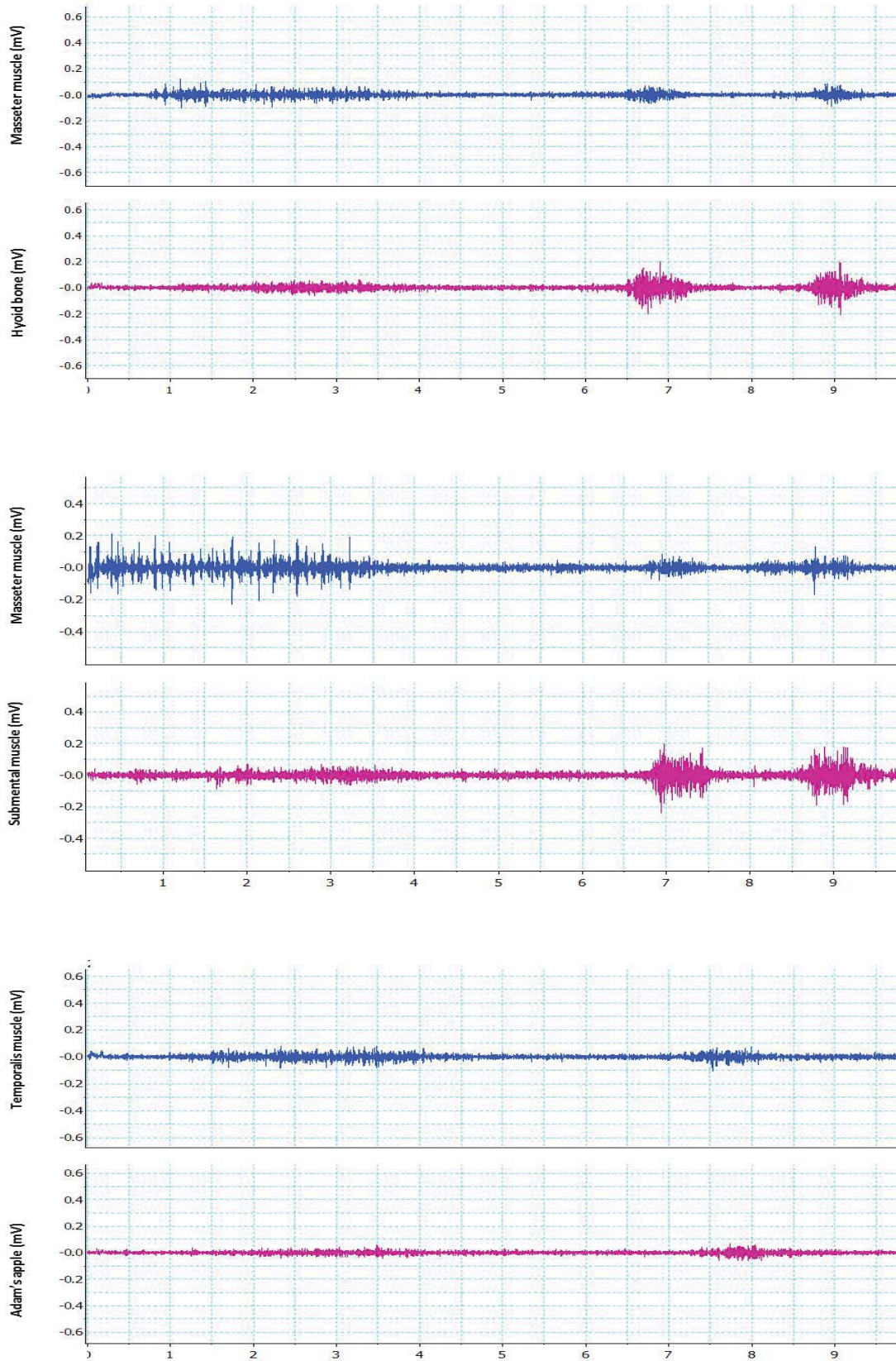


Figure 3-19. The EMG traces of right masseter, submental muscle, temporalis, hyoid bone, and Adam's apple during consumption of standard milk for subject A in 3 sessions.

EMG traces show that the signals from the masseter and the temporalis muscles have similar intensities in muscle activities during consumption of the same food sample (Figure 3-14 to Figure 3-18). The signal from the hyoid bone and the submental muscles also have similar intensities in muscle activity, but the intensity of the hyoid bone is slightly less than the submental muscle during consumption of the same food sample. The intensity of the Adam's apple is significantly lower than the hyoid bone and submental muscle during consumption of the same sample for all 6 food samples (Figure 3-14 to Figure 3-19). In order to reduce the interference between electrodes in the small facial area, only 2 positions were selected. One involved in chewing activity / oral processing behaviour, the other one involved in swallowing movements. The former position was determined as the masseter muscle because of the easiness of location and preparation; the latter position was determined as the submental muscle because of the intensity of muscle activity and the easiness of location.

The EMG signal from the Adam's apple was not as high as from the submental muscle, because there is little muscle under the skin at this position. In addition, the Adam's apple is hard to determine and fix electrodes to, because it keeps moving during oral processing. The hyoid bone also has the same problem.

The EMG signal from the masseter muscle showed similar muscle intensity, burst frequency and movement style during consumption of the same food samples across different trials. The submental, temporalis muscle, hyoid bone and Adam's apple also showed similar results. This indicates that the masseter, submental, temporalis muscle, hyoid bone and Adam's apple have acceptable reproducibility. The minimum, maximum and mean voltages of above 5 positions were collected from EMG traces (Table 3-3) during consumption of different food samples.

The voltages measured for the masseter muscle were not significantly different in different measurement sessions (Table 3-3), which indicates that this measurement is reproducible. Each food sample was replicated 3 times. The standard deviations of muscle voltages for 6 food samples were significantly smaller than the mean values of muscle voltages, which indicates that this measurement and these electrodes' positions are repeatable.

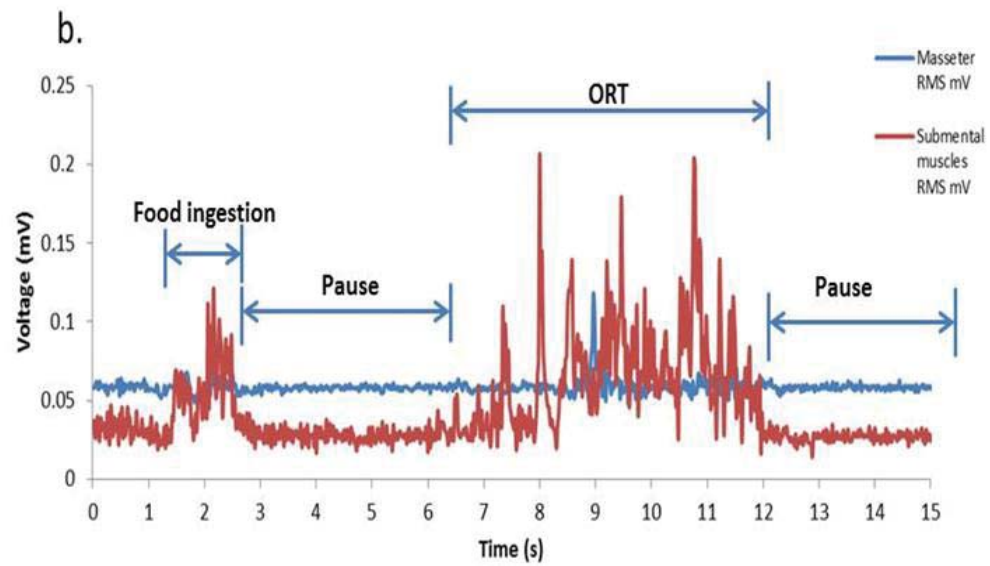
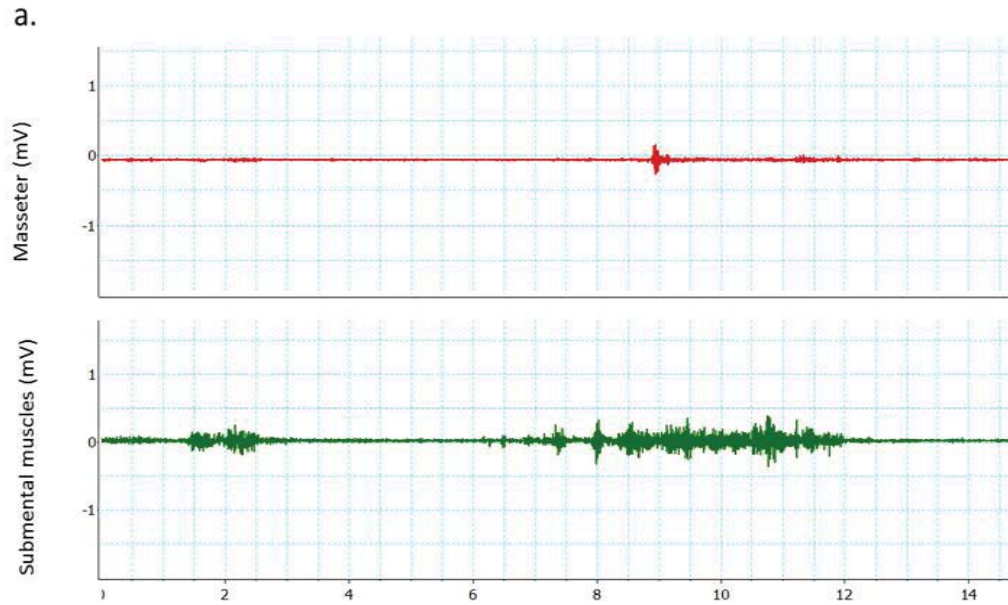
Table 3-3. Muscle voltages during consumption of 6 food samples (mean \pm SD)

Muscle voltages (mV)		Cashew nut	Yoghurt	Jam	Nutella	Cream cheese	Standard milk
Masseter	Minimum	-0.81 \pm 0.06	-0.17 \pm 0.02	-0.17 \pm 0.04	-0.18 \pm 0.01	-0.19 \pm 0.00	-0.10 \pm 0.01
	Maximum	0.63 \pm 0.09	0.17 \pm 0.01	0.17 \pm 0.05	0.21 \pm 0.00	0.21 \pm 0.02	0.12 \pm 0.03
	Mean	0	0	0	0	0	0
Hyoid bone	Minimum	-0.12 \pm 0.02	-0.18 \pm 0.01	-0.21 \pm 0.01	-0.23 \pm 0.03	-0.26 \pm 0.01	-0.19 \pm 0.01
	Maximum	0.10 \pm 0.01	0.20 \pm 0.03	0.20 \pm 0.02	0.23 \pm 0.02	0.26 \pm 0.01	0.18 \pm 0.02
	Mean	0	0	0	0	0	0
Masseter	Minimum	-0.69 \pm 0.09	-0.16 \pm 0.02	-0.13 \pm 0.00	-0.19 \pm 0.05	-0.17 \pm 0.02	-0.17 \pm 0.05
	Maximum	0.47 \pm 0.06	0.18 \pm 0.03	0.14 \pm 0.01	0.20 \pm 0.05	0.21 \pm 0.07	0.19 \pm 0.05
	Mean	0	0	0	0	0	0
Submental	Minimum	-0.29 \pm 0.02	-0.25 \pm 0.05	-0.27 \pm 0.01	-0.42 \pm 0.10	-0.30 \pm 0.04	-0.22 \pm 0.03
	Maximum	0.29 \pm 0.02	0.26 \pm 0.05	0.27 \pm 0.03	0.37 \pm 0.07	0.31 \pm 0.03	0.20 \pm 0.03
	Mean	0	0	0	0	0	0
Temperalis	Minimum	-0.47 \pm 0.02	-0.12 \pm 0.02	-0.14 \pm 0.02	-0.19 \pm 0.04	-0.21 \pm 0.02	-0.10 \pm 0.01
	Maximum	0.39 \pm 0.06	0.13 \pm 0.03	0.14 \pm 0.04	0.21 \pm 0.02	0.27 \pm 0.07	0.09 \pm 0.01
	Mean	0	0	0	0	0	0
Adam's apple	Minimum	-0.12 \pm 0.04	-0.09 \pm 0.03	-0.08 \pm 0.00	-0.13 \pm 0.02	-0.15 \pm 0.05	-0.06 \pm 0.00
	Maximum	0.10 \pm 0.01	0.09 \pm 0.02	0.08 \pm 0.01	0.14 \pm 0.05	0.12 \pm 0.03	0.06 \pm 0.01
	Mean	0	0	0	0	0	0

In summary, electrodes on the masseter and submental muscle collect reliable, intensive, and reproducible signals and are easy to locate and fix electrodes to. Therefore, the submental and masseter muscles on the preferred chewing side were chosen as the most suitable muscles to record when investigating muscle activities during the oral processing of food samples.

Determination of oral residence time using EMG

The RMS plots show more clearly the oral movement than the original EMG traces (Figure 3-20). The food ingestion and the end of swallowing were hard to separate from the whole process of oral processing if there was no pause after food loading on the tongue surface and finishing swallowing. The subjects were instructed to pause for 3s after food loading and after swallowing finished during consumption of food samples. From this the food ingestion time and end point of swallowing were clearer in both EMG traces and RMS plots.



Figures 3-20 a and b. Graphic a shows the EMG traces of right masseter and submental muscles during consumption of Greek yoghurt for subject B. Graphic b is the RMS plot of these EMG traces.

3.3.2.4. Conclusions

The start point and end point of ORT were clear in EMG traces and rectified RMS plots during oral processing of foods. It was concluded that: 1.) EMG is an effective method to measure the ORT and muscle activities during oral processing; 2.) the masseter

muscle and submental muscles are the best positions for measuring the ORT and muscle activities in this research.

3.3.3. *Using EMA and EMG simultaneously to determine oral residence times*

3.3.3.1. Introduction

So far, two methods have been used to determine the ORT. Both of them have strengths and weaknesses. EMG collects muscle activities data during oral processing, while EMA collects dynamic tongue and lower jaw movement data during oral processing of foods. All these data are required for this study. The two methods were therefore simultaneously used to collect data and ORT estimated from each method were compared.

3.3.3.2. Materials and methods

Subjects and food samples

Two male subjects (23 y and 24 y) took part in this experiment. They met the screening criteria outlined in Section 3.2.1.

The same five food samples were used in the previous work were also used in this experiment (Table 3-1.). All food samples were left in a temperature controlled room (20°C) for at least 1.5 h to achieve room temperature before serving. Food temperature was checked using an electronic thermometer.

Master and slave mice

The master and slave mice comprised a custom designed device to link up to three computer mice together in order to start and end different programmes in each computer at the same time. Two computer mice were connected in this experiment in order for EMA and EMG programmes to work simultaneously. Each mouse was connected to its own computer. The left click button of one mouse (master mouse) controlled all left click buttons of the other mouse (slave mouse). Each mouse was connected to its own computer and switch box. Both master and slave mice had full functionality on their own computer (can use the mouse as normal) when the switch box was in independent

mode. In master/slave mode, the left click button of slave mouse was disabled, and the master mouse worked as normal, but it also controlled the left click button of the slave mouse.

Experiment procedure

All food samples were tested in one session in triplicate during one session. Samples were presented in random order. The subjects sat in the EMA cube, and 6 sensor coils were fixed at: a.) near tongue tip; b.) tongue back; c.) upper incisor; d.) lower incisor; e.) behind left ear; f.) behind right ear. Two pairs of EMG electrodes were fixed on the subject's right masseter and submental muscles (Section 3.3.2.1). The experimental procedure was as described in Section 3.3.1.2. The subjects paused for at least 3s after food ingestion and swallowing. The master mouse was used to start and end two programmes on different computers simultaneously during the experiment.

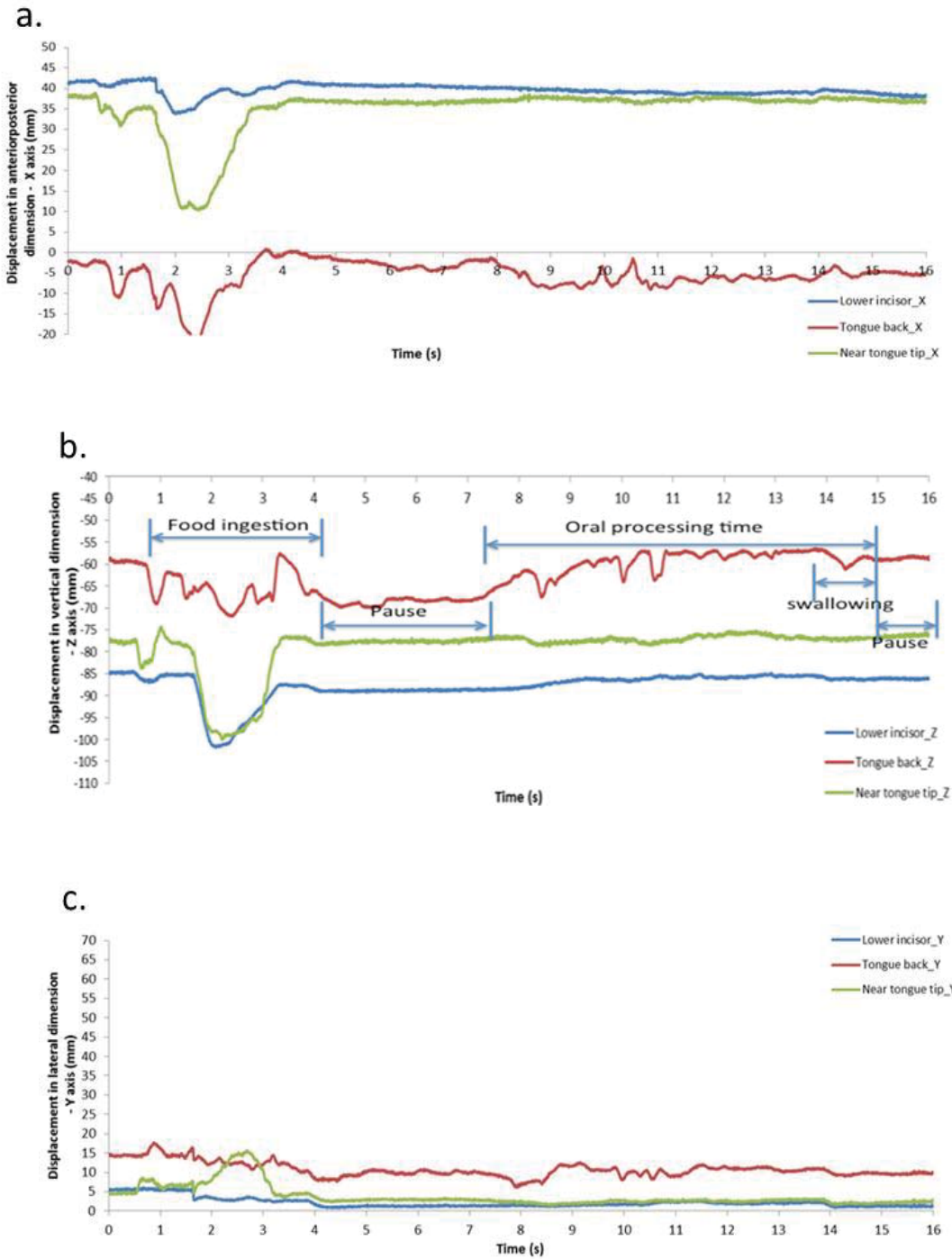
3.3.3.3. Results and discussion

Time lag between two methods

The master / slave mouse was connected to EMA and EMG computers to check the time lag between the two methods. EMA collected data every 0.005 seconds (200Hz). EMG recorded 1000 points per second, but the collected data was rectified to RMS data every 0.02 seconds. The EMA method had a longer recording time than the EMG method while using the master / slave mouse. The time lag was between 0.14 to 0.35 s, with an average value was 0.26 s. The time lag was attributed to delays in both starting and ending of the programme.

The oral residence time from EMG and EMA trials

The ORT was easy to determine from displacement-time plots. The tongue and lower jaw movement were displayed in displacement-time plots and 2D displacement plots (Figure 3-21).



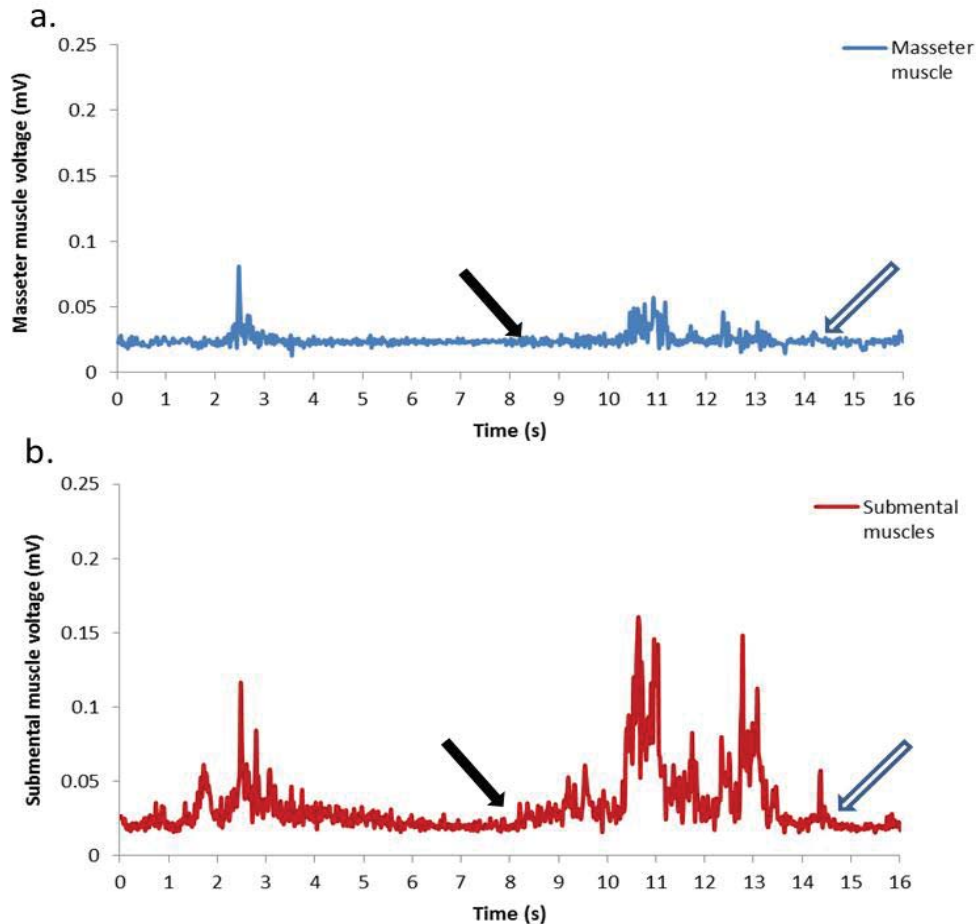
Figures 3-21a, b and c. Three sensor coils movement on tongue and tooth on X axis (a), Z axis (b), and Y axis (c) during consumption of plum jam from EMA for subject A.

In this case, the ORT starts at 7.14 s and ends at 14.69 s on the X axis; on Z axis it starts at 7.19 s and ends at 14.66 s. The earliest start time and the latest end time are used to calculate ORT – that is 7.55 s (the same as in the ORT on X axis). Plots show the tongue and lower jaw movement during food processing as well. As plum jam is a semi-solid food, it flows when certain a shear stress is added (e.g. the tongue is tilted, or

pressed against the hard palate) under certain temperature. It explains why there is no typical rhythmic chewing activity. The sensor coil on the lower incisor does not move much, indicating that the subject does not use their teeth to chew. Only the tongue back is active; it moves slowly and irregularly and the displacement is within 10 mm both on the X and Z axis. The amplitude of movement reduces in turn from the Z axis to the X axis, to the Y axis. The movement pattern on X and Z axes are similar; the start and end time of ORT on both axes are similar. This indicates that the subject processes plum jam without teeth, and the tongue rubs and squeezes the food on the hard palate mainly in the anterior-posterior and vertical directions.

In EMG RMS plots (Figure 3-22), the ORT of plum jam starts at 7.78 s (masseter muscle), and ends at 14.48 s. The ORT is 6.7 s. EMA recorded ORT (ORT_{EMA}) is 7.55 s, 0.85 s longer than the EMG recorded ORT (ORT_{EMG}). It is likely that the tongue movement is earlier than where the masseter and submental muscles are activated; because after being activated the first movement during food processing after ingestion is to transport food to the molars on one side (soft-solid and hard-solid) or to the back of the oral cavity (liquid and soft-solid) by the tongue.

The EMG data provides not only the ORT, but also muscle activity information, such as muscle voltage which relates to the muscle force, the area under the curve which relates to the muscle work, chewing pattern or oral processing style and swallowing. For example, in the case of consumption of plum jam, the right masseter muscle does not use much voltage to process food (Voltage_{max} is 0.04 mV) and there are no regular chewing cycles. The submental muscle data shows the subject swallows twice and uses more voltage than with the masseter muscle (Voltage_{max} was 0.15 mV). The masseter muscle does 0.02 mV.s work and the submental muscle does 0.15 mV.s work. These data indicates that plum jam is easy to process, but the ORT is not short, the reasons are considered to relate to food properties and individual preferences.



Figures 3-22 a and b. The rectified EMG RMS plots from right masseter muscle and submental muscles during consumption of plum jam. The black arrow indicates the start time of oral residence time; the white arrow indicates the end of oral residence time.

Strengths and weaknesses of both methods

Both EMA and EMG methods have strengths and weaknesses. Based on the findings presented above, the strengths of EMA are: 1) accuracy of ORT recording; 2) tracking of tongue, tooth and jaw movement, even when the oral cavity is sealed; 3) dynamic recording of sensor coils' data in three dimensions during oral processing. However, its weaknesses are: 1) taking more time to fix sensor coils on the tongue surface; 2) restricting oral movements due to sensor coils and wires in the oral cavity, especially when chewing activity is required; 3) difficult to guarantee the sensor coil is fixed to the exact same position across different sessions.

The EMG has been widely used in many fields for a few decades, the strengths are: 1) the instrument is easy to operate, and the electrodes are easy to fix on subject; 2) it is

accurate on ORT measurement and muscle activity (muscle voltage, work, and oral processing style) recording; 3) the recorded data is easy to interpret. It also has some weaknesses, such as 1) the researcher cannot tell whether the movement of the muscle is caused by the tongue, tooth or lower jaw; 2) the muscle voltage and the area under the curve is highly related to the positions of the electrodes; 3) for liquid and some semi-solid food, the muscle activity is weak, and the data is not as accurate as for soft-solid and hard solid foods.

When using both instruments simultaneously, the restriction feature of EMA (due to wires restricting movement) makes EMG data collected simultaneously with EMA different from using EMG separately. The ORT time is longer and the maximum voltage (especially masseter muscle) is smaller when using EMG simultaneously with EMA than EMG on its own in ORT and food ingestion time (e.g. Figure 3-23 and 3-24). Therefore, using EMG on its own was chosen to investigate muscle activities during food oral processing and for recording the oral residence time. The trajectories of EMA sensor coils are not significantly different when using EMA separately and using EMA simultaneously with EMG.

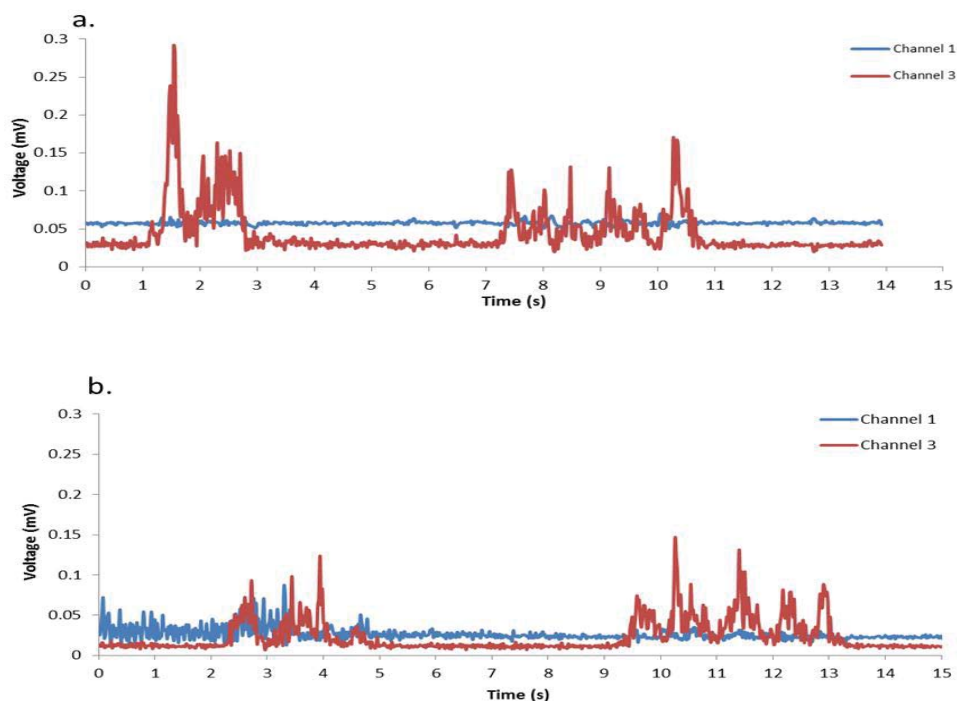


Figure 3-23. Plot a shows the masseter (channel 1) and submental muscle (channel 3) EMG traces during oral processing of plum jam using EMG on its own from subject B. Plot b shows EMG traces during consumption of Nutella when using EMG simultaneously with EMA from subject B.

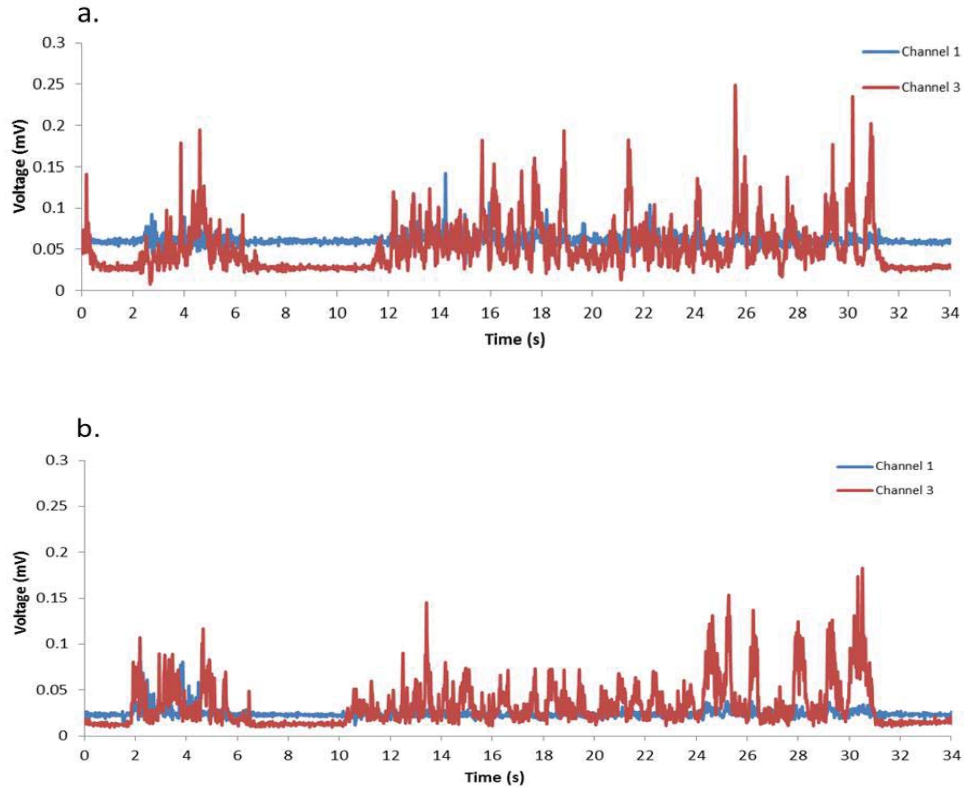


Figure 3-24. Plot a shows the masseter (channel 1) and submental muscle (channel 3) EMG traces during oral processing of Nutella using EMG on its own from subject B. Plot b shows EMG traces during consumption of Nutella when using EMG simultaneously with EMA from subject B.

3.3.3.4. Conclusions

- a) To measure ORT, EMG alone is the best method, because it is simple, accurate and non-invasive. Alongside this, it does not interfere with natural oral processing behaviours. This is described further in Chapter 5.
- b) To detect chewing appearance, EMA alone is the best method because of its accuracy and dynamic multipoint tracking feature in the oral cavity. This is also described further in Chapter 5, even though the wires may affect oral movements.
- c) To characterize tongue movement, EMA is the only approach (Chapter 7).

Generally, both methods are accurate to measure ORT, but the EMA method has an earlier detection of the tongue movement during oral processing. However, considering the difficulty of operation and the purpose of the research, using the EMG only method is preferred for further studies determining ORT.

3.4. Conclusions

The sensors position was determined to be the near tongue tip, tongue back and lower incisor in the oral cavity; reference sensors were located at the upper incisor and behind both ears. The start point of ORT was defined as the time when the subject starts oral processing after the food sample is loaded onto the tongue surface and the subject has paused for a few seconds. The end point was defined as the time when clearance and the terminal swallow have finished.

EMA and EMG methods are both accurate to measure the ORT: the former tracks the tongue and lower jaw movement dynamically; the latter records muscle activity. Further research will use EMA and EMG separately for different purposes and with different food types.

These experiments also indicate that oral processing behaviour is affected by various factors, the food physico-chemical and material properties being the most important. Therefore, food properties must be characterised before further investigation and this is the purpose of Chapter 4.

Chapter 4: Characterisation of foods

4.1. Introduction

It is well documented that oral processing behaviour (including ORT, tongue and lower jaw movements, and muscle activity) is affected by food properties. Rahman (2009) defined a food property as “a particular measure of a food’s behaviour, which involves energy, or its interaction with the human senses, or its effect in promoting human health and well-being”. Food properties, such as viscosity, hardness and stickiness are known to affect oral processing patterns and time (Foster, Woda, & Peyron, 2006; Steele et al., 2015; Togashi, Morita, & Nakazawa, 2000). Food properties are divided into various groups according to different viewpoints (as stated in Chapter 2, Section 2.3.2.3). Because the food samples used in this research are liquid, semi-solid and soft-solid foods, the rheological properties (storage modulus and loss modulus), stretch-ability and moisture content are believed to be important.

Food rheology has long been used to study food flow in the mouth and its relationships with sensory perception (Chen, 2009; Chen & Lolivret, 2011; Chen & Stokes, 2012; Nishinari, 2004), but research has rarely focused on the relationship between food rheological properties and tongue and jaw movements and masticatory muscle activities.

Measurement of rheological properties before and after oral processing may provide information to aid understanding of oral processing and the triggering of swallowing. However, it was difficult to measure the rheological properties of all food samples using the same rheological instrument and the same geometry, so for this research, only the rheological properties (measured using a rheometer) of the original food samples (before oral processing) were measured. Original and expectorated food samples were tested for a reduced range of 9 foods produced by 8 subjects.

4.2. Materials and methods

4.2.1. Materials

Food samples tested in this research were commercial food products purchased from a local supermarket (Pak’n Save, Auckland, New Zealand). Twenty-three food samples were selected across a wide range of food products from liquids to soft-solid foods. All food samples and their brands are listed in Table 4-1. They were stored on the basis of

their label requirements before measurement. Prior to measure, the samples were placed in a 20°C environment for 1.5 hours.

Table 4-1. Twenty-three food samples information

Food type	Brand and details
Bottled water	Waiwera water. Natural artesian water.
Breakfast tea	Twining Earl Grey Tea bag, English breakfast tea. One tea bag soaked in 250ml boiling tap water for 3 minutes, then the tea bag was removed.
Cheese tube	Kraft brand, original Philadelphia cream cheese, mini tubs (60% less fat)
Chocolate mousse	Fresh'n Fruity- Simply Chocolate, 97% fat free
Chocolate shake	Sanitarium, Up & Go.
Cold coffee	Egberts brand (Frucor beverage), Moccona Double Shot.
Condensed milk	Nestle, Highlander sweetened condensed milk
Cream	Anchor (pure cream, cow's milk)
Custard	Mainland
Greek yoghurt	Yoplait Greek style (natural, gluten free)
Hazelnut spread	Nutella (Ferrero)
Mashed potato (frozen)	Watties, steam 'n' mash
Melted ice-cream	Tiptop
Nature yoghurt	Yoplait brand, Yoplus (natural yoghurt)
Orange juice	McCoy, real orange juice (Frucor beverages LTD.)
Peanut butter	Delish (smooth)
Philadelphia cheese	Kraft brand, Original Philadelphia cream cheese.
Plum jam	Craig's, Black Doris Plum fruit jam
Sour cream	Tararua brand, traditional sour cream
Standard milk	Anchor (blue top), fresh cow's milk
Tomato juice	McCoy, real tomato juice (Frucor beverages LTD.)
Trim milk	Anchor (green top), fresh cow's milk
Whipped cream (canned)	Tatua (Dairy whip)

4.2.2. Rheological properties

An Advanced Rheometer AR 550 (TA instruments, US) and AR Instrument control Taar 32 system was used to determine the flow curves, storage modulus (G') and loss modulus (G'') for all food samples at both 20 and 37°C. A cone-plate geometry 2°/ 60 mm (cone angle of 2° and cone plate diameter of 60 mm) was used for measuring the flow curves. A parallel-plate geometry 40 mm was used to measure G' and G'' . The gap between the platform and geometry was set at 2 mm. At least three replications were conducted for each food sample. The metal sealed lids were used to minimize the moisture loss during measurement at 37°C.

Flow curve, G' and G'' of food samples used in Table 4-1 were separately measured by two experiments: one experiment was controlled at a temperature of 20°C (representing an average room temperature) and the other was at 37°C (simulating an average oral cavity temperature). Liquid materials have no elasticity, therefore, G' and G'' data of liquid samples (e.g. bottled water, breakfast tea, cold coffee, chocolate shake, cream and milk) were meaningless and therefore they were omitted from the plots.

4.2.2.1. Flow curve

A flow curve represents the behaviour of flowing material. It demonstrates the shear stress or viscosity change subject to ascending or descending shear rate. The shape of the flow curve indicates the type of flow behaviour of a food sample. The flow curve was determined over the range of shear rates from 10 to 100 s^{-1} , where the constant shear stress flow procedure was used. The viscosity at 10 s^{-1} shear rate was used as the large deformation viscosity for each food sample.

4.2.2.2. Storage modulus (G') and Loss modulus (G'')

G' and G'' were measured (using oscillation procedure) when the frequency ranged from 0.01 to 30 Hz, and the constant strain was at 0.5 % strain. The frequency range was determined by the most accurate and stable part of the G'/G'' – frequency plots and ranged from 0.001 to 1000 Hz.

4.2.3. Stretch-ability

Stretch-ability of the food samples were determined by a Texture Analyser (TA. XT. Plus Texture Analyser, TA instruments, US). A 50 kg load cell and a 30 mm diameter aluminium cylinder probe were used. The gap between the probe and the platform was pre-set to 0.1 mm. Before each test, the surfaces of the probe and platform were cleaned with detergent and distilled water, then dried with a soft tissue. The probe was brought downwards at a speed of 1 mm/s to gently squeeze the sample to the pre-set gap. The squeezed out sample was removed carefully with a plastic spatula. At the start of the test, the probe was raised away from the platform at a constant speed of 10 mm/s. The force against the time and the separation distance were recorded at the rate of 50 points per second. The maximum tensile force (F_{max}) and the work until the maximum force (W_{max}) were collected using Texture Exponent 32 software (version 2.0). The temperatures of the probe, platform and food samples were all controlled at 20 and 37°C respectively during two tests using an air conditioner and heater to adjust the room temperature. The

measurement process followed the method described by Chen *et al.* (Chen & Lolivret, 2011; Chen, Feng, Gonzalez, & Pungaloni, 2008).

4.3. Results and discussion

4.3.1. Rheological properties

4.3.1.1. Shear stress and viscosity

The shear stress and viscosity value for the 23 food samples measured at 10 s^{-1} shear rate at 20 and 37 °C are provided in Table 4-2. The results show that shear stress and viscosity mostly decreased with increasing temperature. The exception was tomato juice where viscosity and shear stress increased with increasing temperature.

The logarithmic shear stress and viscosity at 10 s^{-1} shear rate were also calculated (Table 4-2) to allow easier comparison between the foods.

Table 4-2. Shear stress, viscosity and logarithmic values of 23 food samples measured at 10 s^{-1} shear rate at 20 and 37°C (mean \pm SD).

Food samples	Shear stress (Pa)		Log ₁₀ (shear stress)		Viscosity (Pa.s)		Log ₁₀ (viscosity)	
	20°C	37 °C	20°C	37 °C	20°C	37 °C	20°C	37 °C
Bottled water	0.01	0.01	N/A	N/A	0.00	0.00	N/A	N/A
Breakfast tea	0.16±0.03	0.06±0.02	-0.81±0.07	-1.26±0.13	0.02±0.00	0.01±0.00	-1.81±0.07	-2.26±0.13
Cheese tub	337.33±15.97	145.63±4.21	2.53±0.02	2.16±0.01	33.71±1.61	14.56±0.43	1.53±0.02	1.16±0.01
Chocolate mousse	30.02±1.53	0.32±0.03	1.48±0.01	-0.49±0.03	3.00±0.15	0.03±0.00	0.48±0.01	-1.49±0.03
Chocolate shake	1.03±0.08	1.04±0.94	0.01±0.03	0.02±0.01	0.10±0.01	0.10±0.00	-0.99±0.03	-0.98±0.01
Cold coffee	0.24±0.01	0.11±0.00	-0.62±0.02	-0.98±0.00	0.02±0.00	0.01±0.00	-1.62±0.02	-1.98±0.00
Condensed milk	78.69±7.83	36.15±1.38	1.89±0.04	1.56±0.02	7.87±0.87	3.62±0.14	0.89±0.04	0.56±0.02
Cream	0.43±0.04	0.07±0.00	-0.37±0.04	-1.13±0.01	0.04±0.00	0.01±0.00	-1.37±0.04	-2.13±0.01
Custard	24.74±0.95	15.58±1.46	1.39±0.02	1.19±0.04	2.47±0.10	1.56±0.15	0.39±0.02	0.19±0.04
Greek yoghurt	17.04±0.87	7.57±0.34	1.23±0.02	0.88±0.02	1.70±0.09	0.76±0.04	0.23±0.02	-0.12±0.02
Hazelnut spread (Nutella)	566.95±66.83	250.57±23.44	2.75±0.05	2.40±0.04	56.71±6.70	25.05±2.34	1.75±0.05	1.40±0.04
Mashed potato	972.63±0.05	966.37±8.96	2.99±0.00	2.99±0.00	297.39±164.45	93.91±17.04	2.35±0.37	1.97±0.09
Melted ice-cream	0.93±0.08	0.52±0.00	-0.04±0.04	-0.29±0.00	0.09±0.01	0.05±0.00	-1.04±0.04	-1.29±0.00
Natural yoghurt	12.93±2.93	4.76±0.48	1.11±0.02	0.68±0.04	1.29±0.07	0.48±0.05	0.11±0.02	-0.32±0.04
Orange juice	0.64±0.15	0.37±0.05	-0.21±0.10	-0.44±0.06	0.06±0.01	0.04±0.01	-1.21±0.10	-1.44±0.06
Peanut butter	611.28±210.88	200.07±40.90	2.76±0.13	2.29±0.09	58.09±16.01	19.94±4.02	1.75±0.11	1.29±0.08
Philadelphia cheese	551.07±54.55	354.13±12.45	2.74±0.04	2.55±0.02	54.98±5.36	35.38±1.23	1.74±0.04	1.55±0.02
Plum jam	91.90±6.20	53.42±4.75	1.96±0.03	1.73±0.04	9.19±0.62	5.34±0.48	0.96±0.03	0.73±0.04
Sour cream	180.15±10.15	50.70±3.11	2.26±0.02	1.70±0.03	18.02±1.02	5.07±0.31	1.26±0.02	0.70±0.03
Standard milk	0.08±0.06	0.04±0.02	-1.22±0.30	-1.79±0.33	0.01±0.01	0.00±0.00	-2.22±0.30	-2.52±0.15
Tomato juice	3.64±0.68	9.04±5.52	0.55±0.08	0.83±0.37	0.36±0.07	0.90±0.55	-0.45±0.08	-0.17±0.37
Trim milk	0.17±0.15	0.02±0.00	-0.96±0.47	-1.68±0.04	0.02±0.02	0.00±0.00	-1.96±0.47	-2.68±0.04
Whipped cream	11.94±7.16	0.78±0.08	0.93±0.47	-0.11±0.05	1.19±0.72	0.08±0.01	-0.08±0.47	-1.11±0.05

A paired T-Test showed that the shear stress (at 10 s^{-1} shear rate) of 22 food samples were significantly ($T = 2.59$, $p = 0.017$) greater at 20°C than at 37°C . The viscosity of 22 food samples were not significantly different ($T = 1.67$, $p = 0.110$) at 20 and 37°C , although most viscosity values were greater at 20°C than at 37°C . The exceptions were tomato juice and chocolate shake where the logarithmic shear stress ($T = 4.34$, $p = 0.000$) and viscosity ($T = 4.62$, $p = 0.000$) were significantly greater at 20°C than at 37°C .

The shear stress and viscosity of chocolate mousse and whipped cream decrease dramatically with increasing temperature as both contain high levels of fat which melts at a higher temperature (oral cavity). These products also contain a large volume of air which is released from the sample as it melts causing a change in food structure (porous foods). Tomato juice is a special case. The shear stress and viscosity of tomato juice increase significantly with increasing temperature. The main reasons are: 1) tomato juice behaves like a weak gel, storage modulus is higher than loss modulus in the measured frequency; 2) Consistency of tomato juice increased when tomatoes are exposed to 35°C , as higher temperature results in an increase in pectin methylesterase activity (Held, Anthon, & Barrett, 2015).

Mashed potato had a significantly high value of shear stress and viscosity in both experiments. During the measurement, nearly half of sample was squeezed out of texture analyser probe and platform because of the structure of mashed potato. Therefore, the Rheometer AR550 was not suitable for assessing mashed potato.

Shama and Sherman used viscosity at a constant shear stress to classify foods. The viscosity of liquid samples was set below $0.1 \text{ Pa}\cdot\text{s}$. A viscosity above $0.1 \text{ Pa}\cdot\text{s}$ was used to classify foods as being semi-solid and soft-solid foods (Shama & Sherman, 1973).

Van Vliet et al. (2009) use the foods' initial properties to divide semi-solid foods into solid-like and softer products. For solid-like foods, a sample is usually bitten off by the front incisors, then further processed between the tongue and palate. For soft products, the food is usually put on the tongue directly.

The shear stress and viscosity of 22 samples (10 s^{-1} shear rate) do not show significant gaps to classify food samples into different groups in this experiment and the number of food samples are not enough to do a formal classification. The logarithmic value of

shear stress and viscosity tend to show gaps between samples only at 20°C. This may be useful for further studies on food classification.

When considering the consumption of these foods, they would enter the oral cavity at 20°C, but the temperature of the oral cavity is 37 °C, so the temperature of food samples during processing would be between 20 - 37 °C. The temperature depends on the texture of the food, oral residence time, and degree of oral manipulation and so on.

This rheometer and its geometry are not suitable for a few food samples. For example, chocolate mousse is a porous food which contains a lot of air. This is continuously released during the geometry rotation, so the flow curve fluctuates. Philadelphia cream cheese and mashed potato are very thick and sticky and the food structure is broken when the geometry rotates, which causes a different shape of flow curve. The flow curves of the 22 food samples (exclude bottled water) vary greatly (Appendices: A3 and A4). However, the logarithmic plots show a narrower value range and there is some grouping of foods at 20°C (Appendices: A5 and A6).

Nine food samples were chosen from the 23 foods described above for further investigation (Chapter 6). They were tomato juice, Greek yoghurt, chocolate mousse, condensed milk, plum jam, sour cream, cheese tub, peanut butter and Nutella, as further studies focused on semi-solid and soft-solid foods. Tomato juice was selected because it is different from other foods in that the viscosity increases with an increase in temperature.

4.3.1.2. Storage modulus (G') and Loss modulus (G'')

The storage modulus (G') and loss modulus (G'') of the 23 food samples (at 13.3Hz frequency) are shown in Table 4-3. Liquid samples have no elasticity at all making the data for liquids meaningless (negative G' or G'' value). For this reason, they were omitted from the tables and plots. Correspondingly, the logarithmic value of negative G' and G'' measurements were omitted.

Data showed that the G' and G'' of porous foods (chocolate mousse and whipped cream) and some viscous foods (e.g. sour cream, cheese tub and Philadelphia cheese) decreased significantly with increasing temperature; while G' and G'' of some viscous foods (e.g. condensed milk, Nutella and peanut butter) increased significantly with temperature increasing.

Table 4-3. G' , G'' , $\text{Log}_{10}(G')$ and $\text{Log}_{10}(G'')$ of 22 food samples (frequency is at 13.3Hz) at 20 and 37 °C (mean \pm SD).

Food samples	G' (Pa)		$\text{Log}_{10}(G')$		G'' (Pa)		$\text{Log}_{10}(G'')$	
	20°C	37 °C	20°C	37 °C	20°C	37 °C	20°C	37 °C
Bottled water	-	-	-	-	-	-	-	-
Breakfast tea	-	-	-	-	-	-	-	-
Cheese tub	27390.00 \pm 1980.72	4308.67 \pm 328.33	4.44 \pm 0.03	3.63 \pm 0.03	6923.33 \pm 424.17	989.47 \pm 78.99	3.84 \pm 0.03	2.99 \pm 0.01
Chocolate mousse	240.10 \pm 15.35	18.79 \pm 10.58	2.38 \pm 0.03	1.16 \pm 0.35	40.53 \pm 3.09	7.19 \pm 1.11	1.61 \pm 0.03	0.85 \pm 0.07
Chocolate shake	-	-	-	-	-	-	-	-
Cold coffee	-	-	-	-	-	-	-	-
Condensed milk	181.03 \pm 61.92	2174.00 \pm 193.96	2.23 \pm 0.15	3.34 \pm 0.04	574.43 \pm 113.29	1233.67 \pm 32.27	2.75 \pm 0.08	3.09 \pm 0.01
Cream	-	-	-	-	-	-	-	-
Custard	111.43 \pm 8.24	74.78 \pm 12.34	2.05 \pm 0.03	1.87 \pm 0.07	62.00 \pm 1.77	45.53 \pm 5.29	1.79 \pm 0.01	1.66 \pm 0.05
Greek yoghurt	412.80 \pm 45.63	215.77 \pm 31.82	2.61 \pm 0.05	2.47 \pm 0.19	98.65 \pm 11.86	47.55 \pm 7.79	1.99 \pm 0.05	1.79 \pm 0.19
Hazelnut spread (Nutella)	539.83 \pm 322.21	28091.95 \pm 27968.05	2.61 \pm 0.38	3.42 \pm 0.63	699.20 \pm 173.13	6664.10 \pm 6315.90	2.83 \pm 0.12	3.33 \pm 0.37
Mashed potato	65410.00 \pm 4825.58	57535.00 \pm 1065.00	4.81 \pm 0.03	4.22 \pm 0.76	21243.33 \pm 10344.06	14855.00 \pm 1355.00	4.28 \pm 0.20	3.86 \pm 0.45
Melted ice-cream	13.09 \pm 4.39	4.56 \pm 0.69	1.09 \pm 0.10	0.65 \pm 0.06	8.89 \pm 0.43	10.47 \pm 0.40	0.95 \pm 0.01	1.02 \pm 0.02
Natural yoghurt	204.47 \pm 22.55	162.50 \pm 26.43	2.31 \pm 0.05	2.21 \pm 0.07	61.00 \pm 5.11	47.96 \pm 7.65	1.78 \pm 0.04	1.68 \pm 0.07
Orange juice	23.78 \pm 11.08	48.55 \pm 12.23	1.32 \pm 0.240	1.67 \pm 0.11	10.13 \pm 2.55	15.92 \pm 4.73	0.99 \pm 0.11	1.18 \pm 0.14
peanut butter	4932.20 \pm 4149.33	11217.27 \pm 13534.13	3.44 \pm 0.53	3.61 \pm 0.64	3666.33 \pm 2101.68	2559.33 \pm 1887.19	3.49 \pm 0.27	3.29 \pm 0.33
Philadelphia cheese	43456.67 \pm 2215.92	9629.33 \pm 424.75	4.64 \pm 0.02	3.98 \pm 0.02	10750.00 \pm 472.09	2312.33 \pm 108.54	4.03 \pm 0.02	3.36 \pm 0.02
Plum jam	893.73 \pm 98.87	976.60 \pm 228.19	2.95 \pm 0.03	2.98 \pm 0.10	440.13 \pm 54.04	465.67 \pm 109.19	2.64 \pm 0.03	2.66 \pm 0.11
Sour cream	1584.00 \pm 122.41	588.80 \pm 51.96	3.20 \pm 0.03	2.77 \pm 0.04	391.67 \pm 28.61	111.77 \pm 6.91	2.59 \pm 0.03	2.05 \pm 0.03
Standard milk	-	-	-	-	-	-	-	-
Tomato juice	120.97 \pm 14.71	165.67 \pm 67.31	2.08 \pm 0.06	2.19 \pm 0.17	48.44 \pm 8.76	50.12 \pm 15.40	1.68 \pm 0.08	1.68 \pm 0.12
Trim milk	-	-	-	-	-	-	-	-
Whipped cream	888.53 \pm 804.54	1.78 \pm 1.92	2.69 \pm 0.30	-0.10 \pm 0.30	456.25 \pm 302.00	10.25 \pm 3.16	2.48 \pm 0.26	0.99 \pm 0.06

A paired T-test analysis showed that G' and G'' of the 23 samples did not significantly vary with temperature between 20 °C and 37 °C (G' : $T = 0.59$, $P = 0.56$; G'' : $T = 1.13$, $P = 0.27$). Correspondingly, neither were the $\log_{10}(G')$ and $\log_{10}(G'')$ values different at 20 °C and 37 °C. These results varied greatly with some liquids samples showing negative G' and /or G'' ; and the G' and G'' of some very sticky samples decreased at 37 °C, while others increased at 37 °C.

The data showed that G' and G'' of whipped cream were very high because of the porous structure at 20 °C; but G' and G'' value decrease dramatically at 37 °C due to the melting of milk fat. G' and G'' of cheese tub and Philadelphia cheese are significant higher than Nutella and Peanut butter. This indicated that the two cheese samples store more energy during shear force being applied at 20 °C. They are more elastic, therefore, subjects need use more energy and apply more shear and force to process these foods before swallowing.

During measurement, nearly half of the mashed potato squeezed out from under the rheometer geometry. Therefore, the G' and G'' of mashed potato are not accurate, and they were omitted.

4.3.2. Stretch-ability

The Stretch-ability of 23 food samples (Table 4-4) were measured at 20 °C and 37 °C. According to previous research, the maximum force (F_{max}) and the work until the maximum force (W_{max}) represent the stretch-ability of food samples.

Table 4-4 showed that Nutella is the stickiest one in Table 4-4, followed by Philadelphia cheese and peanut butter; because the stretch-ability also represents the stickiness of the food.

The F_{max} and W_{max} of most food samples reduced significantly at 37 °C compared to 20 °C (paired T-test analysis; $T_{F_{max}} = 5.53$, $P = 0.000$; $T_{W_{max}} = 2.20$, $P = 0.039$). However, the F_{max} and W_{max} of food samples at 37 °C are not in the same order any more, as the foods responded differently to an increase in temperature.

The F_{max} and W_{max} of whipped cream and chocolate mousse decreased much more than other food samples at 37 °C because of changes in porosity during heating. The stretch-ability of mashed potato increased significantly because the sample was squeezed out of probe and platform during measurement. The F_{max} of bottled water,

trim milk and chocolate shake increased slightly, while W_{max} did not change or slightly decreased as temperature increases. The F_{max} and W_{max} of most food samples decrease as temperature increases.

Theoretically, the temperature and the stretch-ability of each food sample should be measured during oral processing, but it is difficult to measure due to mouth size and the requirement for tongue movement and oral manipulation. In Chapter 6, the stretch-ability of the expectorated bolus for 9 samples is measured.

Table 4-4. Stretch-ability (F_{max} and W_{max}) of 23 food samples at 20 °C and 37 °C (mean \pm SD)

Food type	Stretch-ability (N) (F_{max})		Work to maximum force (N.mm) (W_{max})	
	20°C	37°C	20°C	37°C
Bottle water	0.20 \pm 0.02	0.32 \pm 0.02	0.02 \pm 0.00	0.02 \pm 0.01
Breakfast tea	0.84 \pm 0.01	0.75 \pm 0.01	0.05 \pm 0.00	0.06 \pm 0.00
Cheese tub	87.97 \pm 4.04	33.71 \pm 0.81	33.69 \pm 1.55	6.20 \pm 0.15
Chocolate mousse	12.50 \pm 1.66	0.38 \pm 0.01	1.26 \pm 0.28	0.02 \pm 0.00
Chocolate shakes	2.77 \pm 0.02	2.88 \pm 0.22	0.22 \pm 0.00	0.16 \pm 0.01
Cold coffee	1.46 \pm 0.02	0.57 \pm 0.01	0.08 \pm 0.00	0.04 \pm 0.01
Condensed milk	78.48 \pm 3.54	46.11 \pm 1.78	30.06 \pm 1.36	15.35 \pm 0.59
Cream	2.34 \pm 0.12	0.58 \pm 0.03	0.18 \pm 0.01	0.02 \pm 0.01
Custard	16.07 \pm 0.21	4.48 \pm 0.30	1.72 \pm 0.02	0.35 \pm 0.02
Greek yoghurt	9.69 \pm 1.09	6.77 \pm 1.08	1.04 \pm 0.12	0.47 \pm 0.15
Hazelnut spread (Nutella)	132.28 \pm 5.88	125.80 \pm 10.45	73.91 \pm 6.07	67.42 \pm 10.05
Mashed potato	63.98 \pm 3.05	90.67 \pm 2.06	21.30 \pm 1.01	34.72 \pm 0.79
Melted ice-cream	3.96 \pm 0.21	3.94 \pm 0.26	0.31 \pm 0.02	0.27 \pm 0.04
Nature yoghurt	4.86 \pm 0.91	0.76 \pm 0.08	0.52 \pm 0.10	0.04 \pm 0.00
Orange juice	0.30 \pm 0.02	0.12 \pm 0.01	0.02 \pm 0.00	0.01 \pm 0.00
Peanut butter	112.80 \pm 1.70	89.21 \pm 2.48	60.12 \pm 0.90	43.09 \pm 1.20
Philadelphia cheese	131.98 \pm 4.56	82.53 \pm 2.99	70.34 \pm 2.43	28.58 \pm 2.87
Plum jam	68.35 \pm 1.54	36.08 \pm 0.78	23.65 \pm 2.05	10.21 \pm 0.22
Sour cream	36.33 \pm 1.95	3.24 \pm 0.10	7.62 \pm 1.28	0.35 \pm 0.01
Standard milk	1.06 \pm 0.02	0.11 \pm 0.01	0.08 \pm 0.00	0.01 \pm 0.00
Tomato juice	1.01 \pm 0.17	0.19 \pm 0.01	0.06 \pm 0.01	0.01 \pm 0.00
Trim milk	0.72 \pm 0.01	0.87 \pm 0.01	0.06 \pm 0.00	0.06 \pm 0.01
Whipped cream	9.22 \pm 0.45	0.61 \pm 0.04	0.93 \pm 0.15	0.04 \pm 0.01

When food samples are processed in the oral cavity, these factors are important for structure breakdown and bolus formation of test samples: 1.) temperature change (fat melting); for examples cheese tub, Hazelnut spread, Philadelphia cheese and sour cream have relatively high fat content, the viscosity and shear stress of these samples decreased dramatically at 37 °C than at 20 °C. Higher temperature in the oral cavity makes the oral processing of these foods easier and achieves melting sensation. 2.) Shear and mixing;

The tongue move around to manipulate foods during oral processing, actions like passing, mashing, pushing, and squeezing generate shear force and help mixing food particles or bolus formation. 3.) Original food properties affect the oral processing behaviour and the food bolus properties at the swallowing point; for examples, chocolate mousse and cheese tub have significantly different oral residence time and muscle activities (refer to Section 6.3., Chapter 6. The expectorated bolus of cold coffee and peanut butter at swallowing point have significant different moisture content and stretch-ability (refer to Section 6.3., Chapter 6).

4.3.3. Summary of food properties data

The food properties data of 23 food samples above is summarized in Table 4-5 (20 °C) and Table 4-6 (37 °C) below.

Table 4-5. Food properties data of 23 food samples at 20°C (mean ±SD).

Food samples	Shear stress (Pa)	Viscosity (Pa.s)	G' (Pa) at 13.3Hz	G'' (Pa) at 13.3Hz	F _{max} (N)	W _{max} (N.mm)
Bottled water	0.01	0.00	-	-	0.20±0.02	0.02±0.00
Breakfast tea	0.16±0.03	0.02±0	-	-	0.84±0.01	0.06±0.00
Cheese tube	337.33±15.97	33.71±1.61	27390.00±1980.72	6923.33±424.17	87.97±4.04	33.69±1.55
Chocolate mousse	30.02±1.53	3.00±0.15	240.10±15.35	40.53±3.09	12.50±1.66	1.26±0.28
Chocolate shake	1.03±0.08	0.10±0.01	-	-	2.77±0.02	0.22±0.00
Cold coffee	0.24±0.01	0.02±0.00	-	-	1.46±0.02	0.08±0.00
Condensed milk	78.69±7.83	7.87±0.87	181.03±61.92	573.43±113.29	78.48±3.54	30.06±1.36
Cream	0.43±0.04	0.04±0.00	-	-	2.34±0.12	0.19±0.01
Custard	24.74±0.95	2.47±0.10	111.43±8.24	62.00±1.77	16.07±0.21	1.72±0.02
Greek yoghurt	17.04±0.87	1.70±0.09	412.80±45.63	98.65±11.86	9.69±1.09	1.04±0.12
Hazelnut spread (Nutella)	566.95±66.83	56.71±6.70	539.83±322.01	699.20±173.13	132.28±5.88	73.91±6.07
Mashed Potato	972.63±0.05	297.39±164.45	65410.00±4825.58	21243.33±10344.06	63.98±3.05	21.30±1.01
Melted ice-cream	0.93±0.08	0.09±0.01	13.09±4.39	8.89±0.43	3.96±0.21	0.31±0.02
Natural yoghurt	12.93±2.93	1.29±0.07	204.47±22.55	61.00±5.10	4.86.00±0.91	0.52±0.10
Orange juice	0.64±0.15	0.06±0.01	23.78±11.07	10.13±2.55	0.30±0.02	0.02±0.00
Peanut butter	611.28±210.88	58.09±16.01	4932.20±4149.33	3666.33±2101.68	112.80±1.70	60.12±0.90
Philadelphia cheese	551.07±54.55	54.98±5.36	43456.67±2215.92	10750.00±472.09	131.98±4.56	70.35±2.43
Plum jam	91.90±6.20	9.19±0.62	893.73±98.87	440.13±54.04	68.35±1.54	23.65±2.05
Sour cream	180.15±10.15	18.02±1.02	1584.00±122.41	391.67±28.61	36.33±1.95	7.62±1.28
Standard milk	0.08±0.06	0.01±0.01	-	-	1.06±0.02	0.08±0.00
Tomato juice	3.64±0.68	0.36±0.07	120.97±14.71	48.44±8.76	1.01±0.17	0.06±0.01
Trim milk	0.17±0.15	0.02±0.02	-	-	0.72±0.01	0.06±0.00
Whipped cream	11.94±7.16	1.19±0.72	888.53±804.54	456.25±302.00	9.22±0.45	0.93±0.15

* Water data is from CRC Handbook of Chemistry and Physics, 85th Edition

Table 4-6. Food properties data of 23 food samples at 37°C (mean ±SD).

Food samples	Shear stress (Pa)	Viscosity (Pa.s)	G' (Pa) at 13.3Hz	G'' (Pa) at 13.3Hz	F _{max} (N)	W _{max} (N.mm)
Bottle water	0.01	0.00	-	-	0.32±0.02	0.02±0.01
Breakfast tea	0.06±0.02	0.01±0.00	-	-	0.75±0.01	0.06±0.00
Cheese tub	145.63±4.21	14.56±0.43	4308.67±328.38	989.47±78.99	33.71±0.81	6.20±0.15
Chocolate mousse	0.32±0.03	0.03±0.00	18.79±10.58	7.19±1.11	0.38±0.01	0.02±0.00
Chocolate shake	1.04±0.94	0.10±0.00	-	-	2.88±0.22	0.16±0.01
Cold coffee	0.11±0.00	0.01±0.00	-	-	0.57±0.01	0.04±0.01
Condensed milk	36.15±1.38	3.62±0.14	2174.00±193.96	1233.67±32.27	46.11±1.78	15.35±0.59
Cream	0.07±0.00	0.01±0.00	-	-	0.58±0.03	0.02±0.01
Custard	15.58±1.46	1.56±0.15	74.78±12.34	45.53±5.29	4.48±0.30	0.35±0.02
Greek yoghurt	7.57±0.34	0.76±0.04	215.77±31.82	47.55±7.79	6.77±1.08	0.47±0.15
Hazelnut spread (Nutella)	250.57±23.44	25.05±2.34	28091.95±27968.05	6664.10±6315.90	125.80±10.45	67.42±10.45
Mashed Potato	966.37±8.96	93.91±17.04	57535.00±1065.00	14855.00±1355.00	90.67±2.06	34.72±0.79
Melted ice-cream	0.52±0.00	0.05±0.00	4.56±0.69	10.47±0.40	3.95±0.26	0.27±0.05
Natural yoghurt	4.76±0.48	0.48±0.05	162.50±26.43	47.96±7.65	0.76±0.08	0.04±0.00
Orange juice	0.37±0.05	0.04±0.01	48.55±12.23	15.92±4.73	0.12±0.01	0.01±0.00
Peanut butter	200.07±40.90	19.94±4.02	11217.27±12729.18	2559.33±1646.70	89.21±2.48	43.09±1.20
Philadelphia cheese	354.13±12.45	35.38±1.23	9629.33±424.75	2312.33±108.54	82.53±3.00	28.58±2.87
Plum jam	53.42±4.75	5.34±0.48	933.50±170.08	399.33±90.97	36.09±0.78	10.21±0.22
Sour cream	50.70±3.11	5.07±0.31	588.80±51.96	111.77±6.91	3.24±0.10	0.35±0.01
Standard milk	0.04±0.02	0.00±0.00	-	-	0.12±0.01	0.01±0.00
Tomato juice	9.04±5.52	0.90±0.55	165.67±67.31	50.12±15.40	0.19±0.01	0.01±0.00
Trim milk	0.02±0.00	0.00±0.00	-	-	0.87±0.01	0.06±0.01
Whipped cream	0.78±0.08	0.08±0.01	1.78±1.92	10.25±3.16	0.61±0.04	0.04±0.01

* Water data is from CRC Handbook of Chemistry and Physics, 85th Edition

4.4. Conclusion

This chapter characterized 23 food samples according to food viscosity, shear stress, G' and G'' and stretch-ability at 20 and 37 °C. Paired T-tests showed that the shear stresses and stretch-abilities (F_{max} and W_{max}) of 23 food samples are significantly greater at 20

°C than 37°C. The viscosities, G' and G'' were not shown to be significantly different at 20 °C and 37 °C. Temperature affects food rheological properties.

Besides temperature change, oral movements (e.g. chewing behaviour and tongue manipulation) are the essential factors in investigation of oral processing of foods. The oral processing behaviour (ORT, oral muscle activities and tongue movement) of above foods will be investigated using 2 subjects in the next chapter.

Chapter 5: Oral processing behaviour during the consumption of different food samples

5.1. Introduction

Twenty-three food samples were characterised in Chapter 4 (Table 4-5 and 4-6). Except for mashed potato they were found to be appropriate to use in further EMA and EMG studies to determine food Oral Residence Time (ORT), muscle activities and tongue movements during food oral processing.

The purpose of this chapter was to measure the ORT and muscle activities during consumption of the food samples, and investigate the reproducibility of the EMG and EMA methods. Alongside this, the usefulness of these methods for observing the initiation of chewing (when chewing is necessary) will be investigated along with the function of the tongue during oral processing.

5.2. Materials and methods

5.2.1. Subjects and materials

Two male subjects (23 y and 24 y) took part in this study after giving informed consent. They met the screening criteria outlined in Section 3.2.1.1. The subjects had a natural dental condition, no neurological impairment, neuromuscular complaints, dysphagia or dysphonia. They were not taking any medicine known to influence oral movements or saliva secretion (Appendices A1). The experiments using the EMA and EMG methods were conducted across three sessions respectively in an isolated and quiet laboratory room within the Institute of Food, Nutrition and Human Health, Massey University, Auckland. This work was approved by the university ethics committee (Massey University Human Ethics Committee: Southern A Application 10/12).

Twenty-two food samples (see Section 4.2.1.) were used in these experiments. They were stored as per their label requirements and then weighed and placed in a 20°C room for 1.5 hours prior to each session. This allowed adequate time for samples to reach room temperature (20°C).

5.2.2. Methods

Each subject came to the laboratory at 10am on three occasions for each of the EMA and EMG measurements. The twenty-two characterised food samples were numbered randomly and prepared before the subject came. The subject sat in the EMA magnetic field cube, 6 sensor coils were fixed in the oral cavity and on the skin (refer to Section 3.2). Four sensor coils were fixed in the oral cavity; one of them was fixed on the upper incisor as a reference sensor. Three sensor coils were fixed near the tongue tip, tongue back and lower incisor (Figure 3-1). The other two reference sensors were fixed behind both ears on bone positions. Approximately 5.3 g of food sample was placed in a disposable spoon or a plastic container (liquid). The subject was instructed to consume the food sample as naturally as possible. After consumption, the subject rinsed his mouth at least three times before the next sample.

For EMG measurements, the subjects skin was first cleaned (refer to Section 3.2.2.2) and then they sat in their normal feeding position. Electrodes were fixed on the right masseter muscle and both sides of the submental muscles (Figure 3-13). The subject was instructed to consume the food samples which were presented in a random order. The procedure was as described in Section 3.2.2.1. Food samples were processed on the subjects' preferred chewing side (right side for both subjects).

5.3. Results and discussion

5.3.1. Oral residence time

The oral residence times (ORTs) measured using EMA are provided in Table 5-1. Except for plum jam, sour cream, cheese tub, Philadelphia cheese, peanut butter and bottled water, paired T-Test ($T = -0.76$, $p = 0.455$) did not show the ORT to be significantly different, although subject 1 took slightly longer time to consume most food samples. The ORTs measured using EMG are given in Table 5-2. Again, subject 1 showed, on average, slightly longer ORTs for most samples but this was not found to be significant ($T = 1.34$, $p = 0.196$). When comparing the EMA and EMG methods, the ORTs measured using EMA were significantly longer than those measured using EMG ($T = 2.39$, $p = 0.026$), especially for Nutella and condensed milk (Figure 5-1). This is mainly due to the restriction of the wires from the EMA sensor coils in the oral cavity. For this reason the EMG method is believed to be more accurate for measuring the ORTs during the consumption of a wide range of foods as it does not require sensors to

be placed inside the oral cavity which influences oral processing behaviours (e.g. subjects chewing slower and more carefully to ensure they do not bite a wire and break it). More subjects are required to verify whether there is a significant difference between ORTs measured using EMA and EMG methods. However evidence suggests this to be the case.

Table 5-1. Oral residence time (ORT) of 22 food samples using EMA

Food samples	ORT _{EMA} (s)							
	Subject 1				Subject 2			
	1	2	3	Mean ± SD	1	2	3	Mean ± SD
Bottled water	1.37	2.32	1.36	1.68±0.45	1.67	2.16	1.85	1.89±0.20
Breakfast tea	1.67	1.83	1.58	1.69±0.1	1.59	1.38	1.49	1.49±0.08
Cheese tube	8.21	10.74	9.76	9.57±1.04	18.42	10.82	12.08	13.77±3.33
Chocolate mousse	3.84	2.93	2.78	3.18±0.47	3.42	2.44	2.50	2.79±0.45
Chocolate shake	2.61	2.36	4.40	3.12±0.91	1.60	1.72	1.52	1.61±0.08
Cold coffee	2.1	1.82	1.76	1.89±0.15	1.58	1.66	1.72	1.65±0.06
Condensed milk	8.91	11.88	11.02	10.60±1.25	5.73	4.595	4.20	4.84±0.65
Cream	2.53	2.65	3.04	2.74±0.22	2.02	1.78	1.76	1.85±0.12
Custard	6.88	5.27	4.20	5.45±1.1	2.68	2.80	2.52	2.67±0.11
Greek yoghurt	3.84	3.54	3.59	3.66±0.13	1.68	2.26	3.18	2.37±0.62
Hazelnut spread (Nutella)	16.16	16.03	24.35	18.85±3.89	37.56	32.76	29.04	33.12±3.49
Melted ice-cream	3.58	3.87	2.88	3.44±0.42	1.75	1.68	1.34	1.59±0.18
Natural yoghurt	5.06	3.75	5.24	4.68±0.66	1.84	2.08	2.10	2.01±0.12
Orange juice	1.68	2.07	1.77	1.84±0.17	1.86	1.02	1.86	1.58±0.40
Peanut butter	8.72	7.07	9.18	8.32±0.91	7.56	17.74	10.48	11.93±4.28
Philadelphia cheese	15.11	13.08	14.13	14.10±0.83	25.68	31.43	25.26	27.46±2.81
Plum jam	5.86	5.18	5.12	5.39±0.34	8.18	5.94	7.86	7.33±0.99
Sour cream	4.69	3.28	4.08	4.02±0.58	5.34	3.96	6.07	5.12±0.87
Standard milk	2.34	2.44	1.70	2.16±0.33	1.72	1.80	1.58	1.7±0.09
Tomato juice	2.13	2.35	2.96	2.48±0.35	1.62	1.82	1.92	1.79±0.12
Trim milk	3.22	2.30	4.08	3.2±0.73	2.58	2.94	2.22	2.58±0.29
Whipped cream	3.79	6.80	5.11	5.23±1.23	3.64	2.74	2.64	3.01±0.45

Table 5-2. Oral residence time (ORT) of 22 food samples using EMG

Food samples	ORT _{EMG} (s)							
	Subject 1				Subject 2			
	1	2	3	Mean ± SD	1	2	3	Mean ± SD
Bottled water	1.80	1.96	2.14	1.97±0.14	1.12	1.16	1.26	1.18±0.06
Breakfast tea	1.88	1.58	1.58	1.68±0.14	1.52	1.56	1.68	1.59±0.07
Cheese tube	15.20	20.40	18.50	18.03±2.15	6.02	5.84	5.28	5.71±0.32
Chocolate mousse	2.76	2.62	2.66	2.68±0.06	1.46	1.04	1.06	1.19±0.19
Chocolate shake	2.10	2.60	1.70	2.13±0.37	1.58	1.46	1.44	1.49±0.06
Cold coffee	2.50	2.50	3.20	2.73±0.33	1.22	1.20	1.14	1.19±0.03
Condensed milk	4.38	4.72	4.32	4.47±0.18	5.48	4.88	4.64	5.00±0.35
Cream	4.20	2.00	3.30	3.17±0.9	1.16	1.24	1.20	1.20±0.03
Custard	6.60	6.40	6.00	6.33±0.25	2.78	2.38	2.36	2.51±0.19
Greek yoghurt	3.84	4.06	4.24	4.05±0.16	1.60	1.80	2.94	2.11±0.59
Hazelnut spread (Nutella)	16.90	18.00	24.90	19.93±3.54	23.72	20.10	21.4	21.74±1.5
Melted ice-cream	2.92	2.92	2.72	2.85±0.09	2.12	1.72	1.86	1.90±0.17
Natural yoghurt	3.02	2.72	2.88	2.87±0.12	1.50	1.70	1.50	1.57±0.09
Orange juice	3.22	2.78	2.72	2.91±0.22	1.62	1.46	1.46	1.51±0.08
Peanut butter	10.60	9.20	9.10	9.63±0.68	9.28	10.88	5.42	8.53±2.29
Philadelphia cheese	12.60	17.68	14.98	15.09±2.08	24.74	30.26	24.54	26.51±2.65
Plum jam	6.00	5.40	5.60	5.67±0.25	4.28	3.20	3.18	3.55±0.51
Sour cream	4.22	3.72	4.12	4.02±0.22	5.32	3.34	5.52	4.73±0.98
Standard milk	2.10	2.60	1.80	2.17±0.30	1.04	1.16	1.12	1.11±0.05
Tomato juice	3.28	3.18	2.92	3.13±0.15	2.22	2.08	1.64	1.98±0.25
Trim milk	2.60	2.20	2.10	2.30±0.22	1.08	1.14	1.04	1.09±0.04
Whipped cream	4.30	7.50	4.90	5.57±1.39	1.46	1.98	1.58	1.67±0.22

Paired T-Tests showed that there is no significant difference between ORTs recorded for each replicate using both EMA and EMG methods. This means that both the EMA and EMG methods are repeatable and reproducible for measuring ORTs.

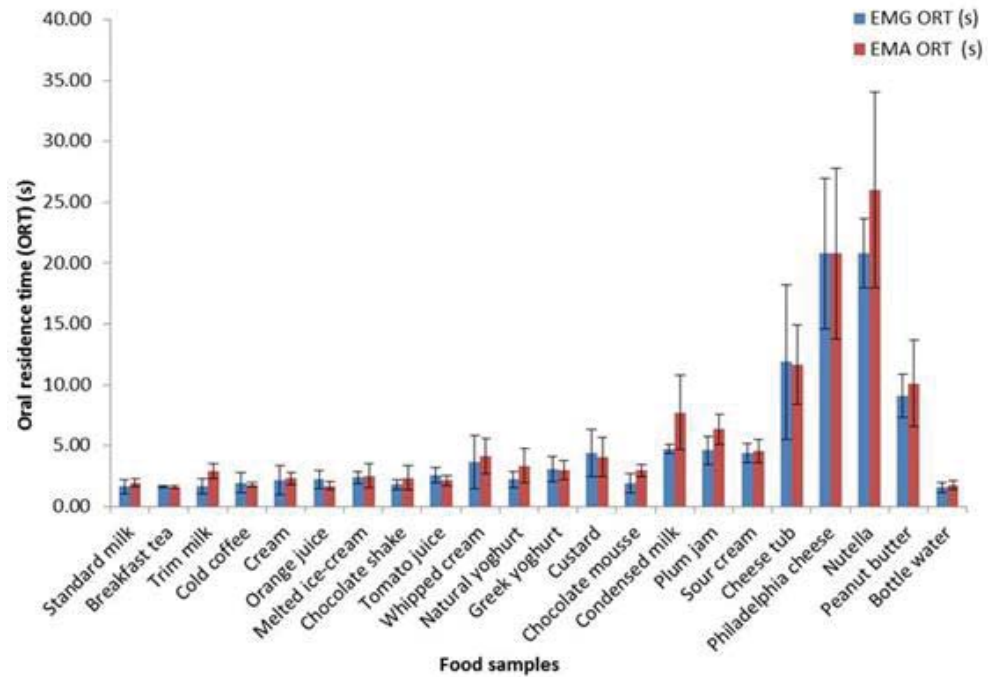


Figure 5-1. The ORTs of 22 food samples using EMA (red) and EMG (blue) methods

Comparing the measured ORTs with the rheological and textural properties (Table 5-1, 5-2 and Figure 5-1), the ORT increases with the food stretch-ability (measured at both 20 °C and 37 °C). Linear regression analysis showed that ORTs measured using both EMG and EMA strongly correlate with the stretch-ability (ORT_{EMG} : $R\text{-sq (adj)} = 80.8\%$; ORT_{EMA} : $R\text{-sq (adj)} = 83.2\%$). This indicates that ORT and food stickiness are strongly correlated. The linear regression analysis shows ORTs positively correlate to the viscosity at 20°C (R^2 (adj) = 78.8%) and 37°C (R^2 (adj) = 86.3%). ORTs also positively correlate to shear stress at 20°C (R^2 (adj) = 76.8%) and 37°C (R^2 (adj) = 86.3%). These results confirm the previous conclusion from Chen & Lolivret (2011), which showed the oral processing behaviour highly correlates to the food rheological properties. ORTs are correlated stronger with viscosity and shear stress measured at 37°C than at 20°C. This is possibly due to the temperature of the consumed food bolus is closer to 37°C due to heating in the oral cavity.

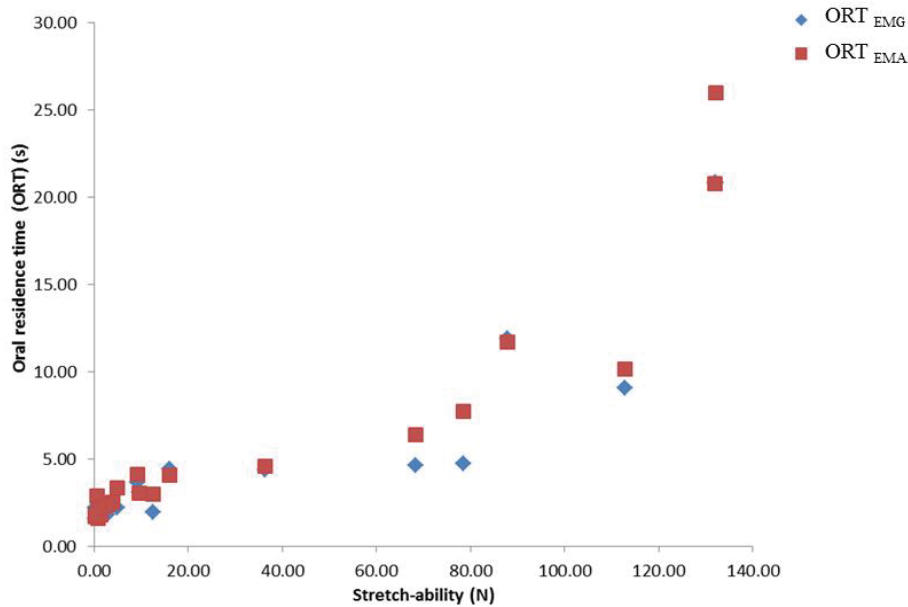


Figure 5-2, Oral residence time versus stretch-ability (measured at 20°C using a Texture Analyser). Oral residence times were measured using both EMG (diamond) and EMA (square). Average ORT data from 2 subjects is presented.

5.3.2. Muscle activities

Three muscle activity parameters were used to summarise the EMG data collected for the masseter and submental muscles: average voltage (AV_{masseter} , $AV_{\text{submental}}$), maximum voltage (MV_{masseter} , $MV_{\text{submental}}$) and the total area under the rectified EMG curve (TA_{masseter} , $TA_{\text{submental}}$). The two subjects' muscle activity data is shown in Table 5-3.

Table 5-3. Muscle activities of 22 food samples during oral residence time

Food samples	Subject 1						Subject 2					
	Average voltage of muscle (mV)		Maximum voltage of muscle (mV)		Area under curve (mV.s)		Average voltage of muscle (mV)		Maximum voltage of muscle (mV)		Area under curve (mV.s)	
	Masseter	Submental	Masseter	Submental	Masseter	Submental	Masseter	Submental	Masseter	Submental	Masseter	Submental
Bottled water	0.08±0.05	0.13±0.08	0.16±0.11	0.46±0.31	0.16±0.1	0.25±0.16	0.02±0	0.03±0	0.04±0	0.12±0	0.03±0	0.04±0
Breakfast tea	0.08±0.05	0.16±0.10	0.23±0.16	0.58±0.39	0.14±0.09	0.27±0.18	0.03±0	0.03±0	0.04±0	0.10±0.01	0.04±0	0.04±0
Cheese tube	0.18±0.12	0.34±0.23	1.82±1.21	1.42±0.95	2.13±1.42	3.97±2.65	0.06±0	0.05±0	0.08±0.01	0.19±0.03	0.32±0.02	0.30±0.02
Chocolate mousse	0.07±0.05	0.16±0.11	0.13±0.09	0.74±0.5	0.20±0.13	0.43±0.29	0.02±0	0.04±0.01	0.06±0.03	0.14±0.04	0.03±0	0.05±0
Chocolate shake	0.07±0.05	0.13±0.09	0.19±0.13	0.45±0.3	0.22±0.14	0.42±0.28	0.02±0	0.03±0	0.03±0	0.14±0.02	0.03±0	0.05±0
Cold coffee	0.06±0.04	0.13±0.08	0.12±0.08	0.45±0.30	0.18±0.12	0.35±0.23	0.05±0	0.05±0	0.06±0	0.15±0.02	0.07±0	0.06±0
Condensed milk	0.09±0.06	0.18±0.12	0.68±0.48	0.79±0.53	0.38±0.26	0.81±0.54	0.03±0	0.03±0.01	0.04±0.01	0.14±0.03	0.15±0.01	0.18±0.06
Cream	0.06±0.04	0.13±0.08	0.10±0.07	0.38±0.25	0.12±0.08	0.25±0.16	0.05±0	0.04±0	0.06±0	0.12±0.02	0.07±0	0.05±0
Custard	0.07±0.05	0.16±0.11	0.22±0.15	0.63±0.42	0.29±0.2	0.70±0.46	0.02±0	0.03±0.01	0.04±0.01	0.17±0.03	0.06±0	0.09±0.01
Greek yoghurt	0.11±0.08	0.16±0.1	1.23±0.82	0.67±0.45	0.54±0.36	0.74±0.5	0.02±0	0.04±0	0.04±0	0.15±0.01	0.04±0	0.06±0.01
Hazelnut spread (Nutella)	0.31±0.21	0.34±0.23	2.32±1.55	1.47±0.98	6.16±4.11	6.80±4.54	0.02±0	0.05±0	0.17±0.18	0.48±0.34	0.81±0.1	1.51±0.22
Melted ice-cream	0.07±0.05	0.12±0.08	0.1±0.07	0.52±0.35	0.2±0.13	0.36±0.24	0.03±0	0.03±0	0.04±0	0.12±0.02	0.05±0	0.05±0
Natural yoghurt	0.08±0.05	0.14±0.09	0.23±0.16	0.59±0.39	0.23±0.15	0.39±0.26	0.03±0	0.03±0	0.04±0	0.12±0.03	0.06±0.02	0.07±0.02
Orange juice	0.12±0.08	0.14±0.09	0.85±0.58	0.69±0.46	0.37±0.25	0.40±0.27	0.03±0	0.03±0	0.04±0	0.10±0.02	0.04±0	0.04±0.01
Peanut butter	0.25±0.17	0.28±0.19	2.13±1.42	1.18±0.79	4.64±3.11	5.21±3.48	0.03±0	0.05±0.01	0.12±0.04	0.20±0.05	0.22±0.04	0.40±0.15
Philadelphia cheese	0.22±0.14	0.26±0.17	1.85±1.24	0.92±0.61	3.29±2.2	3.96±2.65	0.03±0	0.04±0	0.05±0.01	0.21±0.02	0.67±0.05	1.11±0.16
Plum jam	0.16±0.11	0.22±0.15	1.67±1.12	0.90±0.6	1.12±0.75	1.55±1.04	0.02±0	0.04±0	0.05±0.01	0.16±0.01	0.09±0.01	0.14±0.02
Sour cream	0.08±0.05	0.18±0.12	0.30±0.2	0.79±0.52	0.33±0.22	0.73±0.48	0.03±0	0.03±0	0.04±0	0.14±0.02	0.13±0.03	0.16±0.04
Standard milk	0.09±0.06	0.13±0.09	0.29±0.2	0.48±0.32	0.19±0.12	0.28±0.19	0.06±0	0.05±0	0.07±0.01	0.12±0.01	0.06±0	0.05±0
Tomato juice	0.10±0.07	0.12±0.08	0.52±0.35	0.60±0.4	0.31±0.21	0.36±0.24	0.03±0	0.03±0	0.04±0	0.12±0.01	0.05±0.01	0.05±0.01
Trim milk	0.06±0.04	0.19±0.13	0.09±0.06	0.51±0.34	0.11±0.08	0.34±0.23	0.05±0	0.05±0	0.06±0	0.12±0.02	0.06±0	0.05±0.01
Whipped cream	0.07±0.05	0.16±0.1	0.13±0.08	0.49±0.32	0.21±0.14	0.48±0.32	0.02±0	0.03±0	0.03±0	0.13±0.03	0.04±0	0.06±0.01

The AV_{masseter} and $AV_{\text{submental}}$ showed the average muscle voltage increases with food viscosity during ORT of food consumption. Generally, $AV_{\text{submental}}$ is greater than AV_{masseter} , especially for the viscous foods (e.g. sour cream and cheese tub). Muscle voltage is highly related to the muscle force (Hof, 1997; Ibitoye, Estigoni, Hamzaid, Wahab, & Davis, 2014; Boyar & Kilcast, 1986), therefore, MV_{masseter} and $MV_{\text{submental}}$ represent the maximum muscle force during consumption of food. The area under the EMG curves are believed to relate to the muscle work (Brown, Shearn, & Macfie, 1994; Gonzalez, Montoya, & Carcel, 2001), therefore, TA_{masseter} and $TA_{\text{submental}}$ represent the total muscle work during consumption of the food samples.

Data was analysed by a Paired T-Test. The results showed that the muscle activities of subject 1 were significantly different to subject 2 on all measures. The muscle voltage and total area of subject 1 is significantly greater than that of subject 2. Whilst this needs to be verified with more subjects, this indicates that subjects use significantly different muscle forces and work to consume the same food samples. The average voltage (AV) recorded at the masseter were significantly less than those recorded at the submental muscle for both subjects ($T = -10.40$, $p = 0.000$). The same was found for the total area under the curve results (TA) ($T = -4.18$, $p = 0.000$). This indicates that the force and work of the chewing muscle (masseter) are less than for the swallowing related muscle (submental). The data also showed that subjects conducted more work on harder food samples than thin and soft foods. For example, both subjects used much more work during consumption of cheese, Nutella and peanut butter than during consumption of bottle water, milk and cold coffee (Figure 5-12).

Paired T-Test analysis showed that there is no significant difference on any muscle activities between each replicate ($p > 0.05$) for subjects 1 and 2. This indicates that the muscle activity measurement using EMG is repeatable and reproducible. This also indicates that both the subjects used similar strategies for each replicate and on different sessions.

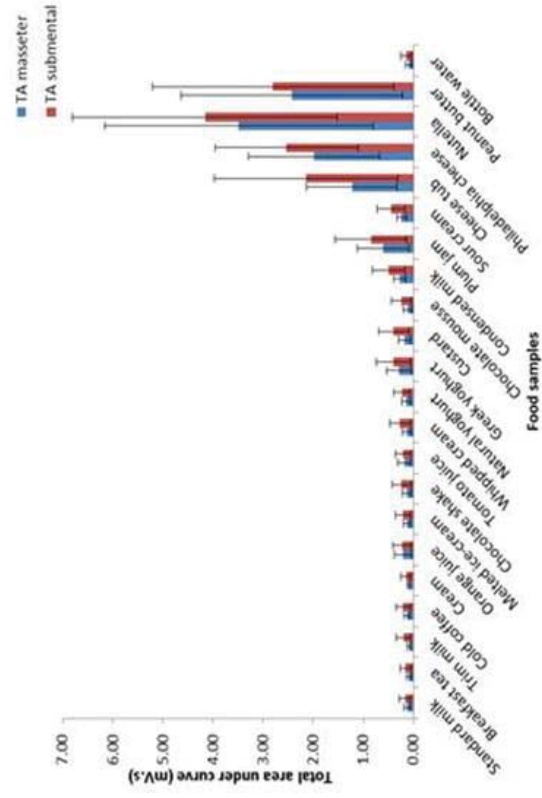
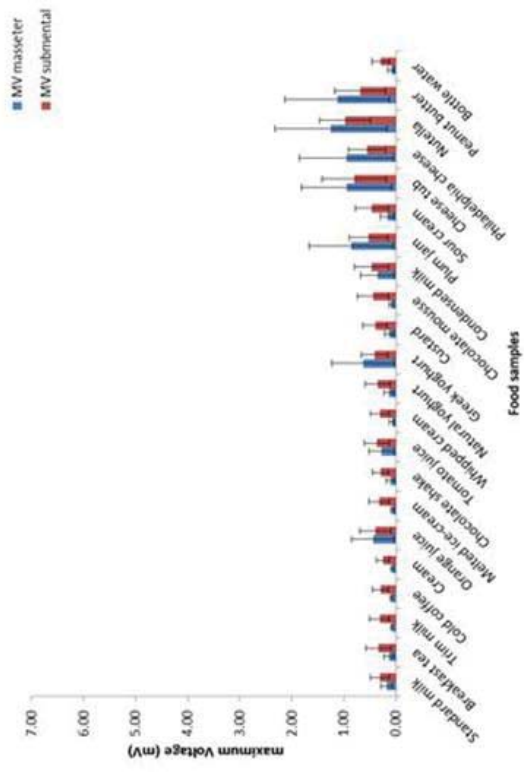


Figure 5-3. Average voltage, maximum voltage and total area under the EMG curve for two subjects during the consumption of 22 food samples.

5.3.3. Reproducibility of the EMA and EMG measurement

Intra-subject variation

Three replicates were done for each sample. These replicates were made across different sessions. Paired T-Test analysis showed there to be no significant differences between replicates from EMA and EMG measurements of ORT and muscle activity within each subject. This indicates that the subjects use similar strategies during each replicate of the same food, and that the EMA and EMG devices give repeatable data.

Inter-subject variation

Paired T-Test analysis showed that there are no significant differences between the two subjects for ORT values measured using both EMA and EMG. There were significant differences between the two subjects on average voltage (AV), maximum voltage (MV) and total area under EMG curve (TA) measurements ($p < 0.05$). This illustrates that individuals can use different strategies to process the same food along with there being physiological differences between subjects (Hertrich & Ackermann, 2000; Kaburagi & Honda, 1996; Neto Henriques & van Lieshout, 2013).

5.3.4. The initiation of chewing activity

Human chewing is an important rhythmic oral processing behaviour during consumption of solid food. It is a complex biomechanical process and the chewing frequency is about 0.9 s^{-1} (Luschei & Goldberg, 1981). The chewing patterns vary within and between individuals and the type of the processed food (Una Soboleva, Lija Laurina, & Slaidina, 2005). Chewing movements do not always appear during oral processing of different foods. Chewing behaviour of solid foods has been widely researched, but there is little mention in literature about the initiation (occurrence) of chewing activity during oral processing of semi-liquid or semi-solid foods.

The chewing activity was investigated using EMA and EMG during oral processing of 22 food samples. The aim of this section is to determine the boundary of food properties which initiates chewing or chewing-like activity during oral processing.

5.3.4.1. Determining the initiation of chewing using lower jaw movements

EMA was used to detect chewing activity by monitoring lower jaw movements as rhythmic lower jaw movements are the main characteristic of chewing activity. Section

3.2.2 showed that the EMA sensor coil on the lower incisor can track the trajectory of the lower jaw, so the EMA is a direct and reliable method to track lower jaw movement during oral processing of various foods (Birkholz, Kroeger, & Neuschaefer-Rube, 2011; Henriques & van Lieshout, 2013; Hertrich & Ackermann, 2000; Kaburagi & Honda, 1996; Mooshammer, Hoole, & Geumann, 2006; Neto Henriques & van Lieshout, 2013; Rong, Loucks, Kim, & Hasegawa-Johnson, 2012; Tabain, 2003; Terband et al., 2009).

The EMA displacement - time plots are shown in Figures 5-5 to 5-9. Chewing activity is noticeable in some of these figures as shown by a white arrow. Generally, these results showed three types of lower jaw movement during oral processing: 1) no lower jaw movement (Figure 5-5 and 5-6) ; 2) had lower jaw movement, but the movement was irregular and weak in frequency and amplitude (Figure 5-7 and 5-8) ; 3) had rhythmic lower jaw movement with greater frequency and certain amplitude (Figure 5-9). These three types of lower jaw movement were considered to potentially correspond to three food types: liquid, semi-solid and soft-solid. However, there are no clear boundaries between liquid and semi-solid, semi-solid and soft-solid foods (Figure 5-4). Hard-solid food definitely requires chewing behaviour before swallowing; therefore hard-solids were not included in this study. However, it is unclear at what point foods do require mastication. This could be somewhere in the semi-solids to soft-solids range. This is the focus of this section.

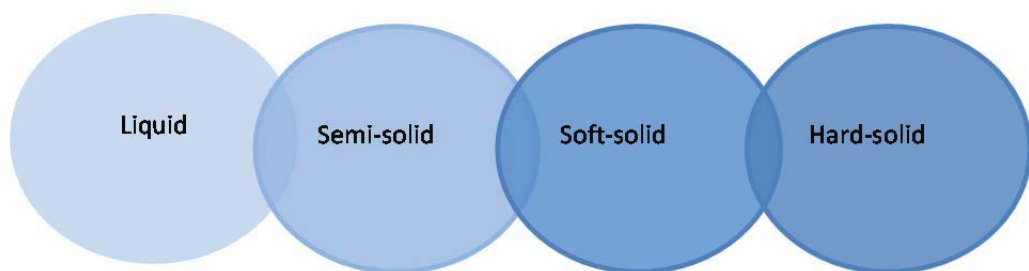


Figure 5-4. Relationships of four types of foods

No lower jaw movement means the amplitude of the tongue and lower jaw movements are less than 3mm in any dimension except for swallowing movements; the number of movement cycles (peaks) is less than 2, and the movement frequency is less than 1 per second (Figure 5-5 and 5-6). The irregular tongue and lower jaw movement means the lower jaw moves in low frequency ($< 1/s$) and the amplitude is weak (≤ 6 mm) and

uneven (Figure 5-7 and 5-8). Chewing activity is defined as regular lower jaw movement cycles, the frequency is about $0.9s^{-1}$, and the amplitude is greater than 6 mm (Figure 5-9). The displacement-time plots show that most food samples do not have rhythmic lower jaw or tongue movement. According to data and plots, both subjects chewed peanut butter, Nutella, and Philadelphia cream cheese during oral processing. Three food samples were unique in this experiment. They were condensed milk, sour cream and plum jam (Figure 5-7 and 5-8). Subjects had lower amplitudes of jaw movements during consumption of these foods. These movements were not rhythmic, but the frequency and the amplitude were close to what would be observed during mastication. Other food samples were classified into the no lower jaw movement group or the rhythmic lower jaw movement group.

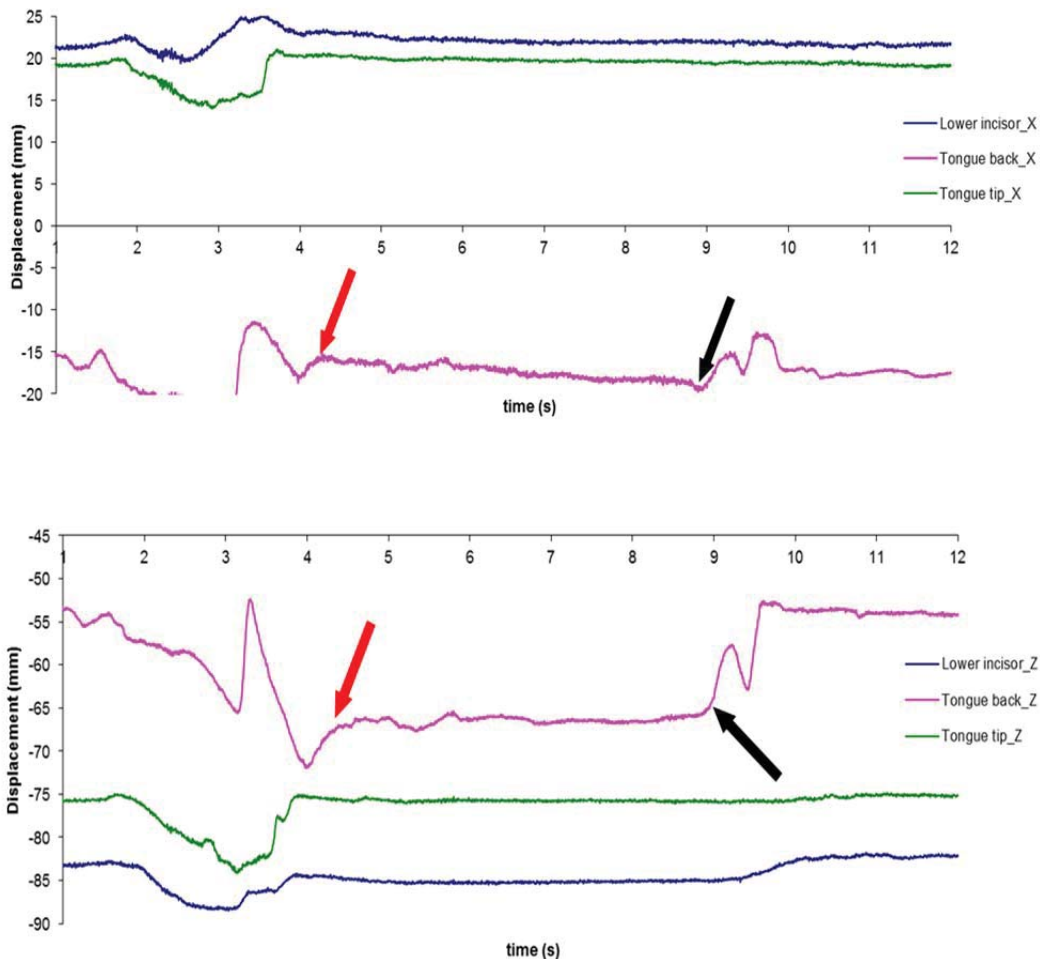


Figure 5-5. The tongue and lower jaw movements during oral processing of bottled water in X and Z axes. There are no tongue and lower jaw movements between food ingestion and swallowing. The black arrow points to the swallowing point, the red arrow points to the end of food ingestion.

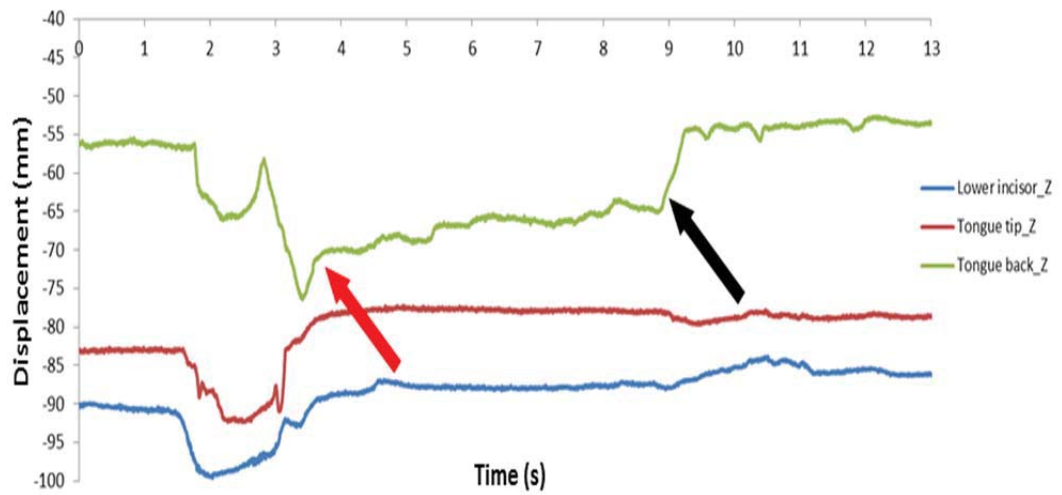
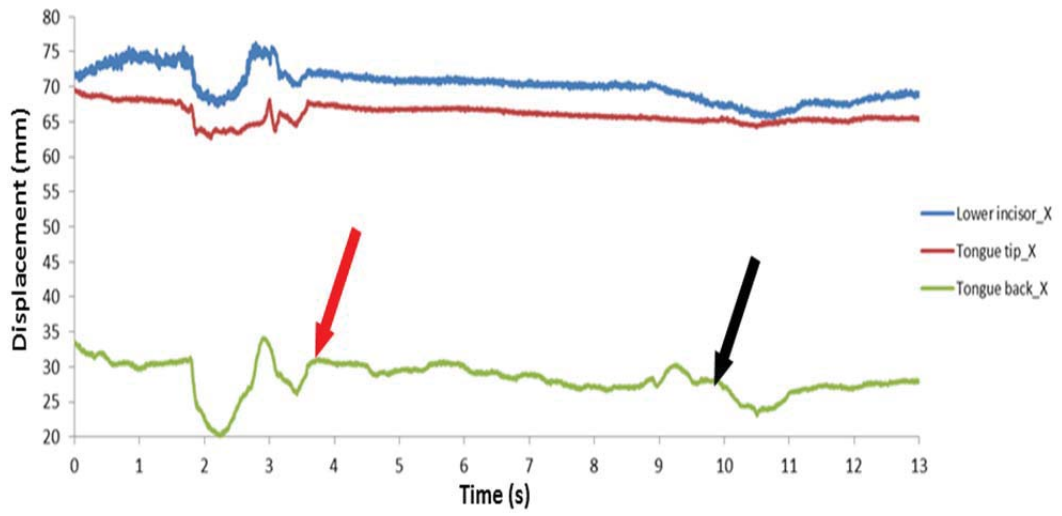


Figure 5-6. The tongue and lower jaw movements during oral processing of chocolate mousse in X and Z axes. There are no tongue and lower jaw movements between food ingestion and swallowing. The black arrow points to the swallowing point, the red arrow points to the end of food ingestion.

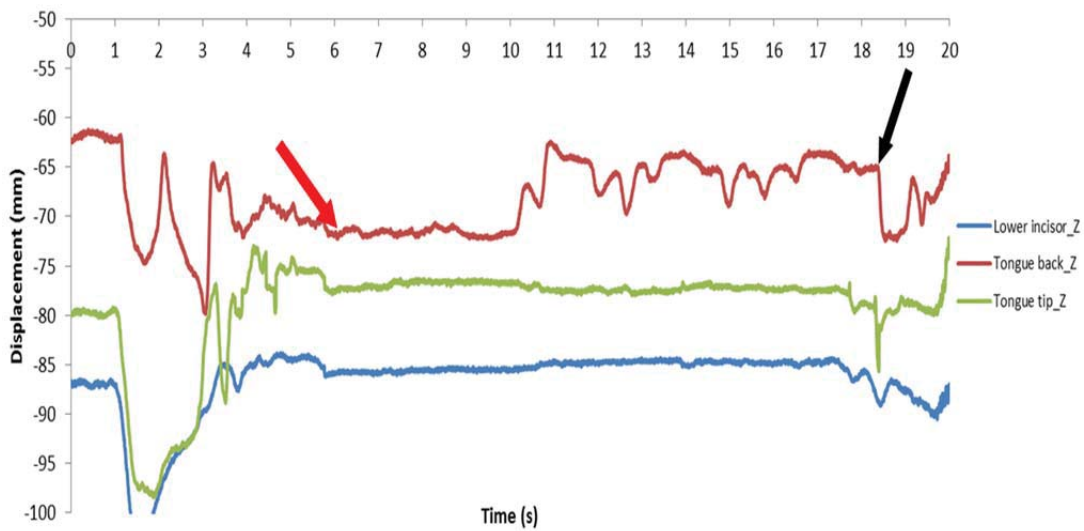
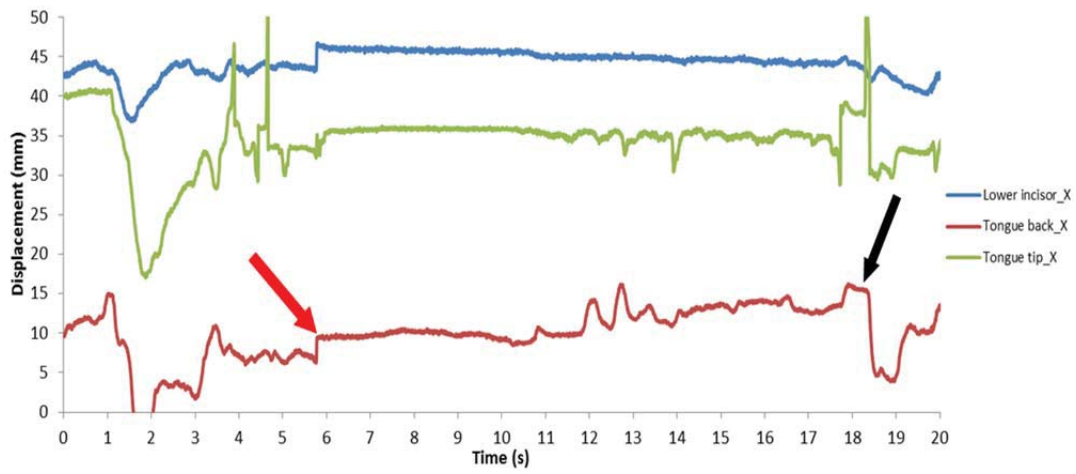


Figure 5-7. The tongue and lower jaw movement during oral processing of condensed milk in X and Z axes. The lower jaw moves in low frequency ($< 1/s$), and the amplitude of the tongue and lower jaw is weak ($< 6mm$) and uneven. The black arrow points to the swallowing point, the red arrow points to the end of food ingestion.

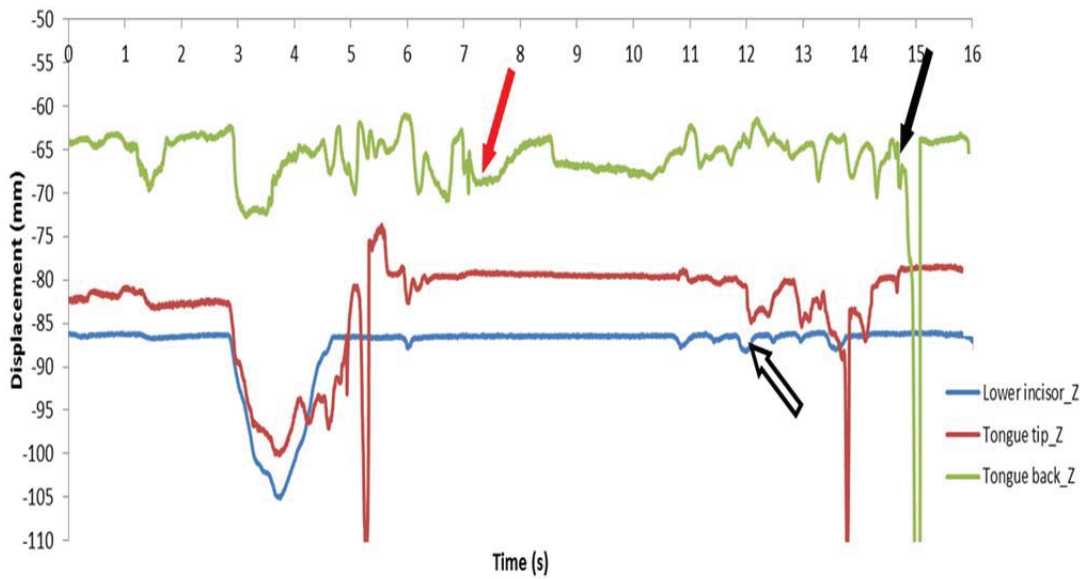
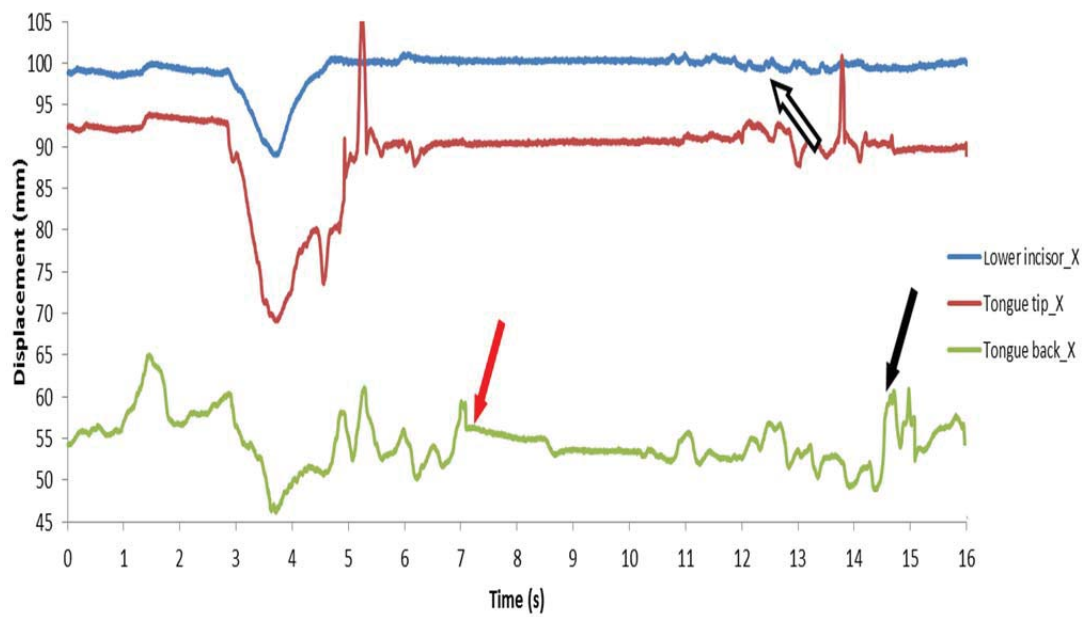


Figure 5-8. The tongue and lower jaw movement during oral processing of plum jam in X and Z axes. The lower jaw moves in low frequency ($< 1/s$), and the amplitude of the tongue and lower jaw is weak ($< 6mm$) and uneven. The black arrow points to the swallowing point, the red arrow points to the end of food ingestion. The white arrow points to lower jaw movement indicative of chewing activity.

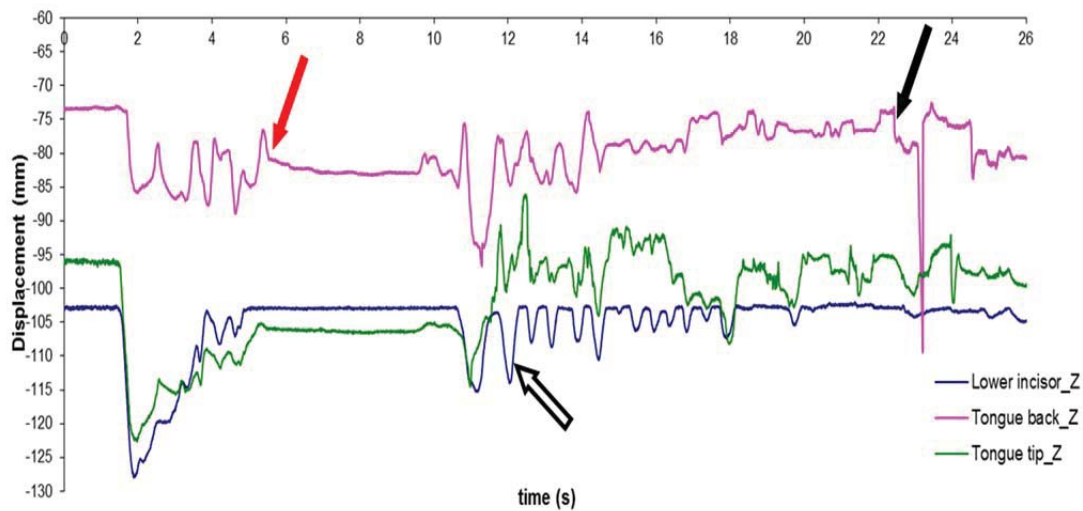
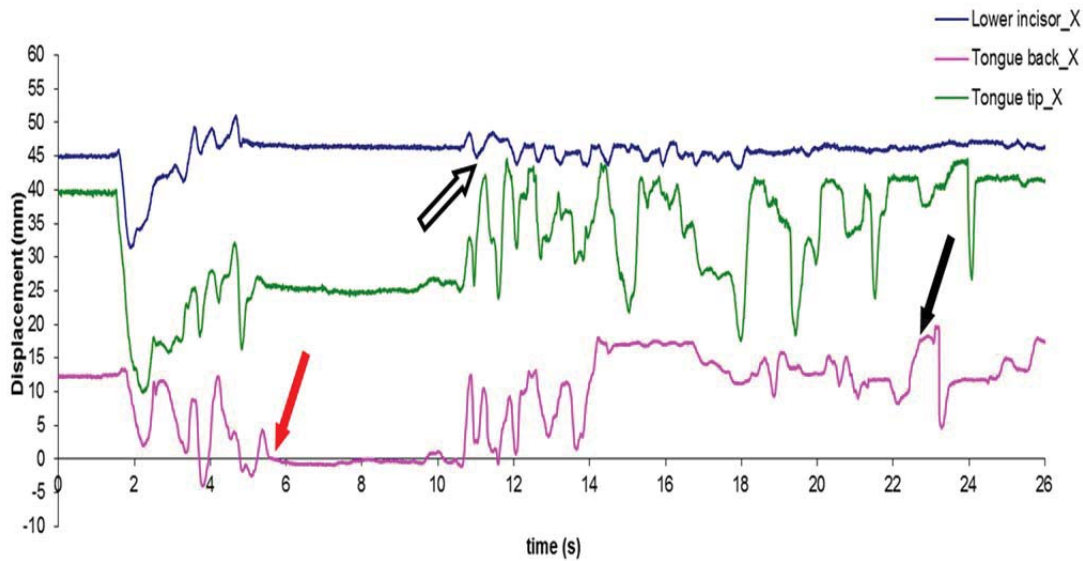


Figure 5-9. The tongue and lower jaw movement during oral processing of Philadelphia cream cheese in X and Z axes. There are regular and greater lower jaw movement cycles ($0.9s^{-1}$) and tongue movements ($> 6mm$) between food ingestion and swallowing. The black arrow points to the swallowing point, the red arrow points to the end of food ingestion. The white arrow points to lower jaw movement indicative of chewing activity.

Based on the results shown in Figures 5-5 to 5-9, these foods probably all sit on the overlap area of semi-solid and soft-solid foods (Figure 5-4), as these foods are considered to have similar rheological and mechanical properties (refer to Chapter 4). The boundary in terms of rheological and mechanical properties required to initiate chewing is not considered to be a clear line as some non-food factors are also likely to

be important, such as individual differences (e.g. age, gender and oral condition), individual preference and personal experience.

From the foods tested in this study using EMA the boundary for initiation of chewing was determined to be condensed milk, sour cream and plum jam. The next step was to determine whether the result would be the same using EMG to observe chewing activity.

5.3.4.2. Determining the initiation of chewing using muscle activities

It is well known that masseter, temporalis and submental muscles move rhythmically and have certain patterns during mastication, especially the masseter muscles (Braxton, Dauchel, & Brown, 1996; Horio & Kawamura, 1989; Kemsley, Sprunt, Defernez, & Smith, 2002; Yozo Miyaoka et al., 2013; Mushimoto & Mitani, 1982; Neyraud, Peyron, Vieira, & Dransfield, 2005; Plesh, Bishop, & McCall, 1996; Shiozawa et al., 2013). Therefore, EMG is suitable to identify the occurrence of chewing activity during consumption.

The rectified EMG plots of masseter and submental muscles during consumption of bottled water, condensed milk, sour cream, plum jam and Philadelphia cream cheese were presented in Figure 5-10 to 5-12. Figure 5-10 (bottled water) shows there is no tongue and lower jaw movement between food ingestion and swallowing. Figure 5-11 (condensed milk, sour cream, and plum jam) show some irregular muscle activities between food ingestion and swallowing. In particular, the voltage of masseter muscle gets greater and greater during consumption of these 3 foods. Figure 5-12 shows more regular chewing-like cycles and greater voltages of masseter and submental muscles. The voltage of masseter muscle is significantly greater than for the submental muscle, which indicates that the chewing behaviour dominates oral movement.

The masseter muscle activity was classified into three types according to the voltage of the rectified RMS EMG data ($\text{Voltage}_{\text{mas}}$): 1) Type 1, there was no movement ($\text{Voltage}_{\text{mas}} \leq 0.02 \text{ mV}$) before swallowing; 2) Type 2, couples of small and irregular spikes appeared before swallowing ($0.02 \text{ mV} < \text{Voltage}_{\text{mas}} \leq 0.035 \text{ mV}$, and have 2 - 5 spikes in masseter or submental muscle traces); 3) Type 3, more regular and greater spikes appeared constantly before swallowing ($\text{Voltage}_{\text{mas}} > 0.03 \text{ mV}$, ≥ 6 regular spikes).

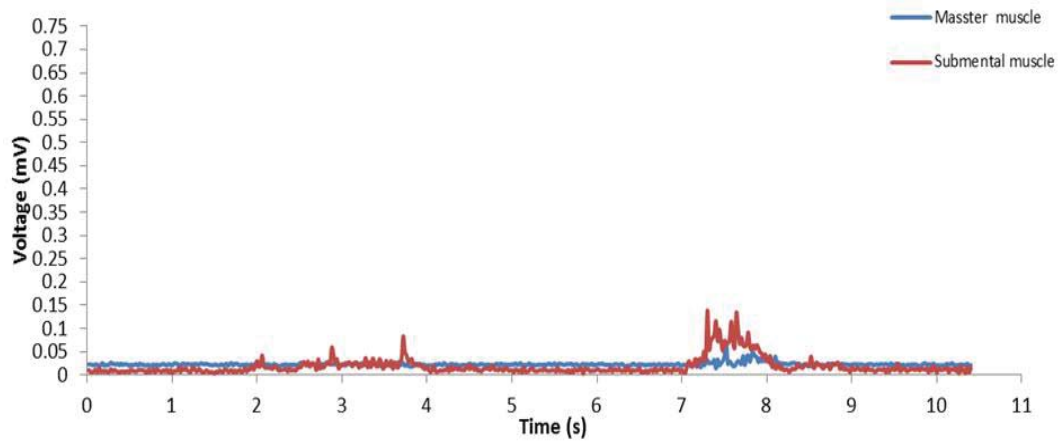
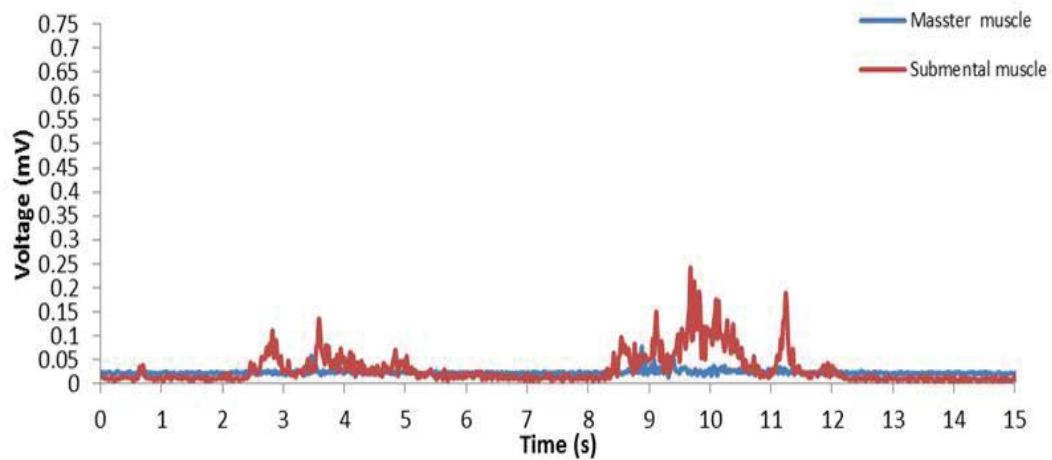
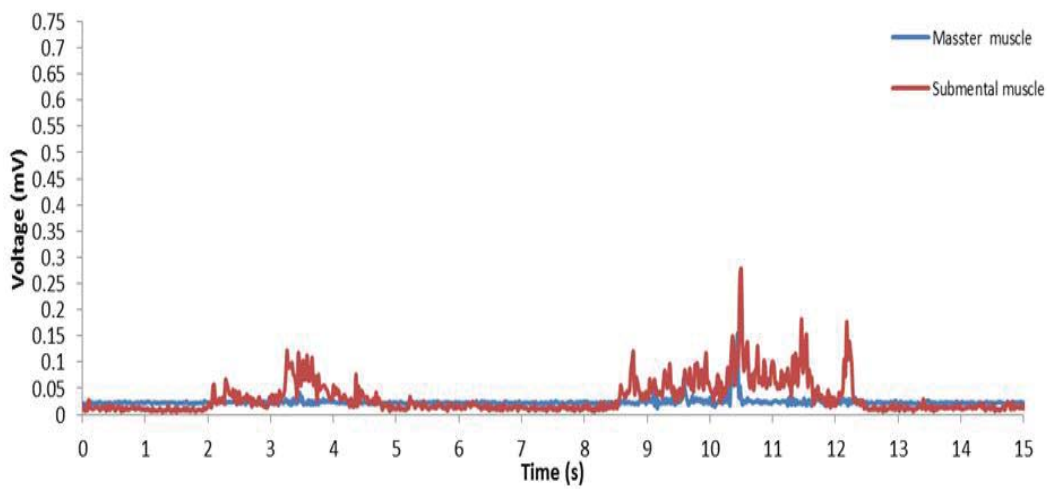


Figure 5-10, EMG RMS plot of masseter and submental muscles during drinking bottled water for subject 1. There is no tongue and lower jaw movement between food ingestion and swallowing (Type 1).



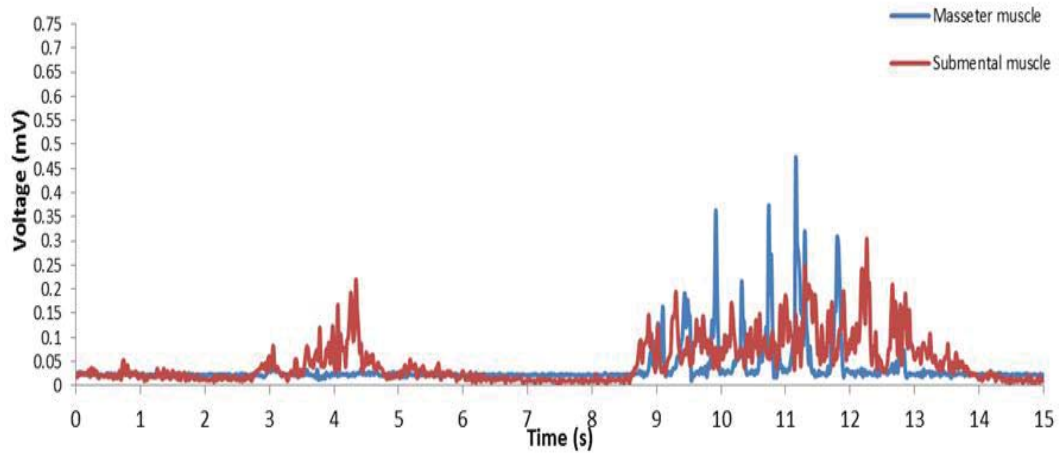


Figure 5-11, EMG RMS plots of masseter and submental muscles during consumption of condensed milk, sour cream and plum jam (from top to bottom) for subject 1. There are some irregular muscle activities between food ingestion and swallowing (Type 2).

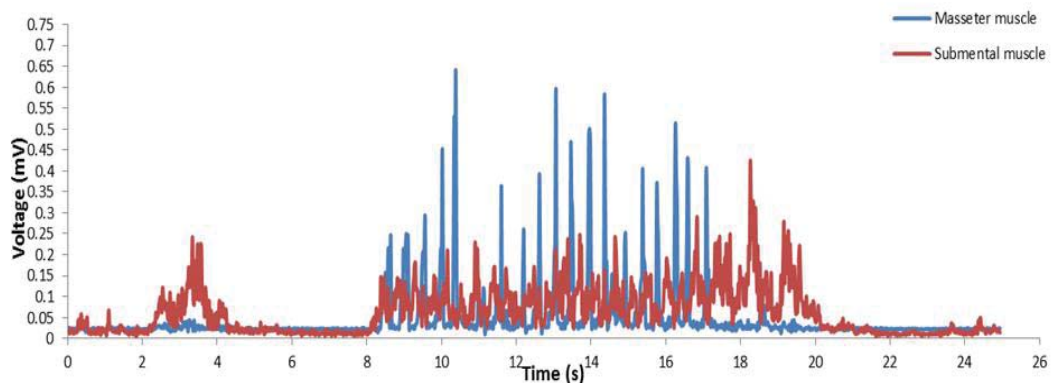


Figure 5-12, EMG RMS plots of masseter and submental muscles during consumption of Philadelphia cream cheese for subject 1. There are numbers of regular spikes (submental muscles or/and masseter muscle) between food ingestion and swallowing (Type 3).

Most food samples were classified into Type 1 according to the muscle activity data (Figure 5-2). Type 1: $TA_{\text{submental}} \leq 0.404 \pm 0.341 \text{ mV} \cdot \text{s}$, maximum submental voltage ($MV_{\text{submental}}$) $\leq 0.441 \pm 0.303 \text{ mV}$ (Figure 5-2). Cheese tub, Philadelphia cream cheese (Figure 5-12), peanut butter, and Nutella were grouped into Type 3, the average voltage of masseter muscle (AV_{masseter}) $\geq 0.119 \pm 0.063 \text{ mV}$, average submental muscle ($AV_{\text{submental}}$) $\geq 0.15 \pm 0.109 \text{ mV}$, maximum masseter muscle voltage (MV_{masseter}) $\geq 0.951 \pm 0.868 \text{ mV}$, maximum submental voltage ($MV_{\text{submental}}$) $\geq 0.563 \pm 0.355 \text{ mV}$. Sour cream, condensed milk (Figure 5-11), custard, Greek yoghurt and plum jam were grouped into

Type 2 because most values were close to Type 1 or Type 3, but always at least one value (mean or maximum value) had a large difference from Type 1 or Type 3. Combining the chewing-like cycle appearance with the voltage of muscle movement, plum jam, sour cream and condensed milk were believed to be foods which sat on the boundary for which chewing activity was required.

Greek yoghurt and custard were excluded from the boundary, because Greek yoghurt had greater muscle force during oral processing, but did not initiate constant chewing cycles, which indicates that the tongue and muscles took part in the oral process more than teeth. Combined with EMA plots, the tongue pressing and mashing behaviour appears to be the main movement during consumption of Greek yoghurt. Custard was closer to Type 1 when muscle force and work were only considered, but if combined with chewing cycles, it should be in the Type 2 group.

The orange juice data was conflicting. One subject had quite high muscle voltage, but did not have any chewing cycles. It was believed that the subject preferred to crush the tiny soft orange pulp during oral processing.

Condensed milk, sour cream and plum jam were determined as the boundary foods for initiating chewing activity using EMG of the 22 food samples. This result is similar to what was found using EMA. These foods initiated chewing-like activities but were not typical chewing activities, as the voltages recorded from the masseter muscles were much less than those reported during consumption of hard-solid foods (Voltage_{mas} is about 2mV during consumption of cashew nut) or softer gel based confectioneries (Voltage_{mas} is about 1mV) which showed rhythmical chewing activity (Foster et al., 2006). It is rarely mentioned in previous studies that foods like peanut butter, cream cheese and Nutella have rhythmic chewing cycles but use less muscle force and lower frequencies than normally used in mastication (Type 3). This was not considered as a typical chewing activity in this thesis because whilst chewing activity was seen, it was not always present across the full oral processing period.

The rheological properties of condensed milk, sour cream and plum jam were found to be within the following ranges (Table 5-4). The shear stress is $78.69 \pm 7.83 - 180.15 \pm 10.15$ Pa at 20°C, $36.15 \pm 1.38 - 53.42 \pm 4.75$ Pa at 37°C; the viscosity is $7.87 \pm 0.87 - 18.02 \pm 1.02$ Pa.s at 20°C, $3.62 \pm 0.14 - 5.34 \pm 0.48$ Pa.s at 37°C; the G' is $181.03 \pm$

61.92 - 1584.00 ± 122.41 Pa at 20°C, 588.80 ± 51.96 - 2174.00 ± 193.96 Pa at 37°C; G'' is 391.67 ± 28.61 - 573.43 ± 113.29 Pa at 20°C, 111.77 ± 6.91 - 1233.67 ± 32.27 Pa at 37°C; F_{max} is 36.33 ± 1.95 - 78.48 ± 3.54 N at 20°C, 3.24 ± 0.10 - 46.11 ± 1.78 N at 37°C; W_{max} is 7.62 ± 1.28 - 30.06 ± 1.36 N.mm at 20°C, 0.35 ± 0.01 - 15.35 ± 0.59 N.mm at 37°C. Do these parameters and the range of their values play important roles in initiating chewing-like activities? More similar property food samples and subjects are required to verify this.

Both EMA and EMG methods were suitable to observe the initiation of chewing-like activity. The 22 food samples covered liquid, semi-solid and soft-solid foods and were classified into three types according to tongue and jaw movements and muscle activities. Type 1 showed no oral movements before swallowing during oral processing; Type 2 showed a small number of low amplitude movement (< 6 cycles) and irregular oral movements appeared during oral processing; Type 3 showed greater amplitude, rhythmic and chewing-like oral movements. These three types of oral movements may be useful for differentiating between liquid, semi-solid and soft-solid foods.

5.3.5. The functions of the tongue during oral processing of different foods

EMA data shows tongue movement directly. Figure 5-5 - 5-9 show that the movement of the tongue back and tongue tip are not always the same. The movement of the tongue back is more active than the tongue tip during consumption of chocolate mousse, condensed milk and plum jam (Figure 5-6 - 5-8), while the movement of the tongue back is less active than the tongue tip in the X axis (anterior-posterior dimension) and similar to the tongue tip in the Z axis (vertical dimension). The tongue movement is significantly more than the lower jaw movement, which means the tongue processing behaviour (pressing, smashing and squeezing, etc.) dominates the whole oral process instead of chewing.

The front belly of the digastric muscles and mylohyoid are attached to the hyoid bone (Figure 3-13). There is evidence that suggests a strong relationship between EMG activity of submental muscles and hyoid bone movement (Ding and Larson, 2002; Wheeler-Hegland and Rosenbek, 2008; Reyes, Cruickshank, Thompson, Ziman, & Nosaka, 2014). This indicates that the movement of submental muscle also causes corresponding tongue movements.

EMG RMS plots showed that there was no tongue and lower jaw movements after ingestion of bottled water. The only EMG peak was elicited by swallowing, in which the submental muscle voltage was much greater than the masseter muscle (Figure 5-10). The submental and masseter muscle activities became more and more pronounced during consumption of sour cream, condensed milk and plum jam respectively. The submental muscle voltage was much greater than the masseter muscle during consumption of sour cream and condensed milk. The active peaks of the submental muscle were more than that of the masseter muscle. This indicates that the tongue movements are more than the lower jaw movements during consumption of sour cream and condensed milk. However, during consumption of plum jam, the number of active peaks and the voltage of the masseter muscle are much greater than during consumption of sour cream and condensed milk. The number of peaks and the voltage of the submental muscle are just slightly more and greater during consumption of condensed milk. The two subjects had significant tongue movements (submental muscle activity) and started to have chewing-like rhythmic muscle activities during consumption of these three food samples. Figure 5-12 showed that subject 1 has rhythmic tongue and lower jaw movements during consumption of Philadelphia cream cheese. The chewing-like activities are similar to the chewing cycles seen during consumption of hard-solid foods, except that the voltage of the masseter muscle is less than 1mV compared to 2mV on average during consumption of brittle cereal foods (Hedjazi, Guessasma, Yven, Della Valle, & Salles, 2013) and greater than 100mV during chewing almonds (Frecka, Hollis, & Mattes, 2008).

5.4. Conclusions

EMG and EMA were both suitable for measuring oral processing times however, the most suitable method depended on the rheological and material properties of the food consumed. Slightly longer ORTs were recorded using the EMA method likely due to the subjects being concerned about damaging the wires located in the mouth required for this method. Chewing activity initiation was investigated using both EMA and EMG methods. The former method detected the chewing activity using the tongue and lower jaw movement, while the later used the masseter and submental muscle activities (voltages). Both methods resulted in the same grouping of the food samples with condensed milk, sour cream and plum jam noted as being the boundary foods for which chewing activity was initiated. The chewing activity initiation study also showed that

before the chewing activity was initiated, the tongue played a more important role than afterwards during oral processing. The importance of the tongue movement in the oral cavity during oral processing of foods will be discussed in chapter 7.

Chapter 6: Relationships between oral processing behaviour and expectorated food bolus properties

6.1. Introduction

Only two subjects took part in the experiments conducted in Chapter 5. To investigate those observations in more detail, the oral processing behaviour of more subjects needed to be recorded. In this chapter, the oral processing of food samples by 8 subjects is investigated (from the original 23 foods). This study focuses on semi-liquid, semi-solid and soft-solid groups; therefore, at least 2 samples were selected from each group. The food samples selected were tomato juice, Greek yoghurt, chocolate mousse, condensed milk, plum jam, sour cream, cheese tub, peanut butter and Nutella. These samples are acceptable to subjects when presented as a teaspoonful. Tomato juice was selected because it is different from other foods in that the viscosity increases with an increase in temperature (Table 4-5 and 4-6).

The pH was presumed to correlate with the moisture content of expectorated bolus and the saliva flow rate of subjects in this research. The aim of measuring pH was to determine whether relationships exist between pH and moisture content of bolus or the saliva flow rate of the subjects.

The objectives of this chapter were to: 1) measure the stretch-ability of the expectorated bolus, and the moisture content of original food and expectorated bolus; 2) measure the saliva flow rate (SFR) and muscle activities during oral processing for 8 subjects; 3) investigate the relationships between food and bolus properties and oral processing behaviours; 4) investigate changes in the material properties by comparing the original food samples and the expected bous.

6.2. Materials and methods

6.2.1. Subjects and materials

Four male and four female subjects (23 y - 28 y, who met the screening criteria outlined in Section 3.2.1.1) took part in this research. Nine food samples (Table 6-2) were selected from the 23 characterised foods from chapter 4 (section 4.2.1). The foods were stored in refrigerator (4°C) before measurement. These food samples were weighed and placed in a 20°C room for 1.5 hours before experiments was allowing samples to

equilibrate to room temperature. This research was approved by the university ethics committee (Massey University Human Ethics Committee: Southern A Application 10/12).

6.2.2. Methods

6.2.2.1. Saliva flow rate

To investigate oral behaviour during food processing, the saliva flow rate was measured. Parafilm ('M'; American National Can, Chicago, IL, USA) was used to collect mechanically stimulated saliva (Para-SFR), as it is tasteless and chewy. Unstimulated (Rest SFR) and mechanically stimulated saliva samples were collected at the same time of day but on different days.

Unstimulated and mechanically stimulated saliva samples were collected over a period of 5 mins. Before collection, the subjects were instructed to initiate a swallow to empty the oral cavity. Saliva was expectorated into a pre-weighed plastic container every 30 s over the 5 min period. The density of saliva is very close to 1.0 g/ml, so 1 g saliva was assumed to be equivalent to 1 ml secreted saliva and then the saliva flow rate was calculated (g saliva/min). For mechanically stimulated saliva, each subject chewed 0.29 g Parafilm and expectorated saliva every 30 s (Richardson & Feldman, 1986; van der Bilt, *et al.*, 2007) over the 5 min period.

6.2.2.2. Ready-to-swallow bolus images

Subjects were instructed to process the 9 selected food samples in the lab and then expectorate them into a petri dish when they felt the impulse to swallow. The experimenter photographed the expectorated bolus immediately (Sony, Cybershot DSC-W170, resolution 2048x1536).

6.2.2.3. Stretch-ability of the expectorated bolus

The stretch-ability of the expectorated bolus was measured using the method outlined in Section 4. 2.3.

The selection of test samples was difficult, because some food samples did not mix evenly during oral processing, were only coated with saliva on the surface or were separated into several parts and mixed with saliva (Figure 6-2 and 6-3). Test samples were collected from the boundary of well mixed food and not mixed food where the

saliva and food sample were not completely mixed (Figure 6-1). A plastic straw was used to extract the test samples.

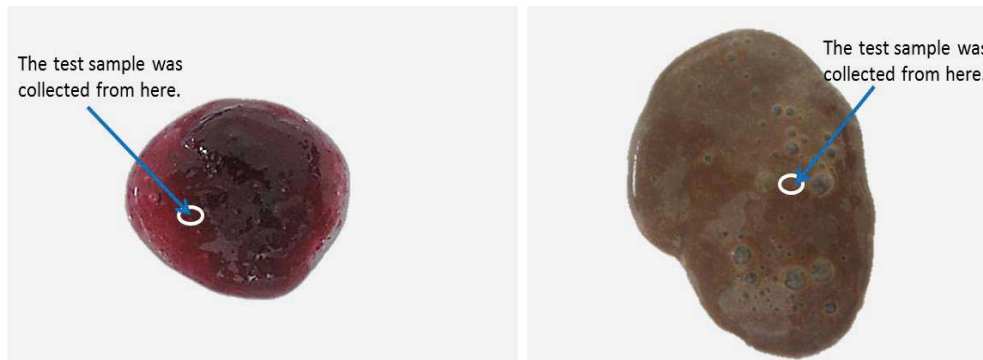


Figure 6-1. The spots where test samples were collected (white circle). Test samples were collected from the boundary of well mixed food and not mixed food where the saliva and food sample were not completely mixed. Expectorated plum jam (left) and chocolate mousse (right) bolus for subject 3.

Each of the 9 samples were replicated 3 times. The consumed food bolus was expectorated into a petri dish just before swallowing. After taking photos of the bolus, the stretch-ability test samples were extracted from the bolus. F_{\max} of the expectorated food bolus was measured and is presented in Table 6-2. The stretch-ability of saliva was also measured and found to be $2.00 \pm 0.14\text{N}$.

6.2.2.4. Muscle activities

The subjects sat in the chair in their normal feeding position, the room temperature was 20°C . The subjects were guided to scrub the skin of the masseter, submental muscles and the collar bones with a rough paper towel, which was wetted with alcohol spray (CV - TRONIC, Germany). The EMG electrodes were fixed on the right masseter (preferred side) and submental muscles (Figure 3-13). Commercial food samples (Table 6-2) were prepared on disposable spoons (5.3 g for each sample) and served to the subjects in a random order. The subjects were instructed to remain still for at least 3 s after food was ingested and then to consume the food sample as naturally as possible. After the major swallow, the subject was instructed to keep still for another 3 s. The subjects rinsed their mouths at least 3 times between samples.

The EMG activity was recorded by a PowerLab/4SP unit (ML750, ADInstruments Pty Ltd, Australia). The bio-amplifier setting was: voltage range 2mV, high pass 10Hz, low pass 200Hz, notch 50Hz and speed rate 1000/s. The collected signal was rectified using RMS in Chart5 software (refer to Section 3.2.2.2).

The ORT and the activity of the masseter and submental muscles were determined from rectified EMG RMS charts. ORT was defined as the time from when the food sample was loaded on the upper tongue surface to when the clearance and the terminal swallow had finished (Section 3.2.2.1). The RMS plot was enumerated from the original EMG trace (data points were recorded every 0.02s).

6.2.2.5. Moisture content of the original foods and expectorated bolus

Eight subjects attended three sessions which took place at 10:30 am on different days. Nine food samples and dried foil containers (in 105°C oven overnight) were weighed (W_{ini} = initial food sample weight, W_{con} = dried foil container) before the subject came in. When the subject arrived, saliva was collected first in order to calculate the saliva flow rate (see Section 6.2.2.1). Then, the subject was instructed to consume the food sample and expectorate at the point they felt the impulse to swallow. The food bolus was expectorated into the foil container, which was weighed ($W_{b\&c}$ = weight of bolus and foil container) straight away, then put into the 105 °C pre-heated oven for 24h. Each food was tested in triplicate and randomly presented. After oven drying, the foil container and dried bolus sample (W_{dry} = dried bolus sample and foil container) were weighed. The weight of moisture in the food sample (W_{moi}) was calculated ($W_{moi} = W_{b\&c} - W_{dry}$), then the moisture content (MC) was calculated ($MC = W_{moi} / (W_{ini} - W_{con})$).

One way-ANOVA was used to analyse the original food samples and expectorated food bolus data between samples and subjects. Significance was defined at $p < 0.05$.

6.2.2.6. pH value

The pH value of food samples were measured using a pH meter (Probe model: L6880). A 20.0 g food sample was put into a cylindrical plastic container and 4 mls distilled water was added using a micropipette (Horwitz, 2000). A glass stick was used to stir and mix for 5 mins till the mixture was even. The pH meter was calibrated using pH 2.00, 4.00 and 7.00 solutions (LabServ Solution, New Zealand). The probe was inserted into the mixture for at least 3 mins, and then the pH value was read. Each food sample was tested in triplicate.

6.3. Results and discussion

6.3.1. Saliva flow rate

Saliva flow rate (SFR) and oral residence time (ORT) are believed to be important for sensory perception (Bramescio & Setser, 1990) and oral processing behaviour (Ablett, Darke, & Lillford, 1991; Hutchings & Lillford, 1988). Food structure breakdown, mixing and lubricating with saliva occur from the beginning of oral processing. The continuous secretion of saliva helps to trigger swallowing (Jalabert-Malbos *et al.*, 2007; Dresselhuis, *et al.*, 2008). Previous research shows that SFR is affected by mechanical chewing behaviour and food texture perception (Engelen *et al.*, 2007; Engelen & Van Der Bilt, 2008; van Vliet, van Aken, de Jongh, & Hamer, 2009). Animal and human experiments have found that the SFR is affected by food moisture content, especially the SFR from the parotid gland (Ito, Morikawa, & Inenaga, 2001; Loret *et al.*, 2011).

This experiment measured the SFR (Table 6-1) of 8 subjects in order to find relationships between any SFR and ORT.

Table 6-1. Eight subjects' rest SFR and Parafilm stimulated SFR (mean \pm SD)

Subjects	Rest SFR (ml/min)	Parafilm stimulated SFR (ml/min)	SFR _{food} (ml/min)
1	0.51 \pm 0.05	0.92 \pm 0.04	8.31 \pm 12.22
2	0.36 \pm 0.04	0.52 \pm 0.06	7.04 \pm 12.20
3	0.76 \pm 0.07	1.35 \pm 0.17	11.26 \pm 15.00
4	0.36 \pm 0.03	1.81 \pm 0.04	4.05 \pm 7.57
5	1.03 \pm 0.08	1.14 \pm 0.05	19.04 \pm 42.03
6	0.47 \pm 0.07	1.69 \pm 0.19	10.83 \pm 19.58
7	0.45 \pm 0.06	2.46 \pm 0.43	3.98 \pm 5.91
8	0.71 \pm 0.23	1.34 \pm 0.15	5.66 \pm 10.74

SFR data showed that rest SFR is the minimum saliva flow observed. There is no mechanical movement and / or chemical (flavour) stimulation during the saliva collection. The value of the rest SFR is within 0.04 – 1.83ml/min as previously observed by Mackie & Pangborn (1989). Parafilm stimulated SFR is significantly higher than rest SFR ($p < 0.05$) because there is a mechanical stimulus during saliva

collection. The mean value of Parafilm stimulated SFR is 1.40 ± 0.46 ml/min, which is similar to previous studies showing 1.29 ± 0.46 ml/min (van der Bilt, *et al.*, 2007) and 1.40ml/min (Gaviao, Engelen, & van der Bilt, 2004). SFR_{food} is the average SFR during consumption of 9 different food samples. The mean value of SFR_{food} is 8.77ml/min, which is similar to human saliva secretion response to citric acid (7.07 ± 2.16 ml/min) (Dawes, 1987; Watanabe & Dawes, 1988). The results showed that SFR_{food} is significant higher than rest and Parafilm stimulated SFR ($p < 0.05$) as the mechanical chewing movements, food texture, flavour, aroma and food ingredients stimulate more saliva secretion during consumption of different food samples.

Parafilm stimulated SFR was suspected to positively correlate to rest SFR, but the linear regression analysis result showed that there is no linear correlation between Parafilm SFR and rest SFR ($S = 0.63$, R-sq (adj) = 0.00). SFR_{food} correlates with rest SFR positively ($S = 3.24$, R-sq (adj) = 0.58), but does not correlate with Parafilm stimulated SFR ($S = 5.04$, R-sq (adj) = 0.00). This result indicated that saliva secretion is influenced more by the physiological mechanism of individuals rather than a stimulus in the oral cavity. While, mechanical and food stimuli do increase the SFR, the level of increase is not proportional to the rest SFR. This implies that saliva secretion is not only influenced by mechanical movement and food properties and that individual psychophysiological factors are also important.

6.3.2. Images of expectorated ready-to-swallow bolus

The images of the expectorated boluses were taken immediately using a digital camera (Sony, Cybershot DSC-W170, resolution 2048x1536). Nine expectorated food bolus images from subjects 3 and 7 are shown in Figures 6-2 and 6-3 respectively.



Figure 6-2. Nine expectorated food bolus images for subject 3. From top left to bottom right, they are: Nutella, peanut butter, cheese tub, sour cream, plum jam, condensed milk, chocolate mousse, Greek yoghurt and tomato juice.



Figure 6-3. Nine expectorated food bolus images for subject 7. From top left to bottom right, they are: Nutella, peanut butter, cheese tub, sour cream, plum jam, condensed milk, chocolate mousse, Greek yoghurt and tomato juice.

Figure 6-2 and 6-3 provide direct views of the expectorated food bolus from two subjects. The first row in Figure 6-2 shows that boluses of Nutella, peanut butter and cheese tub are not well mixed with saliva. The bolus is coated with both saliva and a mixture of food and saliva, but the inside of the bolus contains little saliva and most of the interior of the bolus is unprocessed. This shows that saliva lubricates the cohesive bolus, but does not completely mix with food with lower stretch-ability levels. The second row displays the expectorated boluses of sour cream, plum jam and condensed milk. They are mixed better than boluses in the first row and only a few small pieces are not well mixed, especially for condensed milk. The boundary between the well-mixed area and not-well-mixed areas are observable, even though they are not at the exterior of the bolus. The third row presents the boluses of chocolate mousse, Greek yoghurt and tomato juice. There is no boundary between the well-mixed area and not-well-mixed area, and the mixture looks relatively consistent with no small unprocessed pieces. Figure 6-3 shows the similar view of expectorated boluses, but the top row expectorated boluses are mixed better.

The expectorated Nutella bolus from subjects 5, 6 (Appedices A7) and 7 (Figure 6-3) mixed better with saliva than ones from subjects 3 (Figure 6-2), 4 and 8 (Appedices A7). All expectorated sour cream boluses from subjects 4, 5 and 8 (Appedices A7) mixed no better than cheese tub. Personal preference is considered to explain this outcome. The bubbles in some expectorated boluses are believed to have been created while mixing saliva with the food samples.

6.3.3. Stretch-ability of expectorated bolus

The stretch-ability of the original food (Section 4.3.2) and expectorated bolus were measured and the results are shown in Table 6-2. The F_{\max} of the food samples Nutella, condensed milk and plum jam are similar to those measured by Chen, Feng, Gonzalez, & Pugnali (2008). The F_{\max} of Greek yoghurt (9.69N) is higher than previous yoghurt data (< 5N), because Greek yoghurt is thicker than normal yoghurt. The F_{\max} of most expectorated boluses is smaller than the F_{\max} of the original food samples measured at 20°C except for tomato juice. Three main factors, excluding temperature, were important for this reduction in stretch-ability: 1) the saliva mixed with tested food immediately after food ingestion helped reduce F_{\max} and lubricated the food bolus to assist with swallowing; 2) physico-chemical properties of the food samples influenced

saliva secretion, which plays a role in altering food structure; 3) Personal oral processing behaviour influenced the food bolus formation, which in turn influence food bolus properties, including F_{\max} .

Table 6-2. Stretch-ability (F_{\max}) of nine expectorated food bolus and original food samples

Food samples	Stretch-ability of expectorated bolus (N)	Stretch-ability of original food (N)	
		20°C	37°C
Cheese tube	26.4±4.3	88.0±4.0	33.7±0.8
Chocolate mousse	2.5±0.2	12.5±1.7	0.4±0.0
Condensed milk	14.3±3.0	78.5±3.5	46.1±1.8
Greek yoghurt	3.8±0.1	9.7±1.1	6.8±1.1
Nutella	101.1±20.4	132.3±5.9	125.8±10.5
Peanut butter	93.1±14.9	112.8±1.7	89.2±2.5
Plum jam	32.8±8.8	68.4±1.5	36.1±0.8
Sour cream	9.3±1.3	36.3±2.0	3.2±0.1
Tomato juice	2.1±0.4	1.0±0.2	0.2±0.0

Note: all data presented as mean ± standard deviation. Stretch-ability of saliva is 2.0 ± 0.1 N at 20 °C.

The F_{\max} of expectorated tomato juice was higher than the original tomato juice. The most likely reason for this is because the original F_{\max} of tomato juice is much lower than that of saliva, so the net result is an increase in F_{\max} . Also the pH is low and this stimulates more saliva secretion, further adding to an increase in F_{\max} .

The F_{\max} of expectorated plum jam, cheese tub and Nutella were lower than the F_{\max} of original foods at both 20°C and 37°C, but close to the F_{\max} of original food at 37°C. These foods contain high levels of sugar and /or fat. Normally, sweet and fatty food tastes better, so the ORT is longer than other samples, meaning more saliva is added. This contributed to the lower expectorated F_{\max} of these foods compared to original food at 37°C. These are also foods that showed some degree of mastication. However, these three samples have higher viscosities. The oral processing behaviour with them is unique, where they are chewed a little bit, then mushed for a bit and moved around. Saliva will never be fully mixed in these types of foods (images in Section 6.3.2). As a consequence the expectorated F_{\max} value should not reduce much.

The F_{\max} of expectorated Greek yoghurt and condensed milk were lower than the original food at both temperatures. For Greek yoghurt, ingredients such as starch and the low pH are considered to be the main influencing factors, as starch is broken down by the amylase in saliva (Anonymous, 1968; Bosch, Veerman, de Geus, & Proctor,

2011; Holden & Tracey, 1950; Janssen, Terpstra, De Wijk, & Prinz, 2007), and low pH stimulates more saliva during oral processing. For condensed milk, the high level of sugar dissolution in the mouth and the sticky texture lengthening ORT result in more saliva secretion and the ingested food is diluted during oral processing.

Paired T-test analysis (Minitab 15) showed that the F_{\max} of the expectorated boluses are significantly different to the F_{\max} original food measured at 20°C ($T = - 2.72$, $P = 0.009$). The F_{\max} of the expectorated bolus does not differ significantly with the F_{\max} of the original food measured at 37°C ($T = - 0.25$, $P = 0.805$). This indicates that the stretch-ability of the original food measured at 37 °C has the potential to be a predictor of the stretch-ability of expectorated bolus. Foods change with temperature and moisture addition.

ORT and stretch-ability of expectorated bolus

The stretch-ability of expectorated boluses of 9 selected food samples data were analysed (Table 6-3). Mean F_{\max} (MF_{\max}) of expectorated boluses from 8 subjects and ORT have a strong linear correlation ($MF_{\max} = - 16.4 + 4.41 \times \text{ORT}$, $R^2(\text{adj}) = 0.89$). Mean work until maximum force (MW_{\max}) of the expectorated bolus also has a strong linear correlation with the ORT ($MW_{\max} = - 13.9 + 2.24 \text{ ORT}$, $R^2(\text{adj}) = 0.83$). This indicates that the stickier the food, the longer the food is processed in the mouth and more oral work is required. Foods that are more viscous or stickier will result in longer oral residence time and still produce a bolus with higher levels of stretch-ability. This indicates that the stretch-ability of the expectorated bolus relates to the stretch-ability of the original food. At the same time, the analysis shows that there is a strong correlation between F_{\max} and W_{\max} ($MW_{\max} = -2.48 + 0.267 \times MF_{\max}$, $R^2(\text{adj}) = 0.93$), which is consistent with published work (Chen, 2007; Chen, Feng, Gonzalez, & Pugnali, 2008).

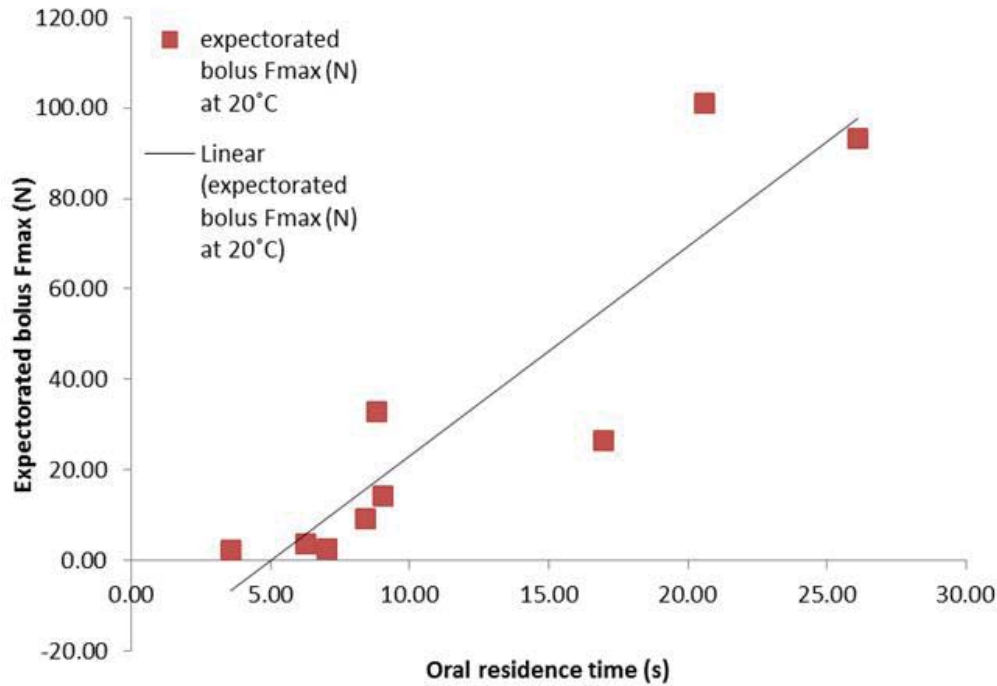


Figure 6-4. The correlation between the expectorated bolus F_{max} and ORT.

This section has shown that ORT closely correlates with the stretch-ability of expectorated food bolus. This indicates that the oral processing behaviour affects the expectorated bolus properties. But in general, foods with higher initial stretch-ability values also had higher bolus stretch-ability. So food affects oral processing which in turn affects the bolus. Bolus properties can correlate with initial food properties.

6.3.4. Muscle activities during oral processing of food samples

The same 3 pairs of muscle activity parameters were calculated from EMG RMS data (Table 6-3). They were average masseter and submental muscle voltage ($AV_{masseter}$, $AV_{submental}$), maximum master and submental muscle voltage ($MV_{masseter}$, $MV_{submental}$) and the total area under the curve for the masseter and submental muscles during oral processing of the food samples ($TA_{masseter}$, $TA_{submental}$).

Table 6-3. Oral residence time (ORT) during consumption of 9 food samples from 8 subjects measured in triplicate (mean \pm standard deviation)

Food samples	Oral residence time (s)								
	Subject 1	Subject 2	Subject 3	Subject 4	Subject 5	Subject 6	Subject 7	Subject 8	Mean \pm SD
Cheese tube	21.3 \pm 0.5	16.1 \pm 3.1	6.6 \pm 0.6	25.0 \pm 4.3	13.3 \pm 1.5	14.7 \pm 1.2	31.6 \pm 0.3	7.3 \pm 1.3	17.0 \pm 8.4
Chocolate mousse	7.3 \pm 1.1	7.1 \pm 1.1	3.0 \pm 0.4	8.9 \pm 0.1	3.4 \pm 0.2	5.0 \pm 0.7	16.8 \pm 4.8	4.9 \pm 1.1	7.0 \pm 4.5
Condensed milk	9.0 \pm 0.7	7.7 \pm 0.8	3.4 \pm 0.6	11.3 \pm 2.3	5.8 \pm 0.9	7.3 \pm 0.4	22.0 \pm 1.1	5.9 \pm 0.6	9.1 \pm 5.5
Greek yoghurt	9.1 \pm 3.4	6.1 \pm 0.1	3.8 \pm 0.4	5.2 \pm 1.3	2.7 \pm 0.2	5.0 \pm 1.1	13.1 \pm 1.7	5.3 \pm 0.3	6.3 \pm 3.4
Nutella	20.0 \pm 2.5	17.4 \pm 2.6	11.8 \pm 4.7	26.8 \pm 1.9	20.5 \pm 0.8	32.0 \pm 5.2	27.1 \pm 3.1	9.2 \pm 2.0	20.6 \pm 7.9
Peanut butter	41.7 \pm 1.7	23.4 \pm 0.5	8.6 \pm 1.7	32.7 \pm 2.9	19.9 \pm 7.4	32.2 \pm 2.1	41.5 \pm 2.6	8.9 \pm 2.6	26.1 \pm 12.9
Plum jam	9.1 \pm 0.6	8.8 \pm 1.1	3.8 \pm 0.2	12.9 \pm 1.7	4.9 \pm 0.4	8.7 \pm 1.4	17.2 \pm 2.3	5.0 \pm 0.8	8.8 \pm 4.4
Sour cream	7.7 \pm 1.4	7.7 \pm 1.1	3.4 \pm 0.3	10.5 \pm 3.0	4.9 \pm 0.4	8.3 \pm 1.5	18.3 \pm 1.8	6.5 \pm 2.2	8.4 \pm 4.6
Tomato juice	2.8 \pm 0.6	3.5 \pm 0.4	1.9 \pm 0.2	4.5 \pm 0.8	1.2 \pm 0.1	3.2 \pm 0.7	8.3 \pm 2.0	3.2 \pm 0.4	3.6 \pm 2.2

Table 6-4. Muscle activity parameters during consumption of 9 food samples from 8 subjects measured in triplicate (mean \pm standard deviation)

Food samples	AV _{masseter} (mV)	AV _{submental} (mV)	MV _{masseter} (mV)	M V _{submental} (mV)	TA _{masseter} (mV.s)	TA _{submental} (mV.s)
Cheese tube	0.004 \pm 0.005	0.035 \pm 0.011	0.175 \pm 0.112	0.244 \pm 0.051	0.075 \pm 0.107	0.555 \pm 0.263
Chocolate mousse	0.001 \pm 0.001	0.024 \pm 0.005	0.097 \pm 0.028	0.196 \pm 0.051	0.011 \pm 0.011	0.169 \pm 0.116
Condensed milk	0.003 \pm 0.005	0.030 \pm 0.008	0.160 \pm 0.102	0.238 \pm 0.049	0.044 \pm 0.072	0.277 \pm 0.179
Greek yoghurt	0.003 \pm 0.006	0.030 \pm 0.010	0.111 \pm 0.051	0.238 \pm 0.088	0.015 \pm 0.020	0.188 \pm 0.111
Nutella	0.013 \pm 0.011	0.041 \pm 0.010	0.373 \pm 0.217	0.298 \pm 0.066	0.218 \pm 0.287	0.769 \pm 0.304
Peanut butter	0.010 \pm 0.009	0.041 \pm 0.011	0.364 \pm 0.209	0.314 \pm 0.081	0.327 \pm 0.399	1.072 \pm 0.616
Plum jam	0.003 \pm 0.003	0.031 \pm 0.008	0.130 \pm 0.073	0.237 \pm 0.087	0.028 \pm 0.030	0.283 \pm 0.181
Sour cream	0.002 \pm 0.002	0.027 \pm 0.007	0.122 \pm 0.058	0.222 \pm 0.060	0.017 \pm 0.015	0.221 \pm 0.112
Tomato juice	0.003 \pm 0.008	0.026 \pm 0.007	0.095 \pm 0.053	0.193 \pm 0.061	0.011 \pm 0.020	0.100 \pm 0.073

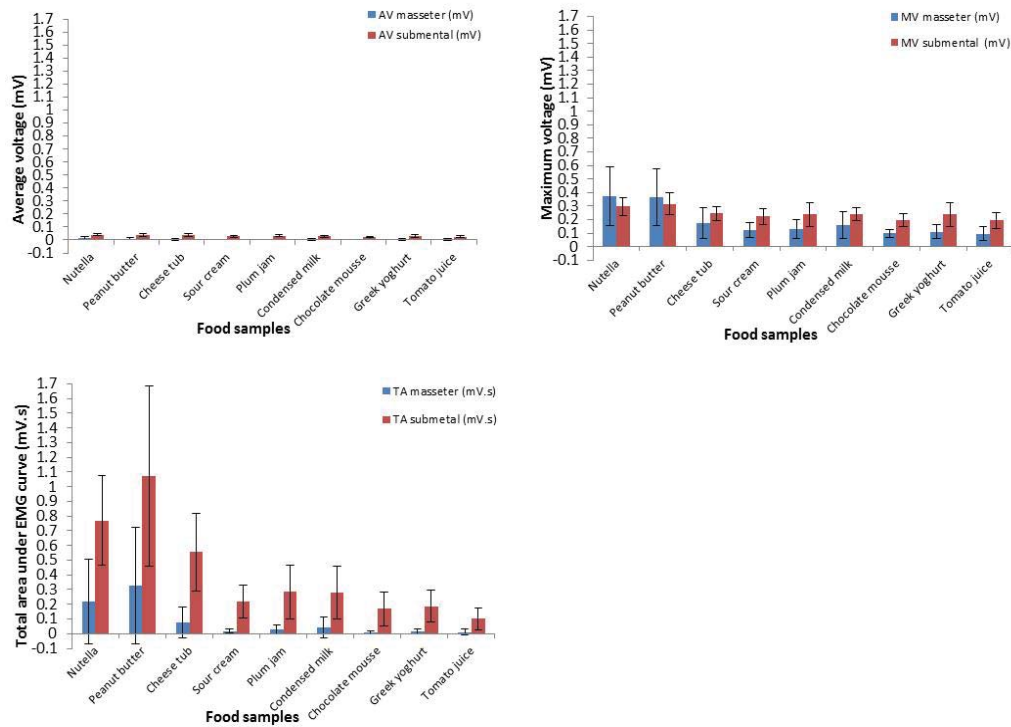


Figure 6-5. The average and maximum voltage of masseter and submental muscle for 8 subjects during consumption of 9 food samples.

Muscle activity data and plots show that AV_{masseter} and $AV_{\text{submental}}$ are not significantly different ($p > 0.05$); $AV_{\text{submental}}$ is slightly higher than AV_{masseter} during consumption of 9 different food samples. During the consumption of Nutella and peanut butter, the maximum voltage from the masseter muscle is higher than that of submental muscle, while the maximum voltage of the submental muscle is higher than that of masseter muscle during consumption of the other 7 food samples. This indicates that the masseter muscle uses greater force to process Nutella and peanut butter and the oral processing involves more jaw (teeth) movements (Fujimoto, 1957; Goto, Langenbach, & Hannam, 2001; Slagter, Bosman, Vanderglas, & Vanderbilt, 1993). TA_{masseter} and $TA_{\text{submental}}$ plot shows that submental muscle produced significantly more work than the masseter muscle during food oral processing. Figure 6-5 shows that MV_{masseter} is more variable than $MV_{\text{submental}}$. This indicates that the swallowing muscle uses similar force to process and swallow most food boluses, while the chewing muscle uses different forces to process food according to its properties (this muscle is seen to be more active for some foods).

Oral residence time data (Table 6-3) shows that peanut butter requires the longest time to process in the oral cavity, while tomato juice requires the shortest time to process. A

linear regression analysis demonstrates that there are positive linear correlations between all muscle activity measures and ORT.

Table 6-5. The correlation coefficients (R^2) between muscular activity and stretch-ability of the expectorated bolus

R^2	M V _{masseter}	M V _{submental}	A V _{masseter}	AV _{submental}	TA _{masseter}	TA _{submental}
Oral residence time (ORT)	0.78	0.78	0.59	0.81	0.84	0.97
Expectorated bolus stretch-ability (F_{max})	0.861	0.863	0.707	0.822	0.912	0.935

The muscle activity was also correlated with the stretch-ability of the expectorated bolus. The coefficients are presented in Table 6-5. The correlation coefficients show that masseter and submental muscle activities correlate strongly with the stretch-ability of the expectorated food bolus. The strongest correlation is between the stretch-ability of the expectorated bolus (Table 6-5) and submental muscle activities. The submental muscle is mostly active during swallowing (Crary, Carnaby, & Groher, 2006; Ding, Larson, Logemann, & Rademaker, 2002; Doeltgen, Ridding, O'Beirne, Dalrymple-Alford, & Huckabee, 2009; Perlman, Palmer, McCulloch, & Vandaele, 1999). This indicates that the properties of the ready-to-swallow bolus affect the muscle activity of the muscle associated with swallowing. But the strong correlations show that the stretch-ability of the bolus influences muscle activity (Bishop, Plesh, & McCall, 1990; Gibbs et al., 1981; Horio & Kawamura, 1989; Iguchi et al., 2015).

6.3.5. Moisture content of expectorated bolus

The moisture content (MC) of the original food samples and expectorated food boluses are shown in Table 6-6. The MC of most expectorated boluses increased significantly after oral processing except for tomato juice. The moisture content of tomato juice (MC = 0.94) does not increase when it is ready to swallow (the increase in MC = 0.00%), because of the high initial MC along with a viscosity and stretch-ability which are smaller than saliva. This indicates that the expectorated moisture content of very high MC foods will not change or increase because of the addition of saliva during oral processing. The MCs of higher MC food samples (cheese tub, sour cream, chocolate mousse, and Greek yoghurt, MC > 0.60) do not change much (the MC increase is from

0.2% to 9.2%). The expectorated MC of medium MC food samples (plum jam and condensed milk, $0.1 < MC < 0.60$) increased significantly after oral processing (the MC increase is from 43% to 60%). The expectorated MC of low MC samples (Nutella and peanut butter, $MC = 0.02$) increased dramatically before swallowing (the MC increase is from 900% to 1000%). This corresponds to previous research which showed that greater amounts of saliva are produced for dry or tough food than for moist or soft food (Anderson, Hector, & Linden, 1985; Bilt, 2009; Mioche, Bourdiol, & Monier, 2003). This research shows that moisture content is an important parameter for ready-to-swallow boluses.

Moisture content appears to reach a certain level before swallowing, which may differ for liquid, semi-solid and soft-solid foods. Loret et al. (2011) found that as cereal boluses had similar water content (50%) before swallowing for different cereals, it might be an important marker for swallowing. However, limited research has been done on liquid, semi-solid and soft-solid foods. The data (Table 6-6) also shows that there is much more residual food left in the mouth for low MC foods than high MC foods.

Table 6-6. Moisture content (MC) of 9 original foods and expectorated bolus (mean \pm SD)

Food Samples	Original food		Expectorated food bolus				
	MC _{IMB} (g _{water} /g _{sample})	MC _{DMB} (g _{water} /g _{drymass})	MC _{IMB} (g _{water} /g _{sample})	MC _{DMB} (g _{water} /g _{drymass})	Lost solid weight (g)	Added moisture (g)	MC increase (%)
Cheese tube	0.65 \pm 0.00	1.82 \pm 0.03	0.71 \pm 0.04	2.58 \pm 0.56	0.44 \pm 0.13	0.76 \pm 0.56	9.2%
Chocolate mousse	0.73 \pm 0.00	2.66 \pm 0.00	0.76 \pm 0.01	3.14 \pm 0.19	0.20 \pm 0.07	0.48 \pm 0.19	4.1%
Condensed milk	0.25 \pm 0.00	0.34 \pm 0.00	0.40 \pm 0.08	0.70 \pm 0.25	1.00 \pm 0.35	0.36 \pm 0.25	60%
Greek yoghurt	0.84 \pm 0.00	5.43 \pm 0.08	0.86 \pm 0.01	6.40 \pm 0.48	0.09 \pm 0.04	0.97 \pm 0.48	0.23%
Nutella	0.02 \pm 0.00	0.02 \pm 0.00	0.22 \pm 0.14	0.32 \pm 0.25	1.91 \pm 0.52	0.30 \pm 0.25	1000%
Peanut butter	0.02 \pm 0.00	0.02 \pm 0.00	0.20 \pm 0.13	0.29 \pm 0.24	1.29 \pm 0.63	0.27 \pm 0.24	900%
Plum jam	0.30 \pm 0.00	0.43 \pm 0.01	0.43 \pm 0.07	0.77 \pm 0.22	0.62 \pm 0.27	0.34 \pm 0.22	43%
Sour cream	0.71 \pm 0.00	2.39 \pm 0.00	0.75 \pm 0.02	2.99 \pm 0.30	0.22 \pm 0.08	0.60 \pm 0.30	5.6%
Tomato juice	0.94 \pm 0.00	14.61 \pm 0.03	0.94 \pm 0.00	16.67 \pm 0.80	0.05 \pm 0.01	2.06 \pm 0.80	0%

MC_{IMB} means initial food sample mass based moisture content, MC_{DMB} means dry mass of food sample or bolus based moisture content. The expectorated bolus data is the average values for 8 subjects.

Paired T-tests show that the moisture content ($MC = \text{water content} / \text{sample weight}$) is significantly different between foods ($p < 0.05$), while there is no significant difference

in the MC of expectorated food boluses between subjects ($p = 0.615$). A linear regression analysis showed that the expectorated bolus MC ($\text{g}_{\text{water}}/\text{g}_{\text{sample}}$) is positively correlated to the original MC ($\text{g}_{\text{water}}/\text{g}_{\text{sample}}$) ($S = 0.009$, $R\text{-Sq} = 0.99$, expectorated MC = $0.193 + 0.794 \times \text{original MC}$). These results indicate that the MC of expectorated bolus is affected by the MC of the original food sample more than oral processing behaviour.

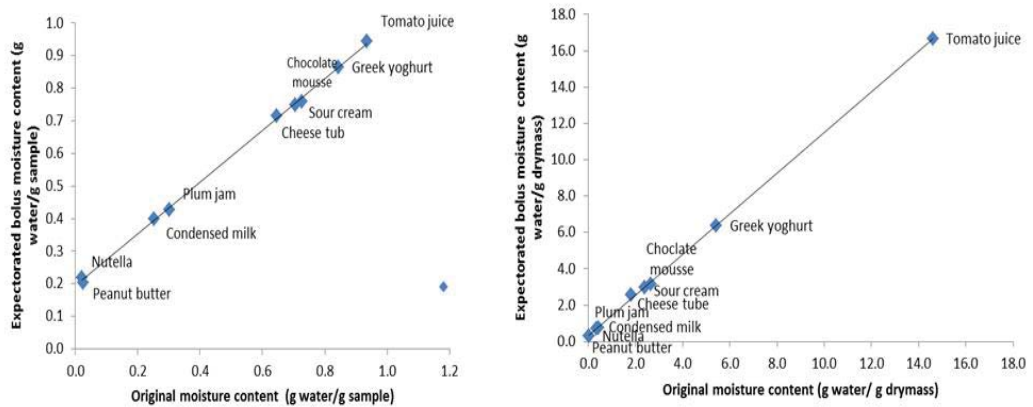


Figure 6-6. The expectorated bolus moisture content increased with the original food moisture content. The black line is the regression trend line. Left: moisture content is based on initial food sample mass (MC_{IMB}), right: moisture content is based on dry mass of food sample and bolus (MC_{DMB}).

The linear regression analysis shows the expectorated bolus moisture content (MC_{exp}) is inversely proportionate to the stretch-ability of the original food at 20°C ($S = 0.127$, $R\text{-Sq}(\text{adj}) = 0.79$, $\text{MC}_{\text{exp}} = 0.903 - 0.005 \times F_{\text{max}}$) and 37°C ($S = 0.130$; $R\text{-Sq}(\text{adj}) = 0.78$, $\text{MC}_{\text{exp}} = 0.803 - 0.006 \times F_{\text{max}}$) (Figure 6-6). Similarly, stretch-ability of the expectorated bolus is inversely proportionate to the original food sample moisture content (MC_{ori} , $S = 18.01$, $R\text{-Sq}(\text{adj}) = 0.74$, expectorated $F_{\text{max}} = 79.4 - 88.0 \times \text{MC}_{\text{ori}}$).

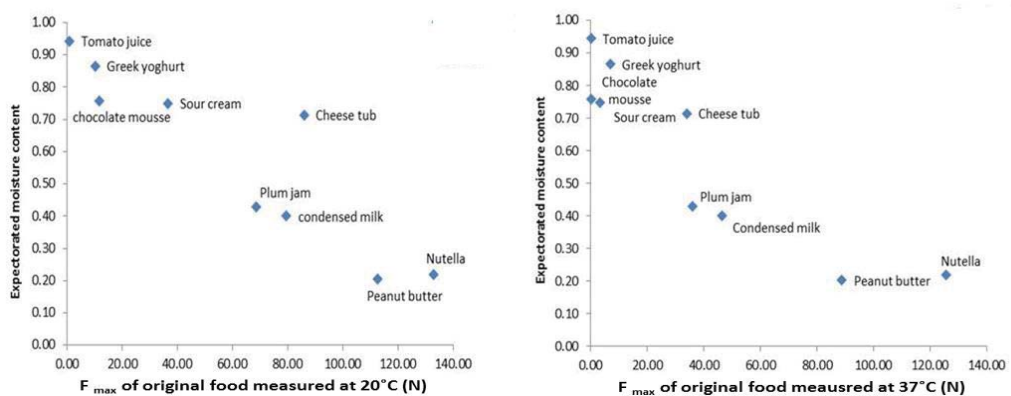


Figure 6-7. Expectorated food bolus moisture content vs. stretch-ability of original food measured at 20°C and 37°C .

One-way ANOVA analysis shows added water was significantly different during consumption of sticky and non-sticky food samples ($p < 0.05$). The sticky (high stretchability) food samples stimulated less saliva secretion (e.g. Nutella and peanut butter) during oral processing, because the expectorated bolus MC is lower than the less sticky food samples. Low moisture content foods become stickier during oral processing due to the addition of saliva and its mixing with the foods.

Rheological properties and moisture content

A regression analysis of rheological properties of nine samples shows that the viscosity and shear stress of original food samples have negative linear regressions with MC_{exp} at $20^{\circ}C$ ($S = 0.142$, $R\text{-sq (adj)} = 0.74$; $MC_{exp} = 0.929 - 0.093 \times \text{viscosity}$; $MC_{exp} = 0.929 - 0.002 \times \text{shear stress}$). The original food moisture content (MC_{ori}) has a strong positive linear regression with MC_{exp} .

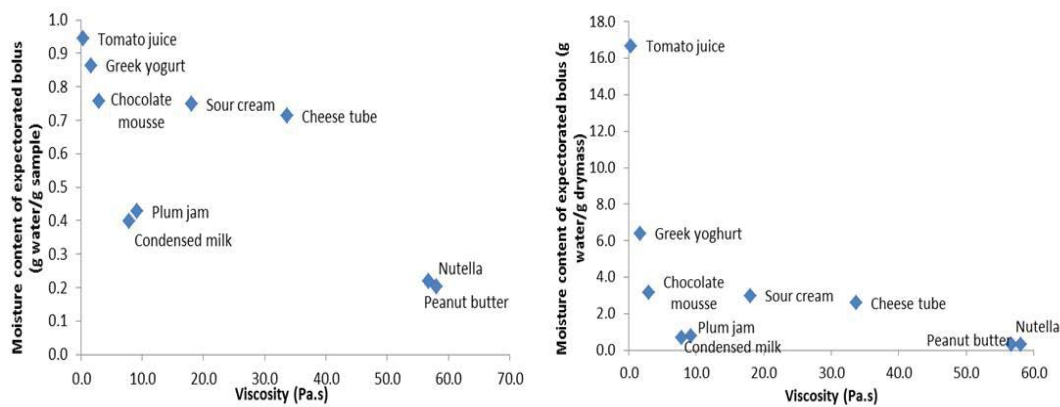


Figure 6-8. Moisture content of expectorated bolus vs. viscosity plot at $20^{\circ}C$. Left: moisture content is based on initial food sample mass (MC_{IMB}), right: moisture content is based on dry mass of food sample and bolus (MC_{DMB}).

These results indicate that MC_{exp} correlates with food original rheological property, especially stretch-ability and viscosity. Viscoelasticity only relates to MC_{exp} at $37^{\circ}C$. Saliva flow rate affects MC_{exp} , but the effect is less than the original food rheological property. The pH value has little effect on MC_{exp} .

6.3.6. pH value

The pH of food samples ranged from 3.18 ± 0.01 to 6.49 ± 0.03 (Table 6-7), which indicates that they are acidic. Previous research has shown that sour food increases SFR more than monosodium glutamate, salt and sugar (Neyraud, Heinzerling, Bult, Mesmin,

& Dransfield, 2009; Spielman, 1990), so it was expected that there would be a correlation between pH and MC of the expectorated bolus. pH is not the only factor to affect SFR. Oral mechanical movement, food MC, individual preference and texture perception also impact SFR (Engelen et al., 2007; van Vliet et al., 2009; Ito et al., 2001; Lorent, et al., 2011).

Linear regression analysis showed that there were no strong correlations between pH and the added moisture in the oral cavity ($S = 0.337$, $R^2(\text{adj}) = 0.07$, added moisture = $1.13 - 0.13 \times \text{pH value}$). The main reason was all samples had different initial food moisture contents, so the MC of expectorated bolus will be different regardless of pH. Individual SFR after food stimulation, oral processing behaviour, food pH and individual food preference are considered to influence the MC of expectorated bolus. This analysis indicates that the pH value is not the main influencing factor on the stimulated SFR of tested foods. No significant linear correlation was found between the pH value and oral processing behaviour (both ORT and muscular activities) (both $R^2 < 0.10$).

Table 6-7. pH value of nine samples (mean \pm SD)

Samples	Nutella	Peanut butter	Cheese tub	Sour cream	Plum jam	Condensed milk	Chocolate mousse	Greek yoghurt	Tomato juice
pH	6.12 \pm 0.01	5.86 \pm 0.01	4.66 \pm 0.00	4.49 \pm 0.01	3.18 \pm 0.01	6.36 \pm 0.01	6.49 \pm 0.03	3.98 \pm 0.01	4.16 \pm 0.01
SFR _{food}	0.90 \pm 0.70	0.78 \pm 1.27	2.91 \pm 2.35	5.25 \pm 3.27	2.70 \pm 1.86	2.96 \pm 2.25	5.27 \pm 2.96	12.07 \pm 9.37	46.12 \pm 40.06

This section shows that pH value of tested food is not the dominant factor for the expectorated bolus moisture content. The original food moisture content has more effect on the expectorated bolus moisture content. The tested foods include semi-liquid, semi-solid and soft-solid foods and different levels of stickiness too. Different types of foods require different oral processing behaviours, which influence saliva secretion. The various oral residence times and tongue - jaw movements also influence saliva flow during food oral processing. Compared to the original food moisture content, oral residence time and oral movements, the pH has much less effect on the MC of the expectorated bolus.

6.4. Conclusions

The results of measurements and analysis on selected food samples indicated that saliva secretion depends more on the physiological mechanism of individuals rather than a stimulus in the oral cavity. Food properties and mechanical movement also influence saliva secretion. Food properties and personal preference dictate the extent of food bolus mixing with saliva. The stretch-ability of the original food measured at 37 °C has the potential to be a predictor of the stretch-ability of expectorated bolus (refer to Section 6.3.3). In addition, stickier foods require longer ORT and more oral work.

The muscle activity data showed that submental (swallowing) muscles use similar forces to process and swallow food bolus during consumption of different foods, while masseter (chewing) muscles use different force to process food according to food properties. The submental muscle conducted significantly more work than masseter muscle during food oral processing. Submental muscle activities have stronger correlations with ORT and the stretch-ability of expectorated food bolus than the masseter muscle. The property of the ready-to-swallow bolus is affected by the muscle activities during oral processing. The properties of the initial food influence muscle activities during oral processing which in turn both influence the stretch-ability of the ready-to-swallow bolus.

Increases in moisture content (MC) of expectorated boluses are associated with the MC of the original food sample. MC of the ready-to-swallow bolus (MC_{exp}) appears to reach a certain level ($0.20 \pm 0.13 < MC_{IMB} < 0.94 \pm 0.0$, where MC_{IMB} means the initial food sample mass based moisture content), which may differ for liquid, semi-solid and soft-solid foods. MC_{exp} is affected by MC_{ori} and rheological properties of the original food sample more than oral processing behaviour of subjects. The saliva flow rate of subject during consumption of food sample and pH value of food sample has less or little effect on MC_{exp} .

In brief, food sample and oral movement in the oral cavity stimulate more saliva secretion to facilitate the bolus formation. The muscle activities and oral residence time determine the stretch-ability of the ready-to-swallow bolus with the MC_{ori} contributing more to MC_{exp} than other factors.

The relationships between food properties and oral processing behaviour, the individual physiological characters and food oral processing and the original food and expectorated food have been investigated in chapters 5 and 6. However, what drives the oral movement in the oral cavity and how it might occur during the oral processing have not been explained. This will be investigated in Chapter 7.

Chapter 7: The behaviour and shear of the tongue and lower jaw during oral processing

7.1. Introduction

Food oral processing is a complex process, involving the tongue, hard palate, and teeth in the oral cavity. Previous research has shown that the tongue plays an important role during oral processing, especially for semi-solid and soft-solid foods (Abdelmalek, 1955; Chen, 2009; Prinz & Heath, 2000). Previous research (Gilbert, Daftary, Campbell, & Weisskoff, 1998; Schwestkapolly, Engelke, & Hoch, 1995) has also characterised the backward and downward movements of the tongue during swallowing and the main behaviours of the tongue during oral processing of semi-solid foods (Prinz & Heath, 2000), to be pressing, mashing and mixing. It is hard to observe dynamic tongue movements during oral processing of food, but tongue movements are important to understanding food behaviour during oral processing, because they are the main contributor of oral pressure and shear forces within the oral cavity.

Kieser et al. (2008) suggested that oral pressure is the power source for bolus movement and swallowing. Several studies (Cutler, Morris, & Taylor, 1983; Nicosia, 2013; Steele & Van Lieshout, 2004) have found that shear stress and shear rate are important during bolus formation, structural change, bolus movement and swallowing, however there is limited research on shear applied to foods during oral processing of food samples (Terpstra, Janssen & Prinz, et al., 2005; Rauh, Singh, Nagel & Delgado, 2012).

Rauh et al. (2012) used a numerical model to simulate the shear conditions during oral processing of water and yoghurt. Terpstra et al. (2005) applied both a decreasing-height model and a constant height model to determine the shear stress applied at the tongue surface during consumption of mayonnaise and custard.

The flow curves of food samples are usually described by Newton's second law of fluid friction

$$\tau = \mu \frac{du}{dy} = \mu \dot{\gamma} \quad (1)$$

Where τ = shear stress (Pa), μ = coefficient of viscosity (Nsm⁻² or Pa.s), $\frac{du}{dy}$ = the velocity gradient in the fluid, more commonly known as $\dot{\gamma}$, the shear rate (s⁻¹).

For a Newtonian fluid the viscosity is independent of shear rate (constant). For non-Newtonian fluids, shear stress is not linearly proportional to shear rate. For shear-dependent fluids the relationship can be described as

$$\tau = f(\dot{\gamma}) \quad (2)$$

For shear thinning fluids the simple power law equation is often used

$$\tau = k(\dot{\gamma})^n \quad (3)$$

Where k = fluid viscosity index ($\text{Ns}^n \text{m}^{-2}$), n = flow behaviour index. For simple geometric models of the tongue motion, the shear rate can be approximated using equation 4.

$$\dot{\gamma} = \frac{v}{h} \quad (4)$$

Where v is the velocity of the tongue, h is the height of fluid or food bolus between the hard palate and tongue (Bourne, 2002). This equation applies to a fluid flowing between two parallel plates, one moving at a constant speed and the other one stationary, a similar situation to the tongue and hard and soft palettes in the mouth.

Previous research has focused on mechanisms and conditions of deformation during oral processing. In order to calculate shear stress or shear rate during oral processing, Campanella et al. (1987), simplified the tongue and palate areas as two parallel plates according to mechanical shear and elongational forces in most existing models. For example, the quench flow model (Campanella & Peleg, 1987; Kokini, et al., 1977; Nicosia & Robbins, 2001), and the Wedge flow model (Chen, 1993) has been described in literature. However, the hard palate and soft palate are not flat (they are an upward convex shape) and the tongue deforms flexibly during oral processing. They do not impinge on each other and only contact at certain areas during food oral processing (Engelen, Prinz, & Bosman, 2002; Terpstra et al., 2005).

Shama and Sherman (1973) investigated the oral evaluation of the viscosity of liquid and viscous foods. They found that for liquids, the shear stress was almost constant (about 10 Pa) and the shear rate was adjusted for different viscosity fluids. For viscous foods the applied shear stress changed for different foods, but the shear rate was approximately constant (about 10 s^{-1}) (Shama & Sherman, 1973). They also found that

not all of the internal structure in highly viscous non-Newtonian foods was destroyed, suggesting some elastic behaviour occurs in the mouth or there is not enough deformation to establish a complete shear stress field within the food sample. Kokini et al. established the decreasing-height model. They found there was a linear relationship between shear stress on the tongue and thickness (Kokini, Kadane, & Cussler, 1977). Other scientists have since found that the lateral movement of the tongue to the shear stress in the decreasing-height model was orders of magnitude larger than the shear stress of squeezing or compression movement of the tongue towards the palate (Terpstra et al., 2005). Nicosia (2013) studied shear rate and oropharyngeal swallowing and found that variation in bolus viscosity, level of lubrication as well as other factors may have a strong effect on shear rate. The extent to which these variations are important to swallowing mechanics is still not clear and requires further study.

Shear applied to foods has attracted scientists' attention, but there is not an agreed method for obtaining shear data in the oral cavity during oral processing of food.

Previous researchers focused on mechanical deformation and modelled the condition of deformation without considering relative oral conditions, such as saliva flow, temperature change, the shape of the oral cavity and so on. However, a number of research problems have been identified in the relationship between physico-chemical properties of foods and their perception before and during the intake (Lucas, Prinz, Agrawal, & Bruce, 2002). These problems include: (a) the complicated geometry of the oral cavity, (b) the transient motion processes, (c) the related three-axial deformations and stresses in the food (Nicosia & Robbins, 2001), (d) the necessity of including thermal boundary conditions in the models (Van Vliet, 2002; de Wijk, Engelen, & Prinz, 2003) and (e) the complex material parameters of foods (Nicosia & Robbins, 2001; Szczesniak, 2002), that are furthermore changed during oral processing due to the influence of saliva (Wilkinson, Dijksterhuis, & Minekus, 2000) and temperature. As a result of these problems, the results of these studies could not reflect the real oral processing.

Velocity is a key parameter in estimating shear rate (velocity gradient, equation (4)), and dynamic shear stress during oral processing. Therefore, developing a method to record or calculate the velocity of food movement during oral processing is essential to determining shear behaviour in the oral cavity. Previous research has used modelling

methods to estimate velocity or shear rate. These methods are less accurate than calculated velocity based on measured data which has been collected during oral processing of food samples.

The aim of this experiment was to record three points of movement in the oral cavity (lower incisor, tongue tip and tongue back) during oral processing of food and to use accurate displacement and time data to calculate velocity, shear rate, and finally determine shear stress during oral processing.

A standard concept in fluid mechanics is that a fluid in contact with a solid surface takes on the velocity of that surface (Kundu, 2008). Based on this theory, velocities measured at the points where EMA sensors are located were taken as the food velocity at those points. Similarly, the hard and soft paletes are not moving and assumed have zero velocity. The shear rate could then be determined from the gap between the tongue and the roof of the mouth. The shear stress of on the fluids could then be estimated using the rheology of the fluids reported in chapter 4.

7.2. Materials and methods

7.2.1. Experimental procedure

Two male subjects (twenty-three and twenty-four years old) took part in this experiment. They passed the screening questionnaire, had natural dental condition, no neurological impairment, neuromuscular complaints, dysphagia, or dysphonia. Each subject sat in the EMA magnetic field cube during the experiment. Sensor coils were fixed in the oral cavity and on the skin (refer to Section 3.2). Four sensor coils were fixed in the oral cavity; one was fixed on the upper incisor as a reference sensor. Three sensor coils were fixed near the tongue tip, the rear of the tongue (back) and lower incisor (Figure 3-1). These sensors were used to record the tongue and lower jaw movements during oral processing of food samples.

Eighteen food samples (Table 3-4, excluding bottled water, breakfast tea, cold coffee, mashed potato, milk shake, cream) were served to subjects randomly. A 5.3 g food sample was placed in a disposable spoon (semi-solids) or a plastic container (liquid) after the food sample had reached room temperature (20°C). The subjects were

instructed to consume the food sample as naturally as possible. The subjects rinsed their mouths with water at least 3 times between samples.

7.2.2. Data analysis

The maximum, minimum and average values of the tongue and lower jaw displacements and velocity in three dimensions were calculated using the recorded data and EMA calculation software.

Dynamic velocity (v) was collected from EMA in three dimensions; the maximum displacement change (Δ_{\max} Dis, Δ_{\max} Dis = maximum displacement – minimum displacement) in the vertical dimension was used as h in the estimation of shear rate. From the intercept and slope of the logarithmic plot of the flow curve between 10 ~ 100 s^{-1} , k and n were calculated respectively (Section 7.3.3.1). The dynamic shear rate and shear stress of the tongue tip, tongue back and lower incisor were calculated using Equations (3) and (4) for each time step during oral processing.

7.3. Results

7.3.1. The displacement of the tongue and lower jaw during oral processing

The dynamic movement of the tongue tip, tongue back and lower incisor in three dimensions were mentioned in Chapter 3 (Section 3.4.2.1). The traces of the three sensors are shown in Figures 7-1a and 1b. The maximum, minimum and average displacement in three dimensions, and total displacement (distance of the trace) of the sensors during oral processing were calculated (Table 7-1) from this data.

Three dimensional (3D) plots of two selected samples (standard milk and cheese tub) for one subject (subject 2) are shown in Figures 7-1a and b respectively. The x-axis is the anteroposterior direction, y-axis is lateral direction, and z-axis is vertical direction.

Generally, the 3D traces for the oral processing of cheese tube are longer and more complicated than for standard milk, especially for the tongue back and tongue tip traces. The lower incisor traces move in a similar direction for both foods, but the trace the cheese tube is longer and steeper. As a reference sensor coil, the upper incisor does not

move much; the movement observed is caused by head movement, which is removed in later calculations. These two graphics indicate that the tongue back and tongue tip move more flexibly when consuming viscous foods (cheese tube) than liquid foods (standard milk). But they do not show any regular movement as can be observed when chewing hard-solid food (e.g. roasted peanut, Figure 3-7 and 3-8) (Shinagawa et al., 2004).

Two dimensional (2D) plots show the displacement and direction clearly in three planes respectively for both food samples (Figure 7-2a and 2b). Figure 7-2a shows the lower incisor and tongue tip move within 3 mm in any plane during oral processing. Only the tongue back has a large displacement (about 15 mm) in the vertical dimension which appears to be at the moment of swallowing, when the hyoid bone moves downwards fast. This result indicates that the tongue back moves more actively than the tongue tip and lower incisor for low viscosity foods. Figure 7-2b shows that the lower incisor moves in a small range (within 5 mm) in all three planes. The movement of the tongue tip and tongue back are more complicated and show a greater range. In particular in the lateral dimension, the tongue tip has greater amplitude (about 30 mm) when consuming cheese tube than standard milk. In the vertical dimension, the tongue tip and tongue back traces also have greater range during consumption of cheese tube than standard milk; the amplitude is about 15 mm, which is less than in the lateral dimension, but similar to the greatest amplitude of the tongue back trace in the vertical dimension when consumption of standard milk. In the anteroposterior dimension, the biggest displacements of the tongue back traces are about 5 mm and 23 mm; tongue tip traces are about 2 mm and 10 mm for standard milk and cheese tube respectively. This implies that the high viscosity food induces more and greater movement in the lateral and anteroposterior dimensions, which corresponds to tongue pressing (anterio-posterior) and smashing (lateral) or other similar behaviours. The amplitude of the swallowing movement does not seem to be significantly different between high and low viscosity foods. Figure 7-3a and 3b show a similar behaviour for subject 2, but the tongue tip and tongue back traces in the lateral dimension are faster and greater. It indicates that the tongue of subject 2 shifts or swipes food more strongly than subject 1.

The maximum displacement changes (Δ_{\max} Dis) of three sensors in three dimensions during the oral processing of food samples are shown in (Appendix A8: Table 1). The column plots of the maximum displacement changes (Δ_{\max} Dis) of three sensors in three

dimensions are shown in Figures 7-4a (subject 1) and 7-4b (subject 2). The sensors traces during oral processing of standard milk and cheese tube are shown in Figures 7-1, 7-2 and 7-3.

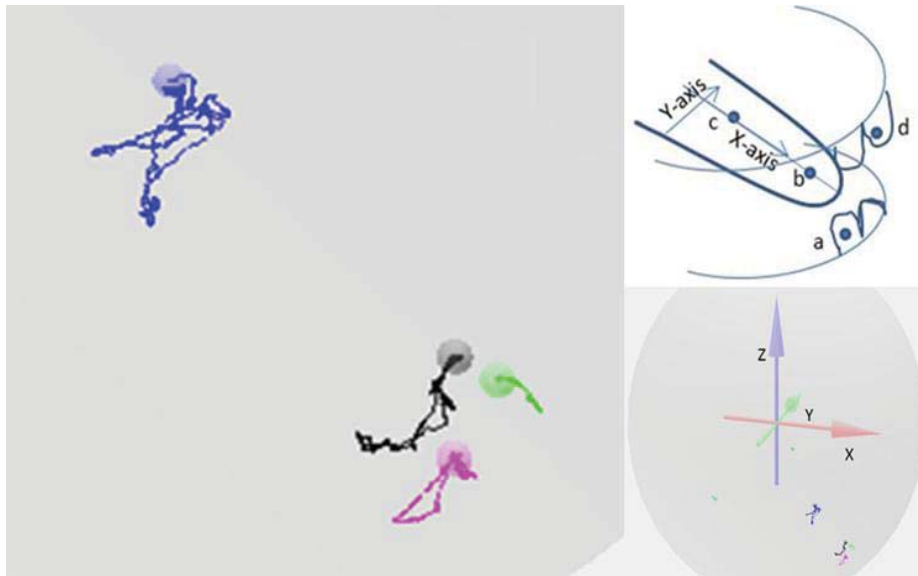


Figure 7-1a. 3 D plot of sensor coils traces during consumption of standard milk. The right top graph shows the positions of the four sensors in the oral cavity. The graph on the left shows the traces of the four sensors in the oral cavity: lower incisor (pink-a), tongue tip (black-b), tongue back (blue-c), upper incisor (green-d). The right bottom graph shows 3D traces of the six sensor coils in the EMA cube. The dark grey circle area (right bottom) describes the measurement range of the EMA AG500.



Figure 7-1b. 3 D plot of sensor coils traces during consumption of cheese tube. The right top graph: positions of the four sensors in the oral cavity. The left graph: traces of the four sensors in the oral cavity: lower incisor (pink-a), tongue tip (black-b), tongue back (blue-c), upper incisor (green-d). The right bottom graph: 3D traces of the six sensor coils in the EMA cube. The dark grey circle area (right bottom) is the measurement range of the EMA AG500.

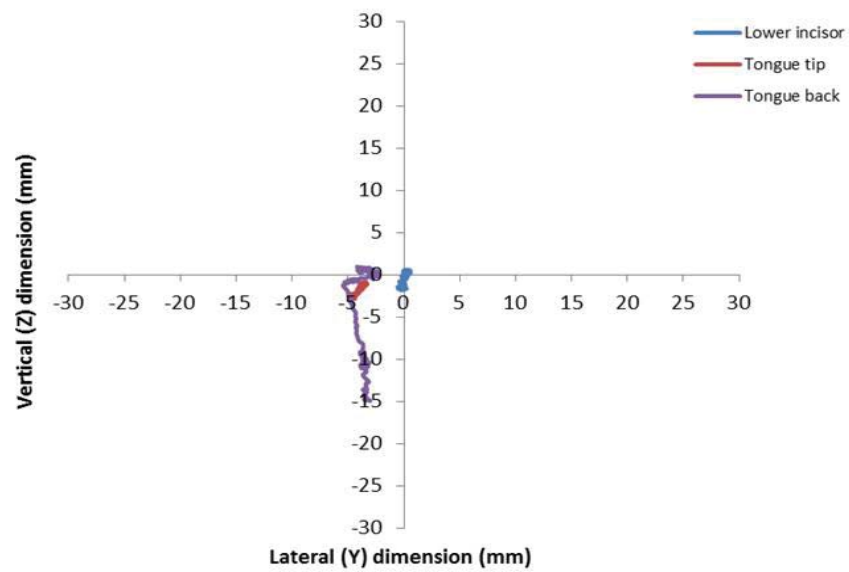
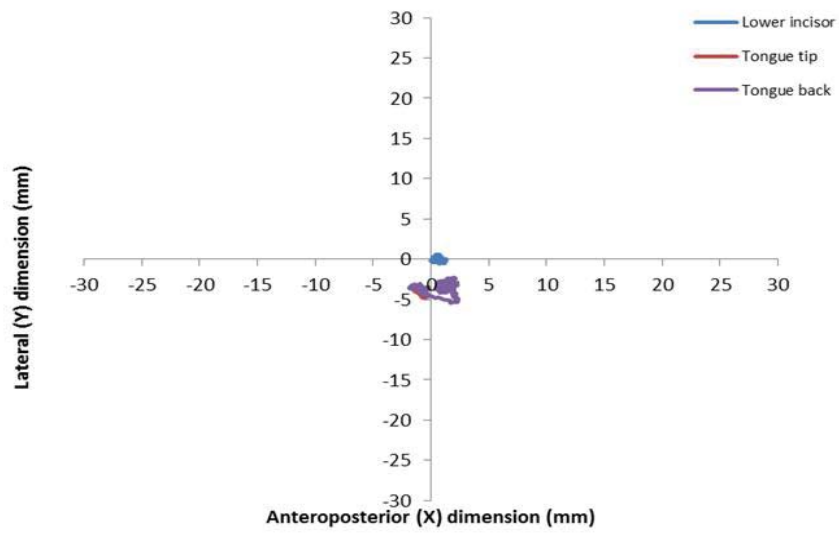
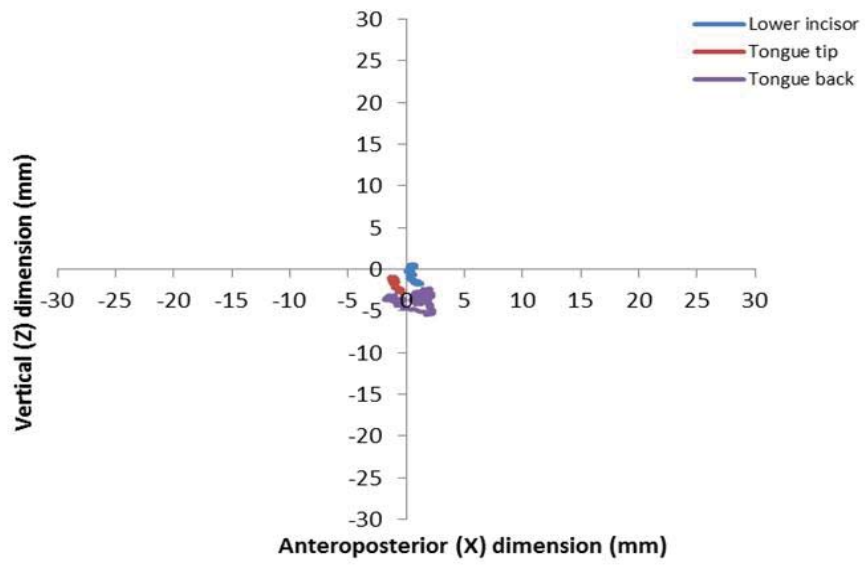


Figure 7-2a. 2 D traces of three sensors (X-Z axis, X-Y axis and Y-Z axis) during oral processing of standard milk (Subject 2).

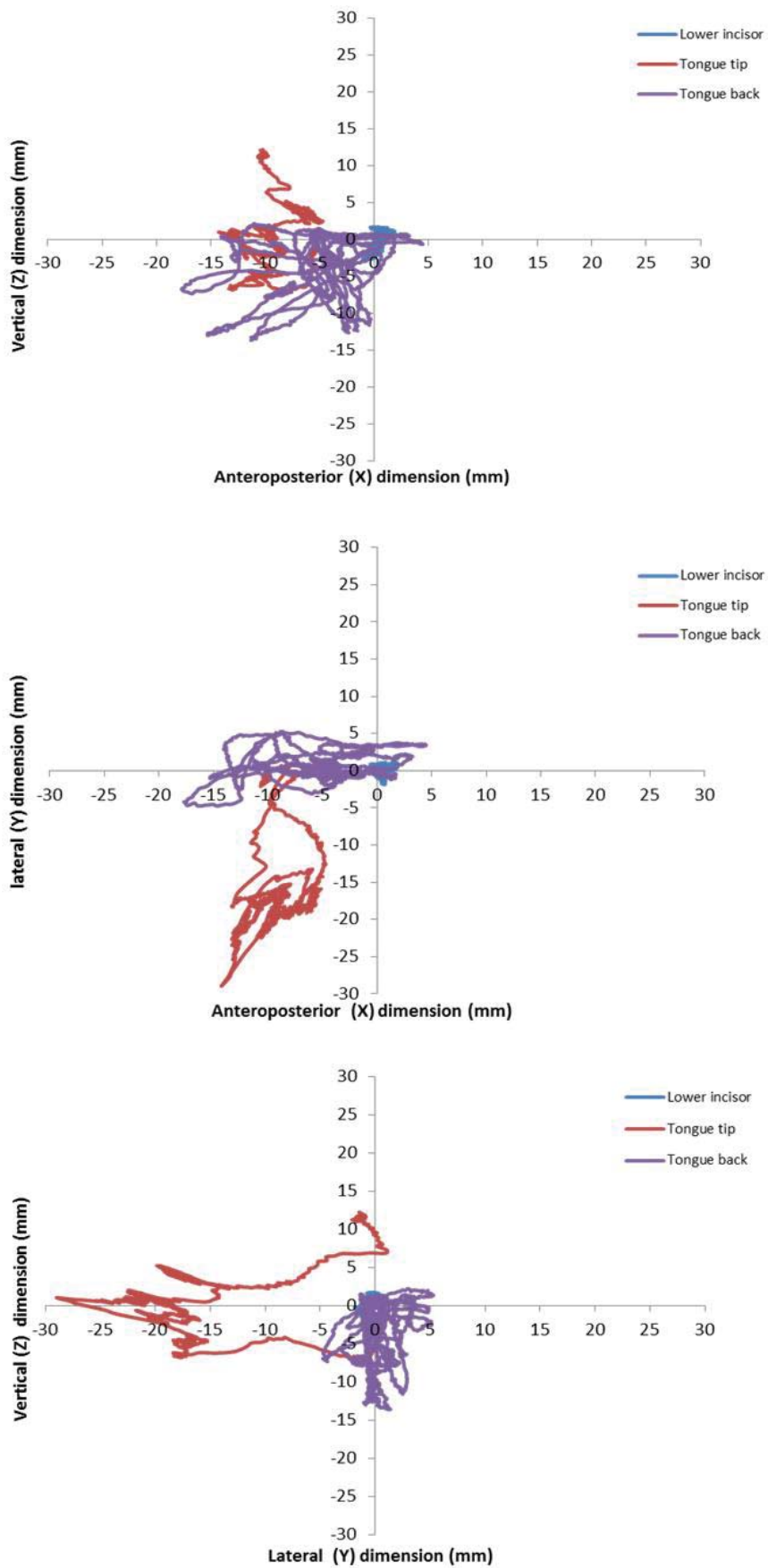


Figure 7-2b. 2 D traces of three sensors (X-Z axis, X-Y axis and Y-Z axis) during oral processing of cheese tube (subject 2).

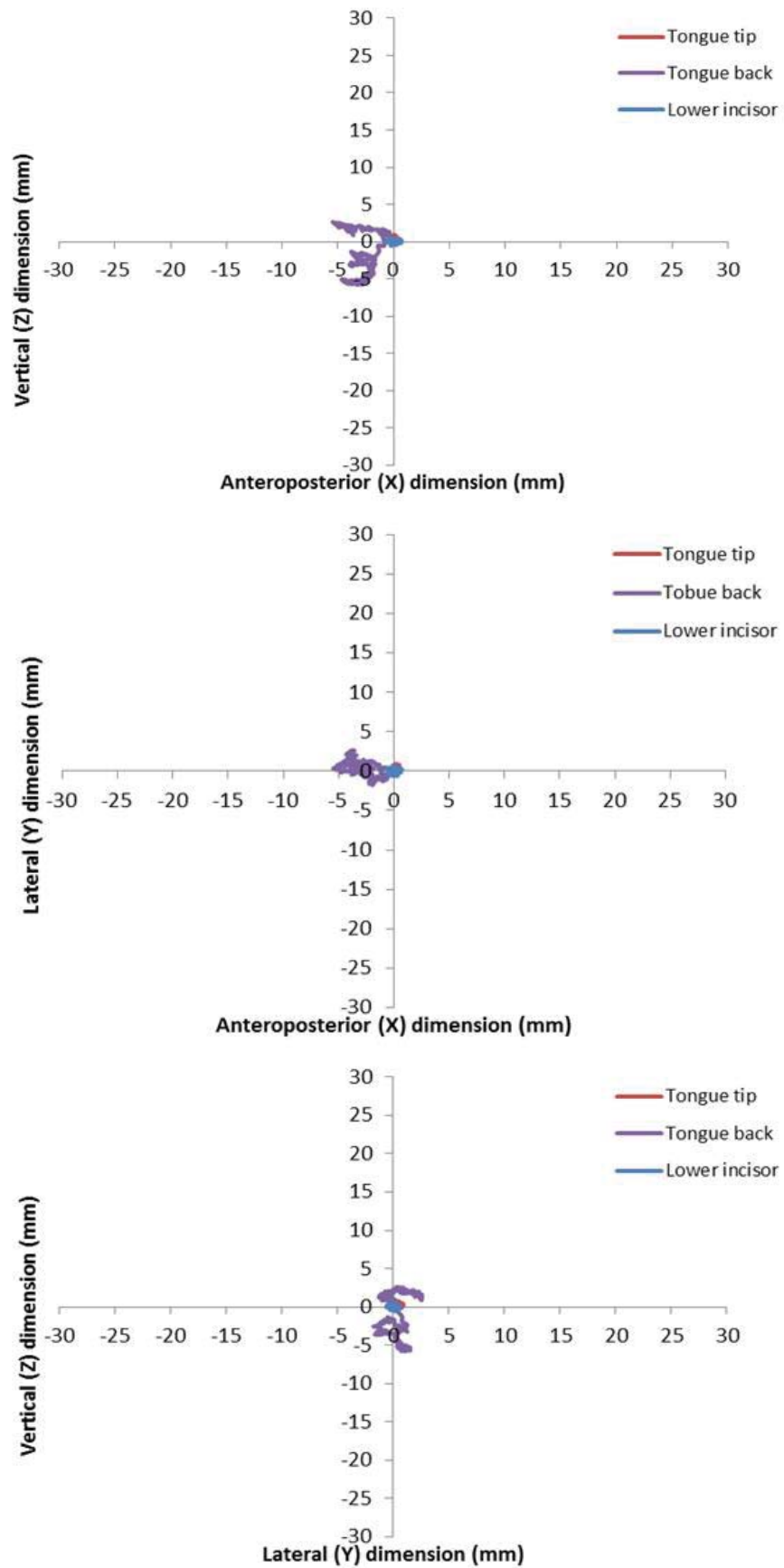


Figure 7-3a. 2 D traces of three sensors (X-Y axis, X-Z axis and Y-Z axis) during oral processing of standard milk (subject 1).

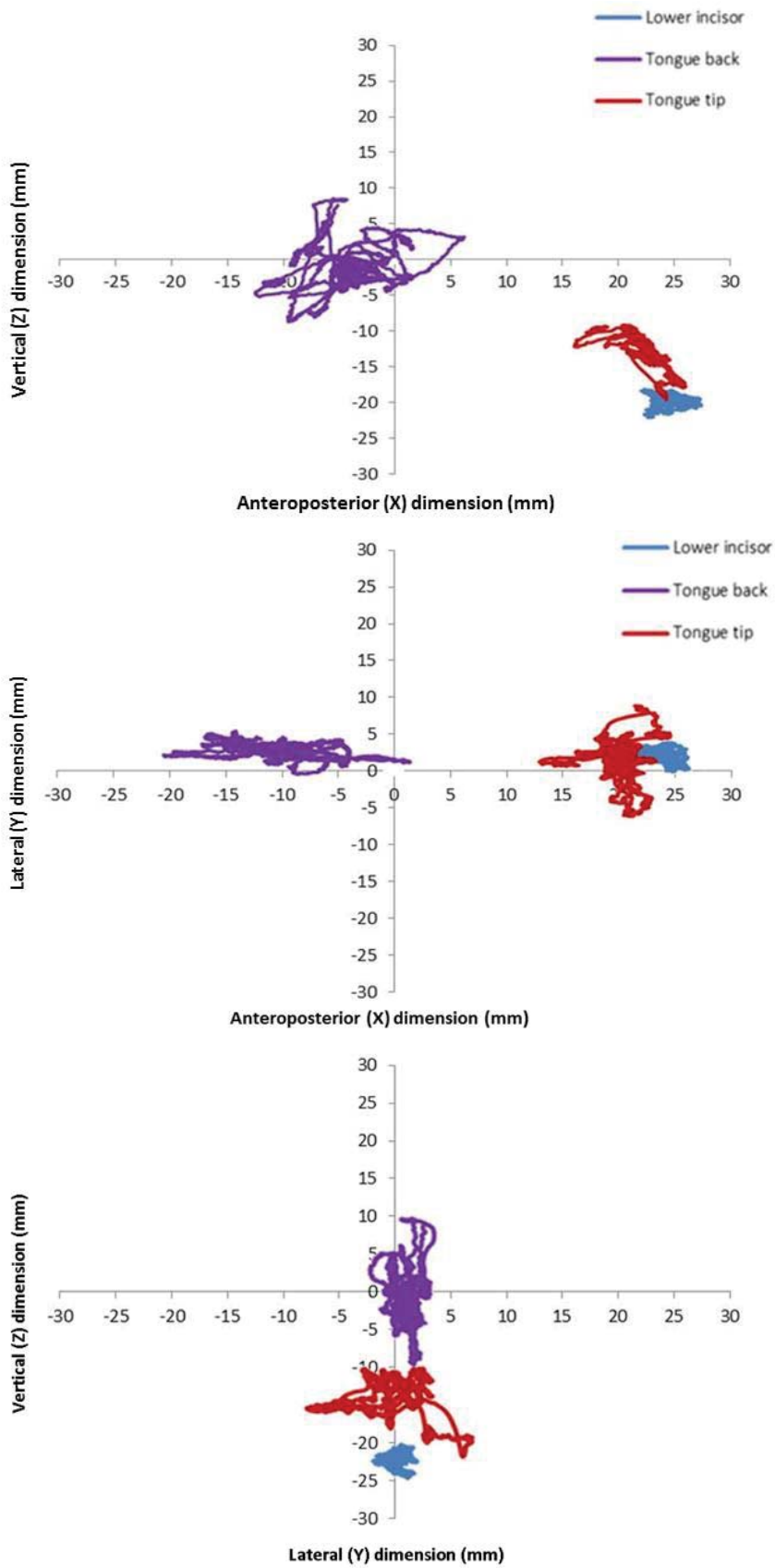
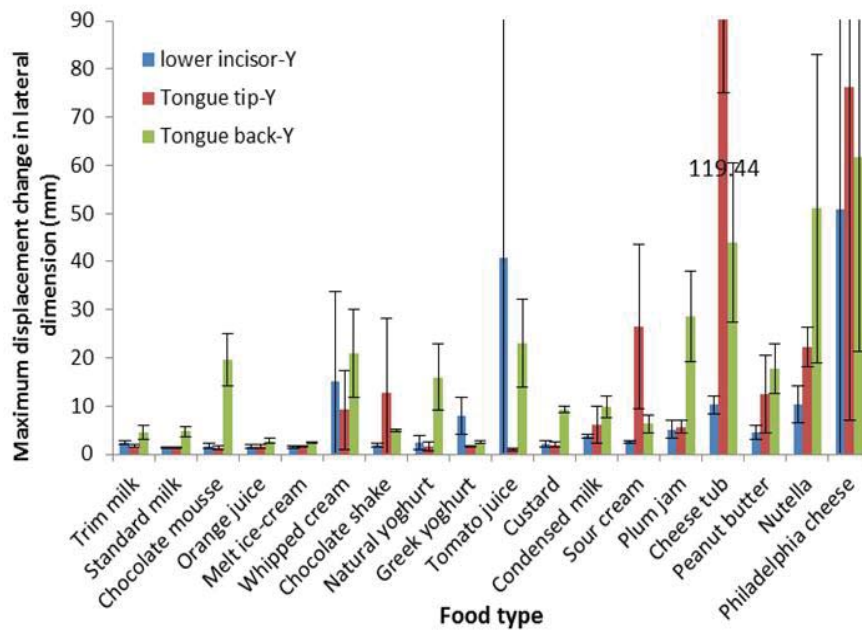
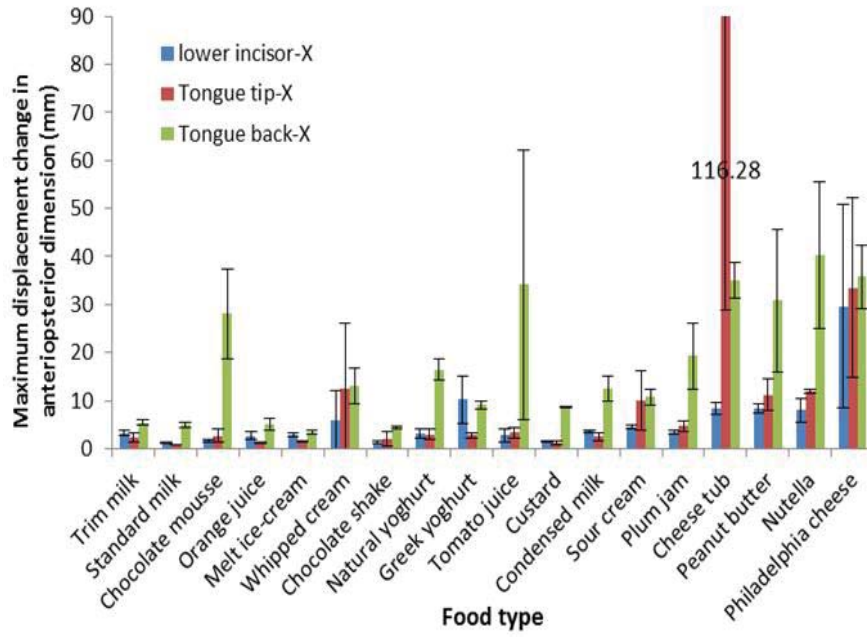


Figure 7-3b. 2 D traces of three sensors during oral processing of cheese tube (subject 1).

The maximum displacement changes (Δ_{\max} Dis) represent the maximum range of movement that the three sensors experience in three dimensions during consumption of food samples. In particular, the Δ_{\max} Dis in vertical dimension was assumed to be the height of the food bolus between the hard palate and the tongue (h) during oral processing of food samples, which is an important parameter to calculate shear rate and shear stress.

Figure 7-4 shows that the Δ_{\max} Dis of the lower incisor, tongue tip and tongue back all tended to increase with increasing food viscosity for both subjects in all three dimensions. However, not all food samples followed this trend; for example, exceptions for subject 1 were: chocolate mousse, whipped cream, natural yoghurt, tomato juice and cheese tub (Figure 7-4a). These exceptions may be attributed to personal preference and other food properties. These exceptions apply in all three dimensions. For subject 2 (Figure 7-4b), the results of the tongue tip and tongue back were more consistent with the lower incisor than for subject 1 during consumption of low viscosity foods. For both subjects, the Δ_{\max} Dis of the tongue back, tongue tip and lower incisor were in descending order in the same dimension during consumption of the same food, except for condensed milk, cheese tub, Philadelphia cheese (subject 2), whipped cream, chocolate shake and sour cream (subject 1). These exceptions apply more in the lateral dimension. The Δ_{\max} Dis of the tongue back in the vertical and anteroposterior dimensions were largely associated with swallowing related movements, especially for low viscosity food samples. For subject 2, the Δ_{\max} Dis of the tongue back and tongue tip increased more than the lower incisor for viscous foods. Subject 1 showed a similar trend though less than that of regular to subject 2. In addition, for subject 2, the greatest Δ_{\max} Dis was not for the most viscous food (Philadelphia cream cheese) in all three dimensions in Figure 7-4b. It was predicted that the Δ_{\max} Dis of the above three positions might decrease with an increase in viscosity to a certain extent. Figure 7-4b showed this trend for subject 2. Other food properties may contribute to the displacement of the tongue and jaw, which may explain this exception to the trend; for example, the stickiness and moisture content might be important for the displacement during food oral processing. More subjects and food types need to be tested to investigate this trend further.



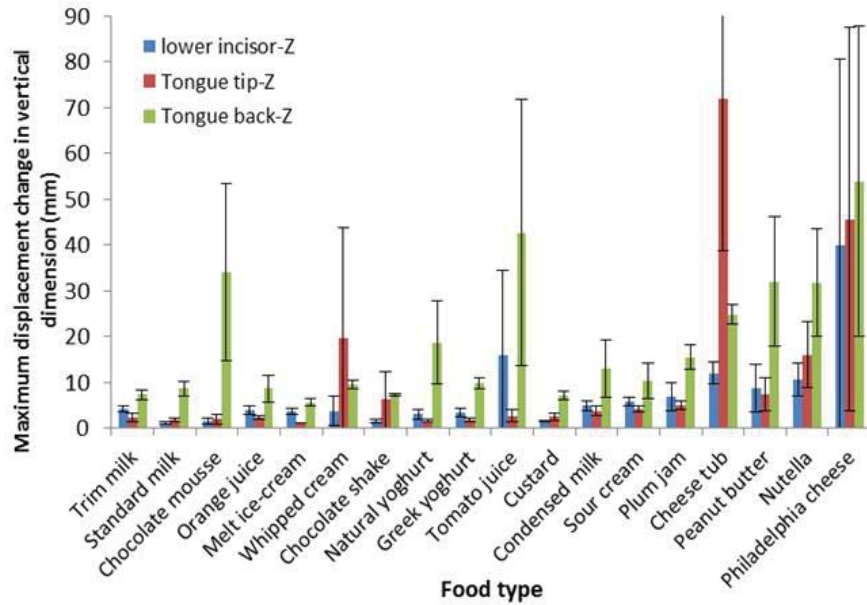
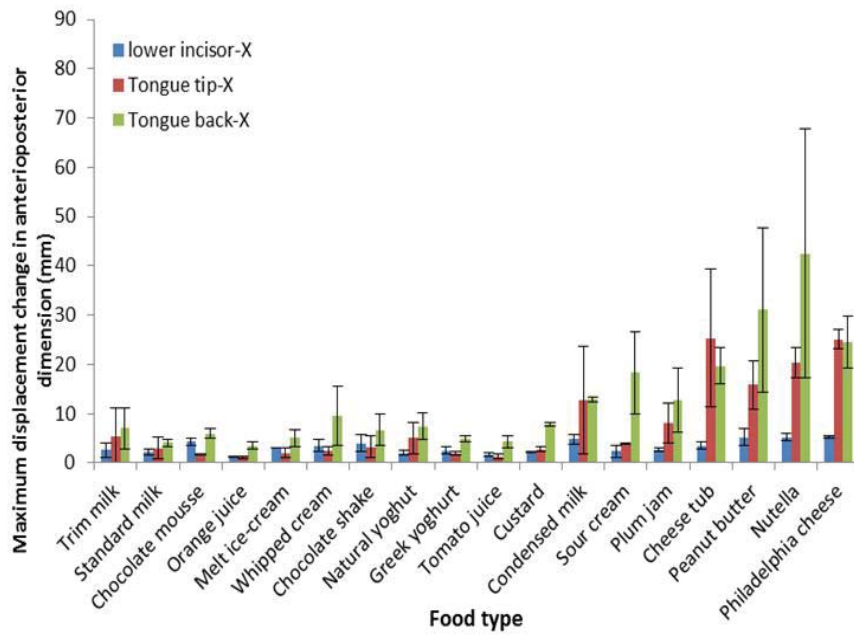


Figure 7-4a. The maximum displacement change of three sensors in three dimensions during oral processing of eighteen food samples for subject 1. From top to bottom, they are anteroposterior (X), lateral (Y) and vertical (Z) dimensions respectively. (Δ_{\max} Dis= maximum displacement – minimum displacement). The error bars represent the standard deviations for each sample in 3 replicates.



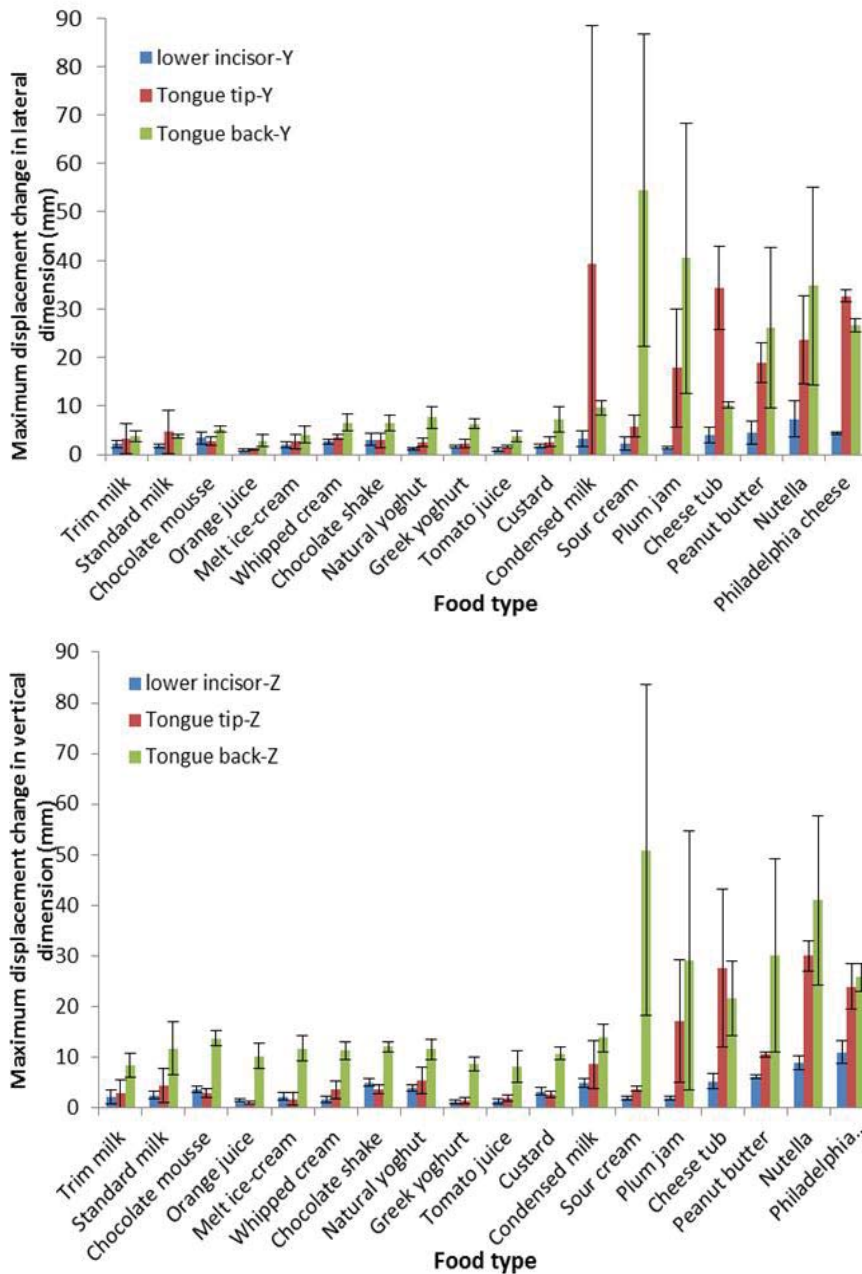


Figure 7-4b. The maximum displacement change of three sensors in three dimensions during oral processing of eighteen food samples for subject 2. From top to bottom, they are in the X, Y and Z dimension respectively. The error bars represent the standard deviations for each sample in 3 replicates.

The total displacements of the three sensors indicate the total distance of the sensors travelled during oral processing. They also show similar trends to the Δ_{\max} Dis of sensors (Figure 7-5 and appendix A8: Table 2). Both subjects had similar total displacements during oral processing of eighteen food samples; but when they consumed thicker food samples (from condensed milk upwards) there was a greater difference in the total displacement between foods. This agrees with the observations seen in Figure 7-4. The greater the total displacement is, the more complicated and longer the oral processing (Figure 7-5). This is consistent with the sensor trace during

consumption of food samples also. For example, the sensor trace during consumption of milk was completely different to that of cheese tub; the former was simple and short (Figure 7-2a and 7-3a); the latter was complex and long (Figure 7-2b and 7-3b). The column plots of the total displacements of three sensors show clearer distance values than the sensor traces. For both subjects, it was also found that the total displacement of the tongue during consumption of Philadelphia cream cheese (all three sensors) was shorter than that of Nutella. This is due to the different material properties. Cream cheese is high in fat, it will be soften on heating in mouth. Nutella is very sticky and requires more oral movement to remove from surfaces of the oral cavity.

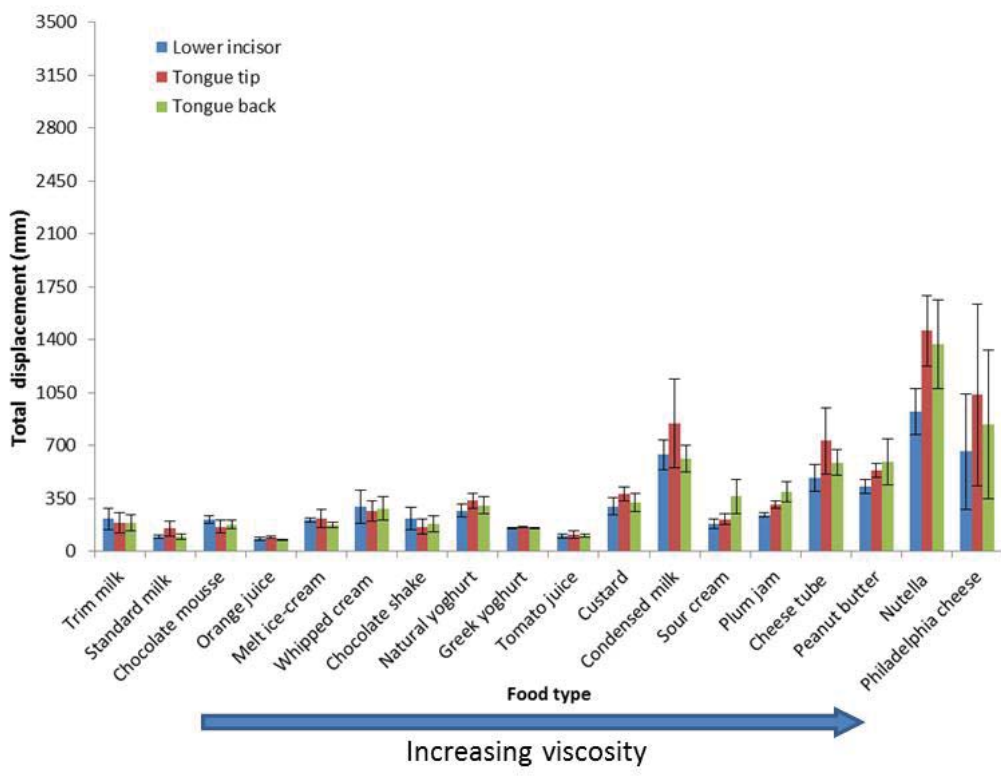
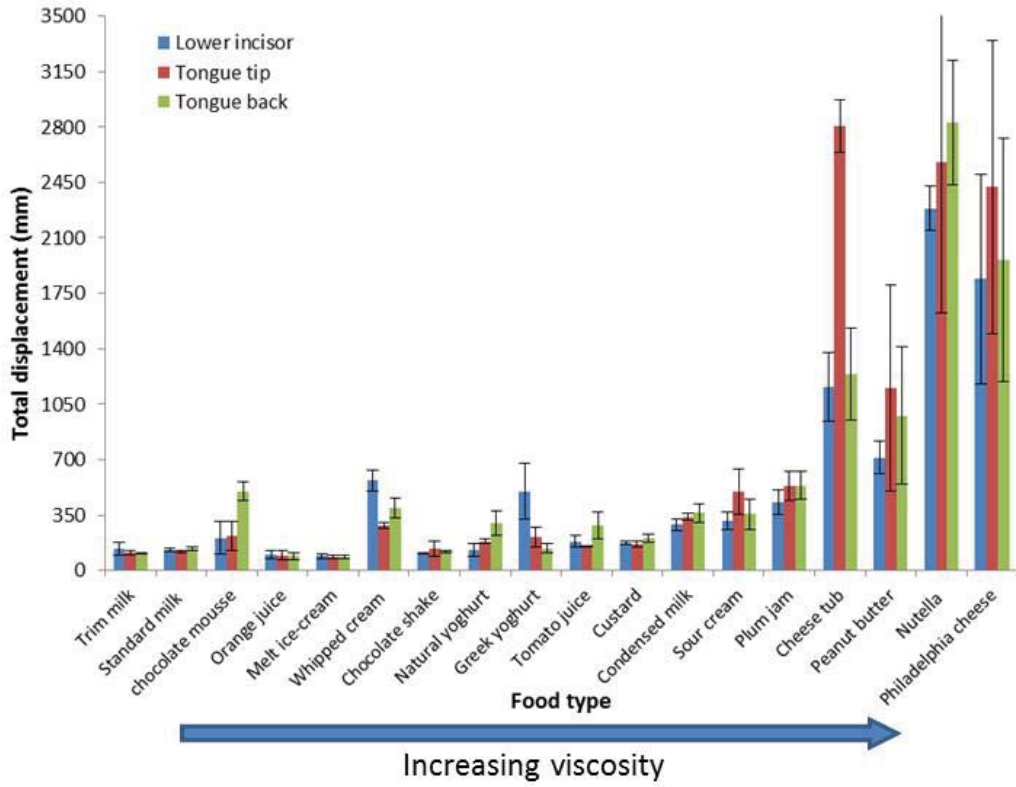


Figure 7-5. Total displacement of the lower incisor (blue), tongue tip (red) and tongue back (green) during oral processing. The top graph is for subject 1; the lower graph is for subject 2. The error bars represent the standard deviations for each sample in 3 replicates.

7.3.2. The velocity of the tongue and lower jaw during oral processing

The velocity of three sensors movements in three dimensions was calculated using EMA data (velocity = displacement / time). The dynamic velocity - time plots in three dimensions during consumption of standard milk and cheese tub (subject 2) are shown in Figures 7-6 and 7-7.

These velocity-time scatter plots in three dimensions show that regardless of food type (thin liquid (milk) or soft-solid food (cheese tub)) the velocity of the lower incisor in the vertical dimension was the slowest for all three sensors. For both samples, the velocities of the lower incisor and the tongue back were in a similar value range in the anteroposterior and lateral dimensions. But their velocity values are different at the same time. For cheese tub, the lateral velocity of the tongue tip appears much higher than the other dimensions and standard milk. It was considered to relate to some special tongue movement, such as smashing around against the hard palate. On the other hand, the velocity-time plots indicate that the velocity of the lower incisor is not consistent with the velocity of the tongue tip and tongue back. Figures 7-7 show that the tongue tip and tongue back movement of high viscosity food samples were dramatically greater than low viscosity foods. More food samples data can be seen in the Appendices (A8: Table 3a and 3b).

The maximum and minimum velocities (Appendix A8: Table 3a and 3b) in three dimensions show completely different value ranges and trends between the two subjects with increasing viscosity. For subject 1, the maximum velocity was 0.09 – 17.54 m/s in the anterior-posterior dimension for 19 food samples (plus bottle water), but for subject 2, it was 0.1 - 2.57 m/s; in the lateral dimension, the maximum velocity for subject 1 was 0.07 – 14.07 m/s, and for subject 2 it was 0.1 – 4.72 m/s; in the vertical dimension, subject 1 was 0.11 - 19.27 m/s, and subject 2 was 0.05 – 7.85 m/s. The minimum velocity (negative values) in the three dimensions for two subjects had similar value ranges and trends. The maximum velocity of the tongue movement for subject 1 was at least twice that of subject 2. Moreover, the food sample which elicited the maximum tongue velocity during consumption was different between the 2 subjects. For subject 1, the maximum velocity happened during consumption of Philadelphia cheese (19.27 ± 17.67 m/s). For subject 2, the maximum velocity happened during consumption of sour cream (7.85 ± 5.49 m/s). The maximum and minimum velocity of three sensors did not

show a clear trend in three dimensions for subject 1. However, the general trend for subject 2 was that velocity increased first as viscosity increased, and then decreased to a certain extent. This may indicate that the two subjects have different oral processing patterns, or the differences are caused by other food properties. In any case, data from more subjects needs to be collected to investigate this further.

The minimum velocity in the anteroposterior, lateral and vertical dimension are negative values, which can be translated to maximum backward, right and downward velocities. The average velocity means the average value of absolute velocity value of each recording time during oral processing, regardless of positive and negative velocity.

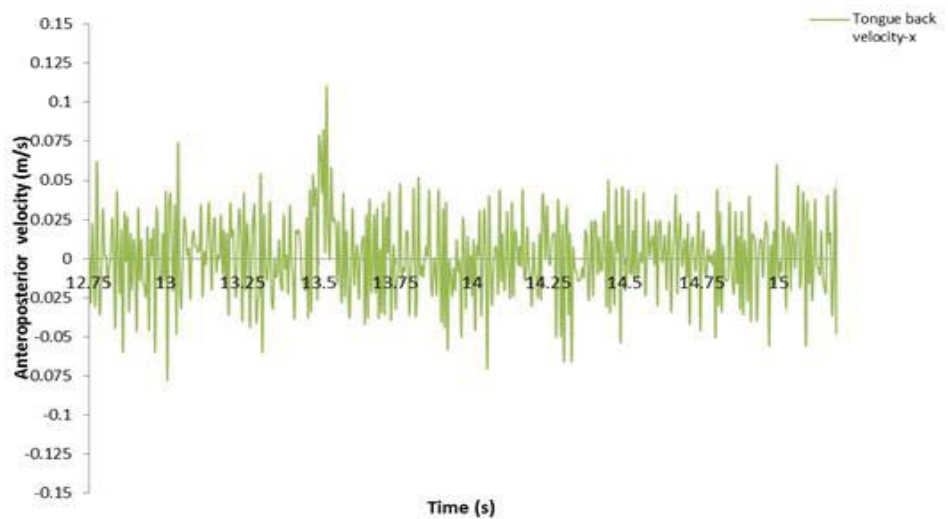
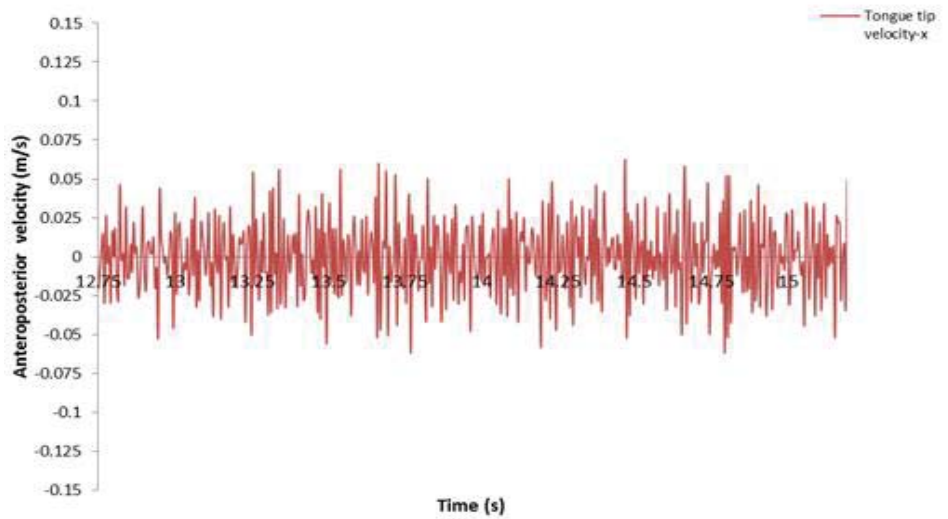
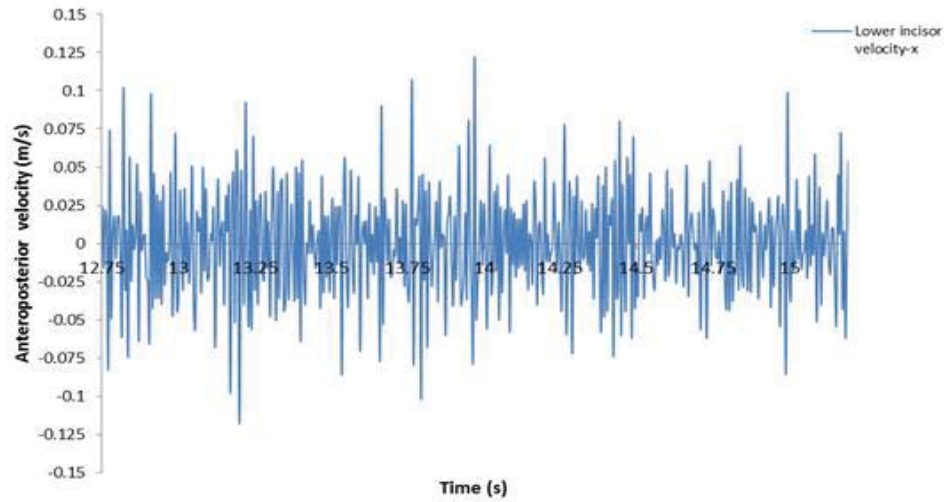


Figure 7-6a Velocity recorded by the three sensors in anteroposterior dimension during oral processing of standard milk for subject 2. Positive velocity means the tongue or lower incisor moving forward; negative velocity means moving backward.

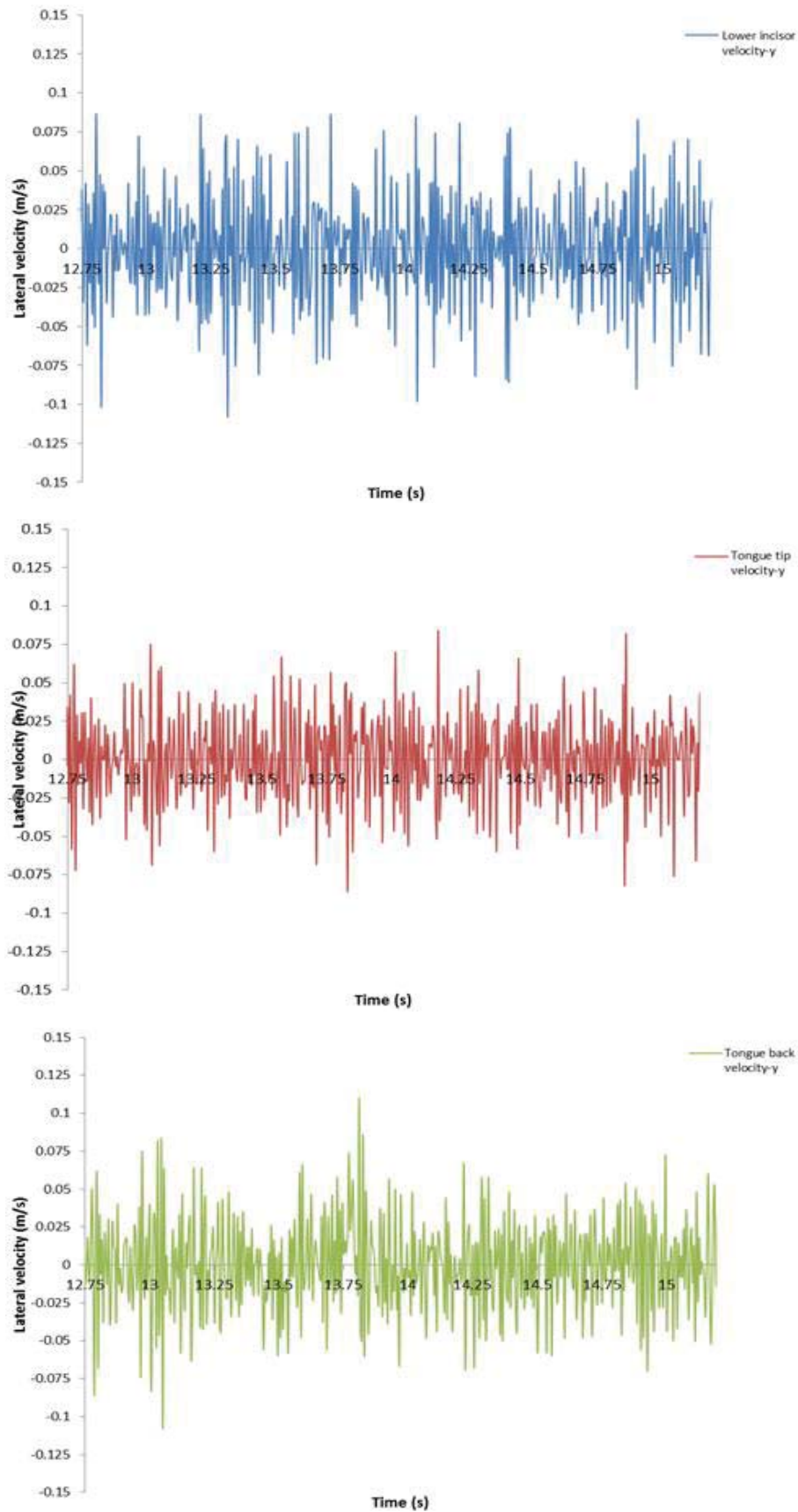


Figure 7-6b Velocity recorded by the three sensors in lateral dimension during oral processing of standard milk for subject 2. Positive velocity means the tongue or lower incisor moving left; negative velocity means moving right.

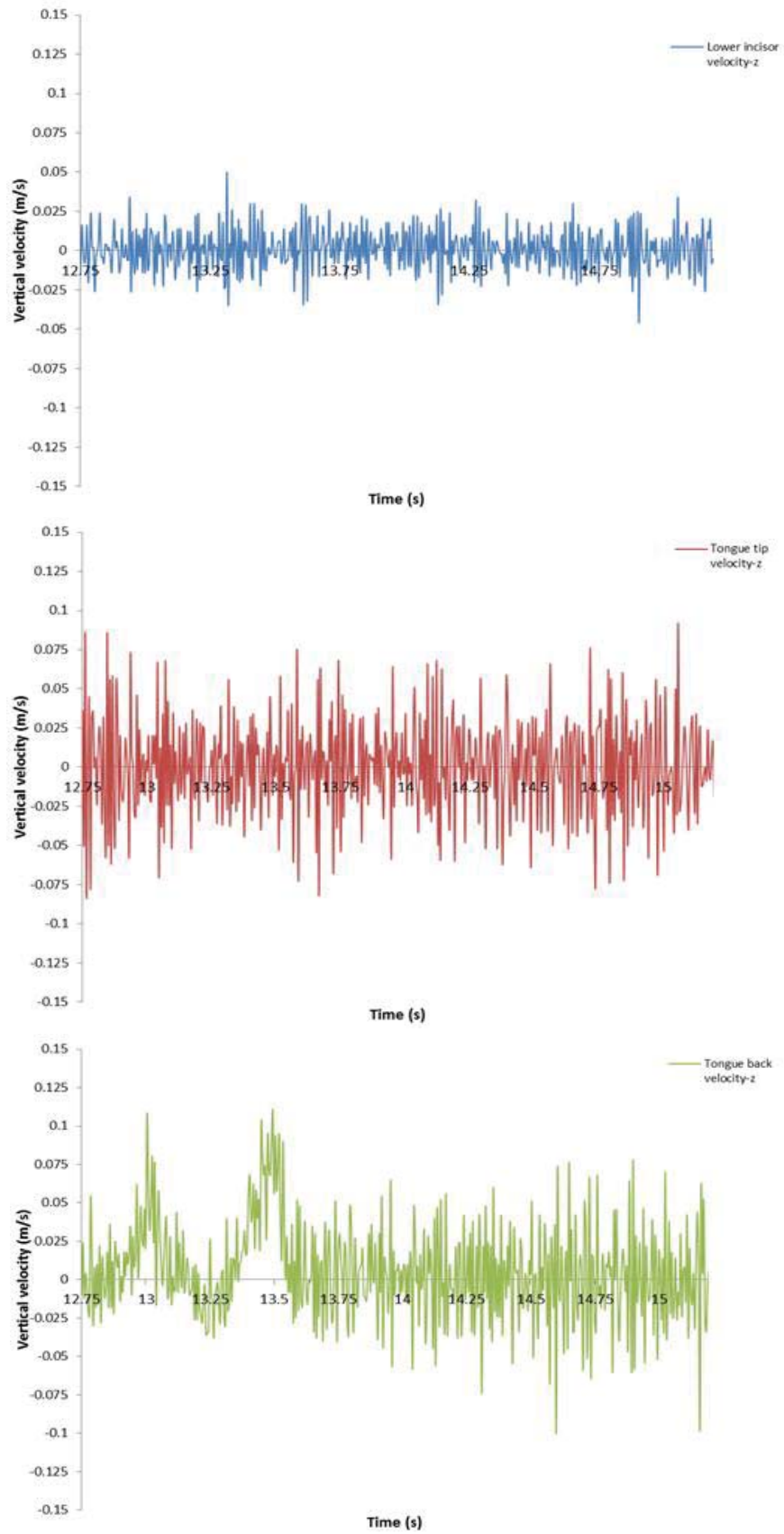


Figure 7-6c Velocity recorded by the three sensors in vertical dimension during oral processing of standard milk for subject 2. Positive velocity means the sensor coil moving upward; negative velocity means moving downward.

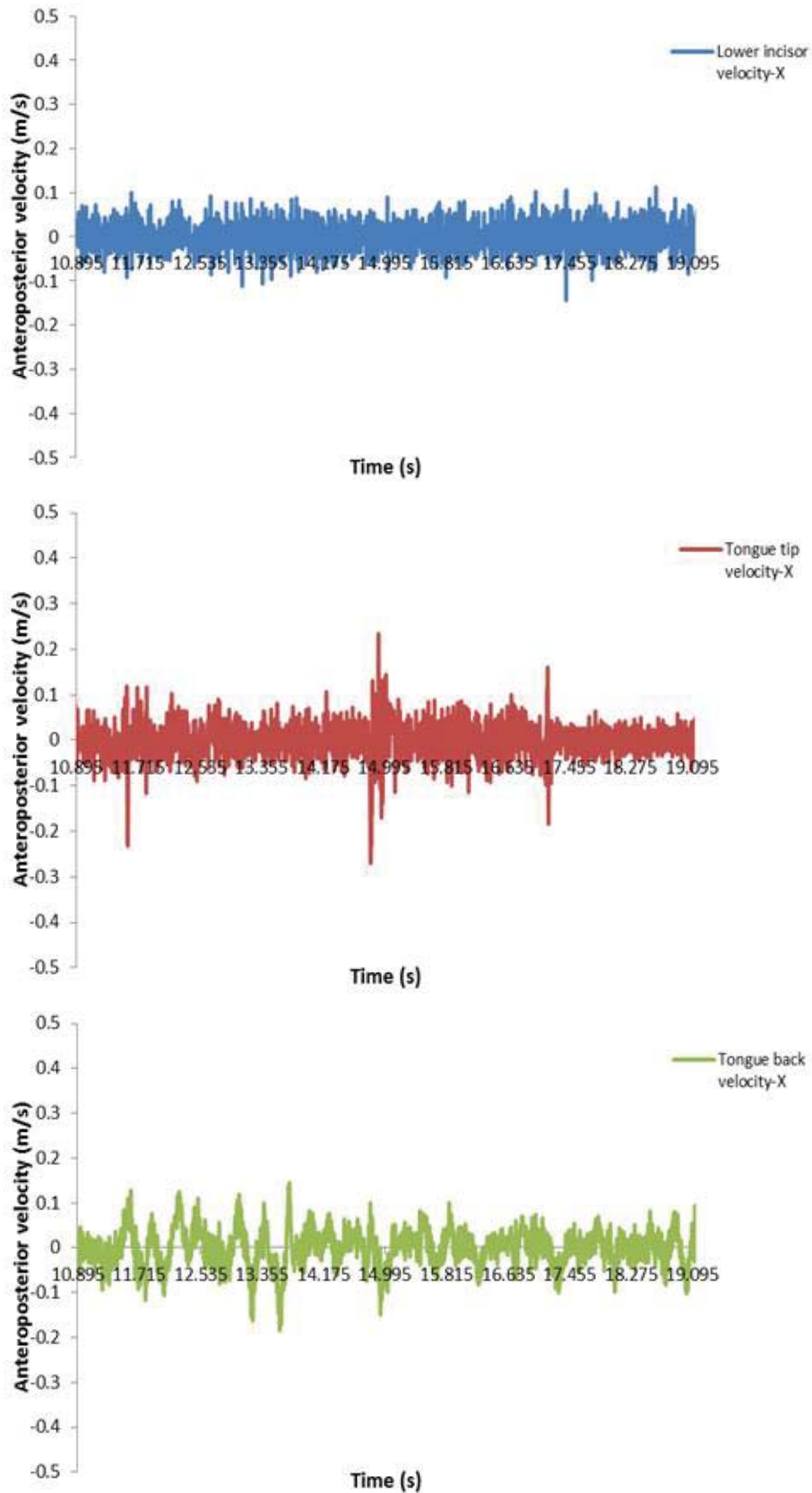


Figure 7-7a Velocity recorded by the three sensors in anteroposterior dimension during oral processing of cheese tube for subject 2. Positive velocity means the sensor coil moving forward; negative velocity means moving backward.

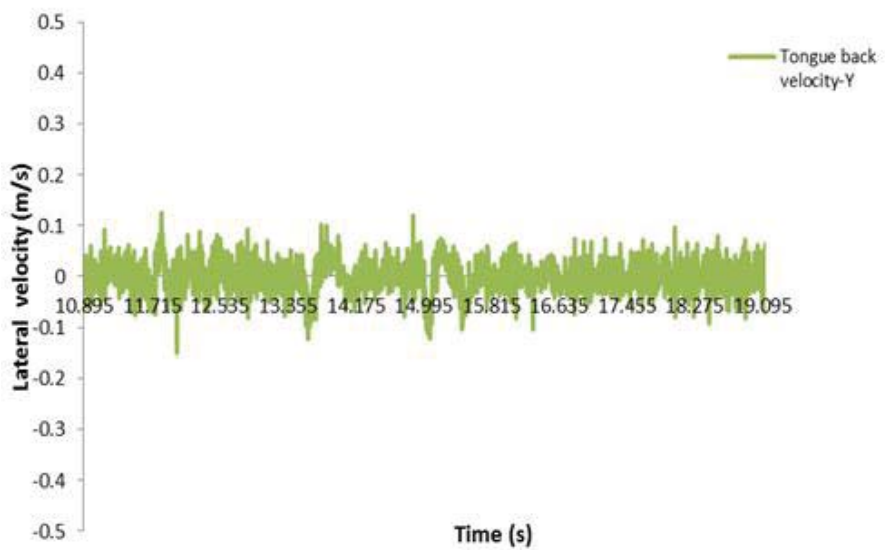
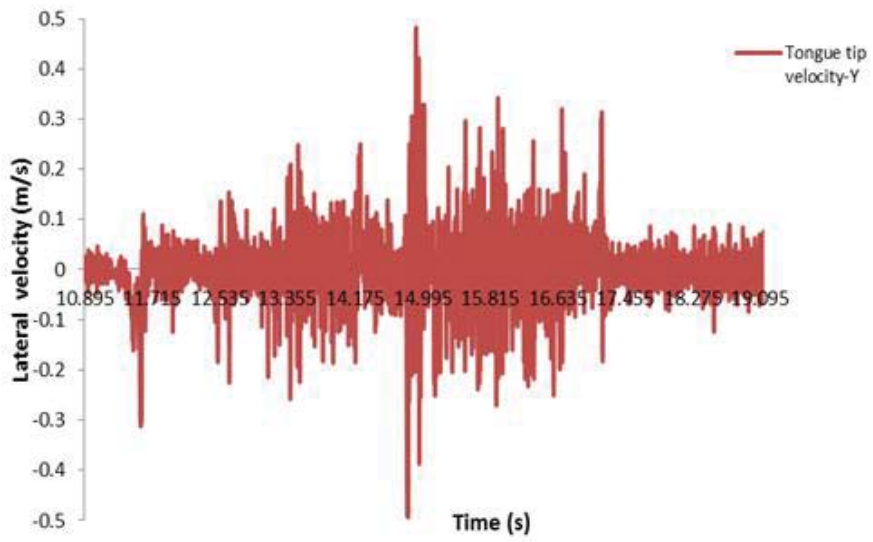
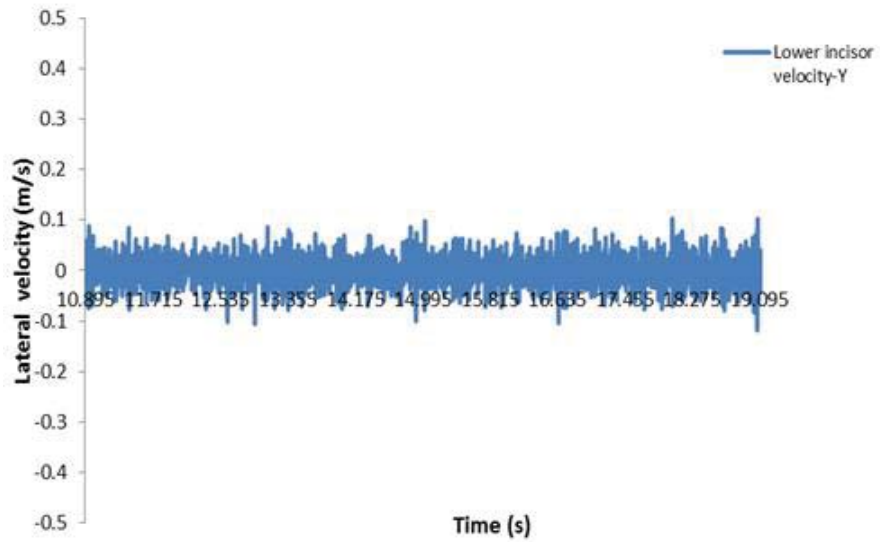


Figure 7-7b Velocity recorded by the three sensors in lateral dimension during oral processing of cheese tube for subject 2. Positive velocity means the sensor coil moving left; negative velocity means moving right.

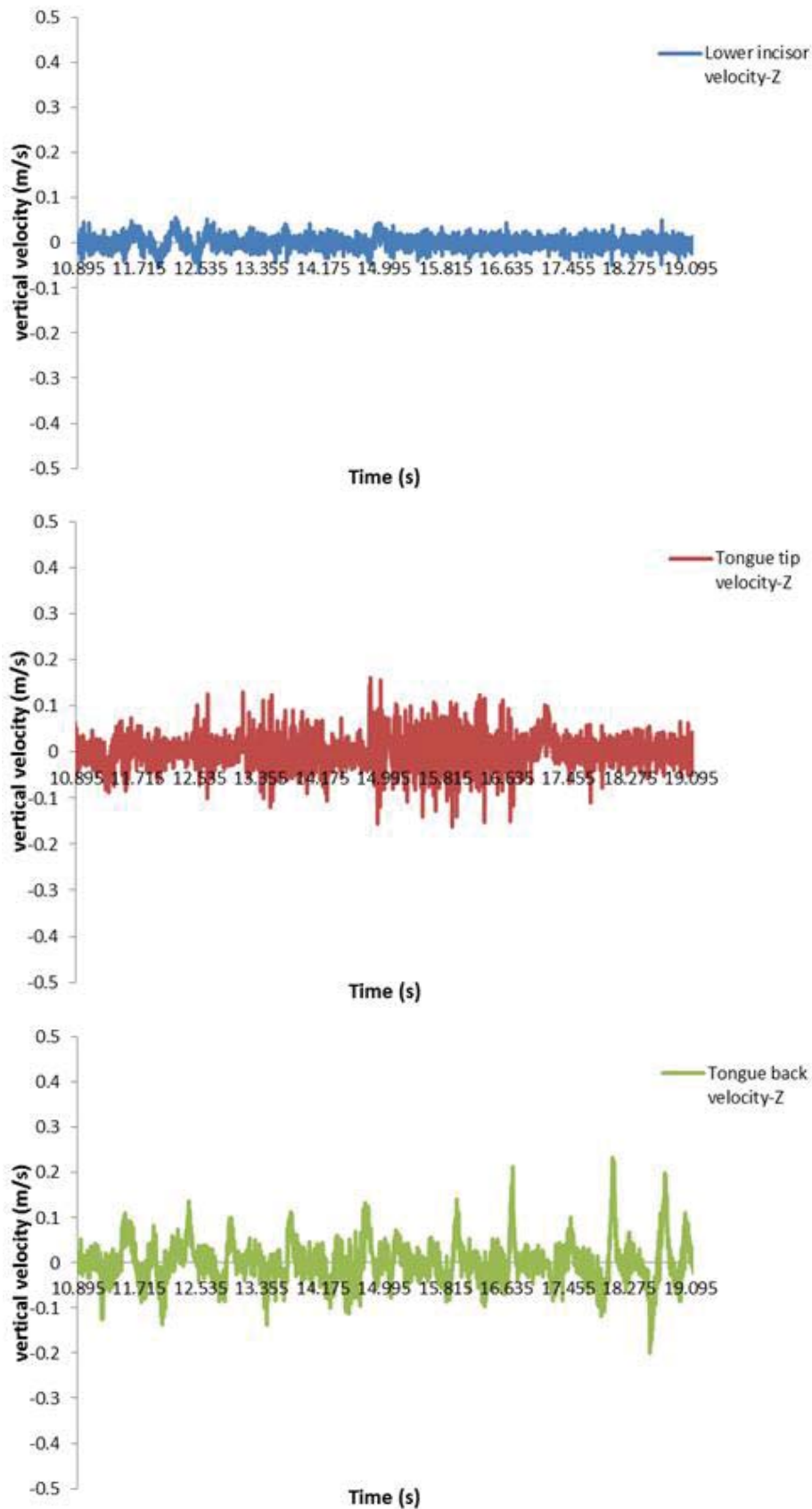


Figure 7-7c Velocity recorded by the three sensors in vertical dimension during oral processing of cheese tube for subject 2. Positive velocity means the sensor coil moving upward; negative velocity means moving downward.

The average velocity values for the lower incisor, tongue tip and tongue back in the three dimensions show no clear trend in the anteroposterior, lateral and vertical dimensions for both subjects. For subject 2, the average velocity of every food sample is very similar (0.04 m/s) in the three dimensions during oral processing. For subject 1, the average velocity of every sample is not as regular as for subject 2. Some foods have significantly high values in certain dimensions; for example, chocolate mousse in three dimensions (0.08 - 0.12 m/s), Greek yoghurt in anteroposterior (0.15 m/s) and lateral dimensions (0.13 m/s), cheese tube in three dimensions (0.08 - 0.14 m/s), and natural yoghurt in vertical (0.09 m/s) dimension (Appendix A8: Table 3a and 3b).


7.3.3. The dynamic shear stress of the tongue and lower incisor during oral processing

7.3.3.1. Determination of the parameters in the shear stress equation

According to the slope of the logarithmic plot of the flow curve between $10 \sim 100 \text{ s}^{-1}$, n was calculated. The intercept of the logarithmic flow curve assisted to determine k . k is the fluid viscosity index ($\text{Ns}^n \text{ m}^{-2}$), which indicates fluid viscosity; n is flow behaviour index, which indicates the type of fluid: 1) $n < 1$, pseudo-plastic fluid; 2) $n = 1$, Newtonian fluid; 3) $n > 1$, dilatant fluid. Shear rate and shear stress of the lower incisor, tongue tip and tongue back were calculated based on Equations (4) and (3). The fluid thickness (height) h was represented by the maximum displacement change, which equals maximum displacement minus minimum displacement. The fluid viscosity and flow behaviour indexes are provided in Table 7-1.

The logarithmic flow curve plots of Philadelphia cream cheese and Nutella curved like a bell-shape, especially Philadelphia cream cheese, which may be attributed to the inaccurate flow curve measurement (the sample was too sticky for the geometry). Therefore, n and k values of these two samples are inaccurate. This explains the negative n value of Philadelphia cream cheese, and the extreme high value of shear stress of Philadelphia cream cheese and Nutella.

Table 7-1 Rheological parameters k and n values for different food samples



Samples	Fluid viscosity index k (Ns^nm^{-2})	Flow behaviour index n
Trim milk	0.003	0.90
Standard milk	0.008	0.69
Chocolate mousse	0.060	0.70
Orange juice	0.168	0.27
Melt ice-cream	0.099	0.70
Whipped cream	0.200	0.61
Chocolate shake	1.671	0.24
Natural yoghurt	2.036	0.45
Greek yoghurt	3.448	0.40
Tomato juice	8.147	0.05
Custard	5.335	0.45
Condense milk	5.294	0.83
Sour cream	46.903	0.04
Plum jam	15.686	0.52
Cheese tub	205.258	0.07
Peanut butter	86.636	0.30
Nutella (chocolate spread)	318.200	0.03
Philadelphia cream cheese	1104.333	-0.37

7.3.3.2. The shear rate and shear stress during oral processing

The shear rate was calculated by Equation (4). v represents absolute velocity instead of velocity in three different dimensions; h represents the maximum displacement change in the vertical dimension (ΔZ_{max}). The maximum, minimum and average shear rate values are shown in Appendix A8: Table 4a. A clear decreasing trend is observed in the minimum and average shear rate plots with increasing food viscosity (Figure 7-8). However, there is not a decreasing trend with the increasing viscosity in the maximum shear rate plot. The shear rate ranges between $0 \sim 0.45 \text{ s}^{-1}$ for subject 1; while the shear rate of subject 2 ranges between $0 \sim 0.34 \text{ s}^{-1}$. These data show that the two subjects have similar value ranges whether the shear rate is maximum, minimum or average shear rate, but subject 1 is slightly higher than subject 2. For both subjects, the shear rates of the tongue tip and lower incisor were much higher than the tongue back in minimum and average values. This indicates that the tongue tip and lower incisor generate a higher shear rate than the tongue back during oral processing, especially for low viscosity foods. For subject 2, the maximum shear rate of the tongue back was higher than the lower incisor and tongue tip for high viscosity foods, such as sour cream, plum jam and cheese. There was no such clear trend on maximum shear rate of subject 1. This also implies that the shear stress of the tongue tip and lower incisor was smaller than the

tongue back, especially for viscous foods. This shows that the tongue back applies more shear stress on viscous foods during oral processing. The shear stress logarithm plots show the same trend, but the difference between the tongue tip, lower incisor and tongue back were minimal (Figures 7-9a and 9b).

The average velocity, shear rate and shear stress probably are the most useful data. Because a maximum or minimum value can be dictated by one extreme movement which is not representative of typical movements. Average values were calculated using the sum of the parameter and then divided by corresponding time; therefore, average values are most likely representing the general movements during the oral residence time.

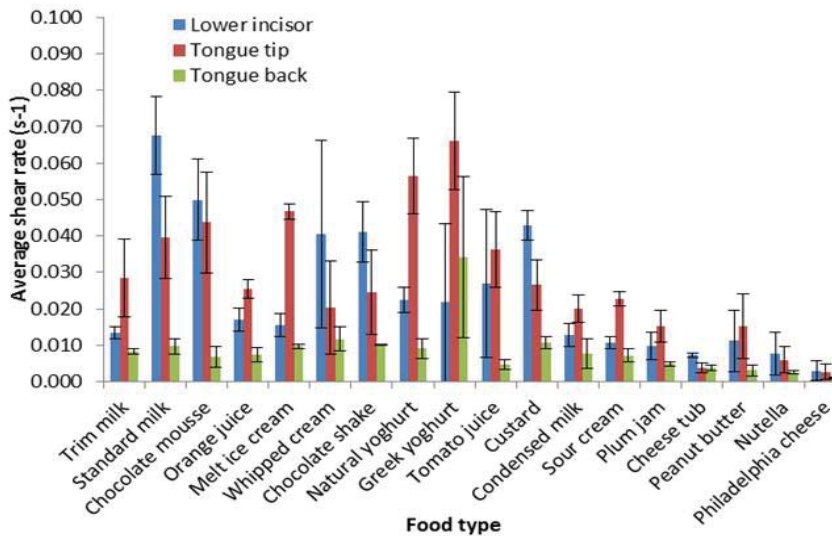
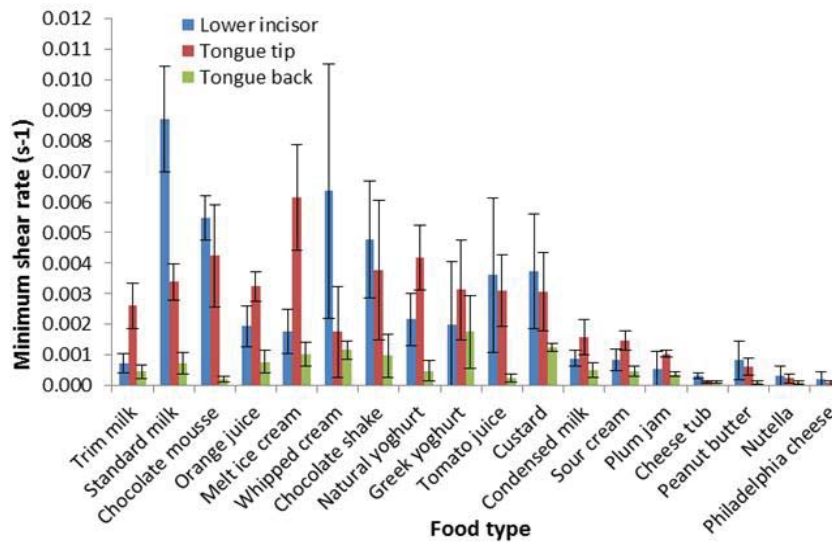
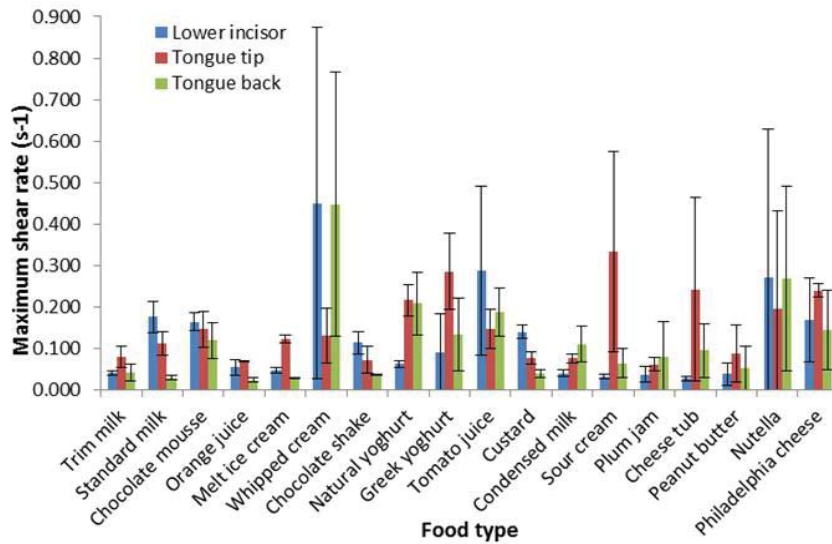


Figure 7-8a. The maximum, minimum and average shear rate during oral processing of food samples (from top to bottom) for subject 1.

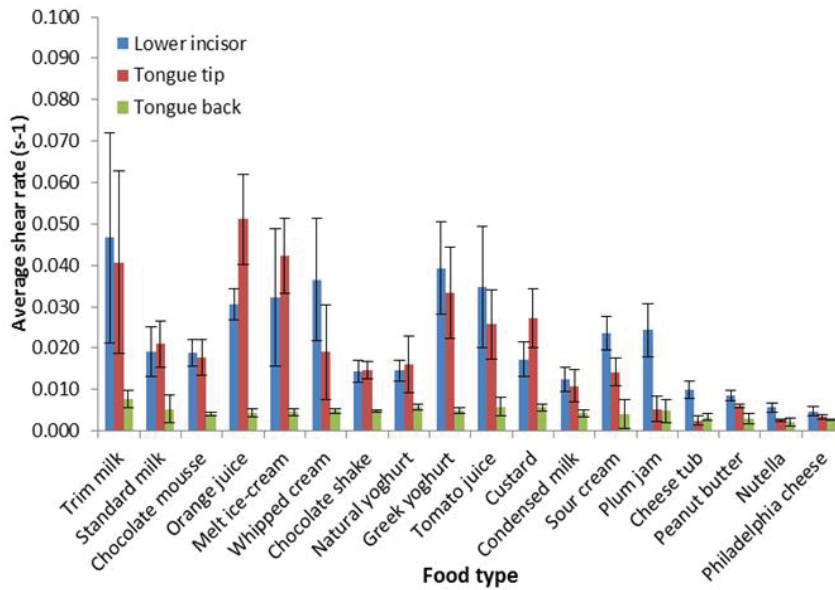
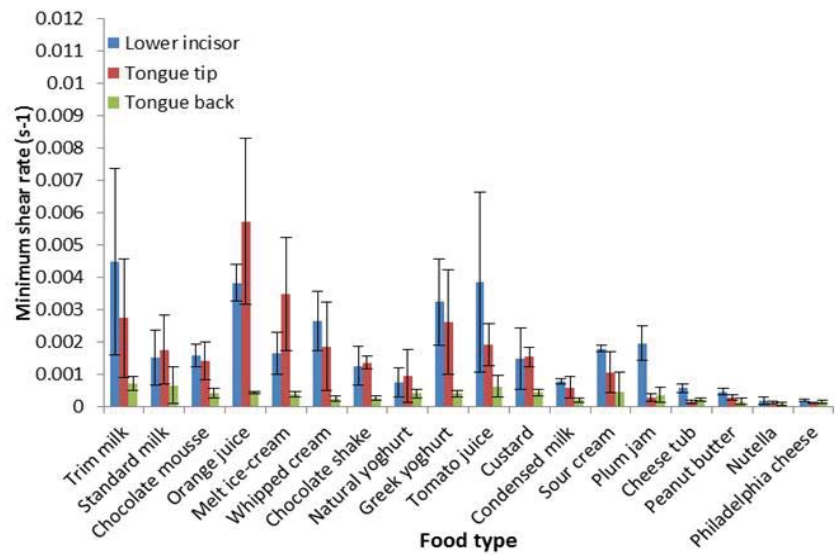
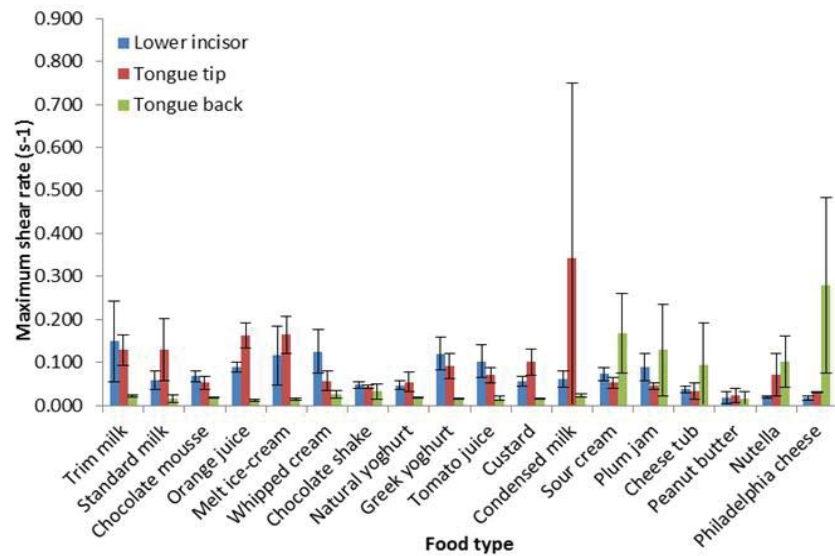


Figure 7-8b. The maximum, minimum and average shear rate during oral processing of food samples for subject 2.

Shear stress was calculated using Equation (3). Shear stress is exponentially related to shear rate, therefore, logarithmic plots were used to present all samples in the same graph clearly (Figure 7-9a and 9b). The height (h) represents the maximum displacement change in the vertical dimension (ΔZ_{\max}). The original shear stress (Appendix A8: Table 4b) shows a clear upward trend with increasing food viscosity, no matter whether the maximum, minimum or average shear stress value was used for subject 1. Subject 2 has a similar trend. Shear stress shows a clear difference in value range between thin and viscous foods. However, the logarithmic plot shows the same trend more clearly. It was clearer in the logarithmic plots that two subjects had a similar trend and same value range (Appendix A8: Table 5). For lower incisor, tongue tip and tongue back, there was no significant difference in the logarithmic shear stress for the same food sample. Some food samples do not follow the trend; for example, orange juice, chocolate shake and tomato juice are higher than the trend line; condensed milk and sour cream are lower than the trend line. This implies that other food properties affect oral shear stress, not just food viscosity. All food samples have similar trend in maximum, minimum and average value plots for both subjects.

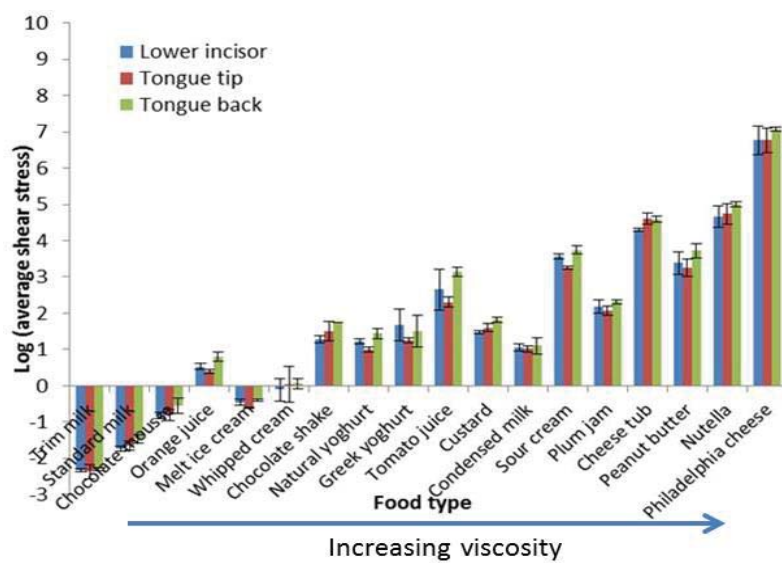
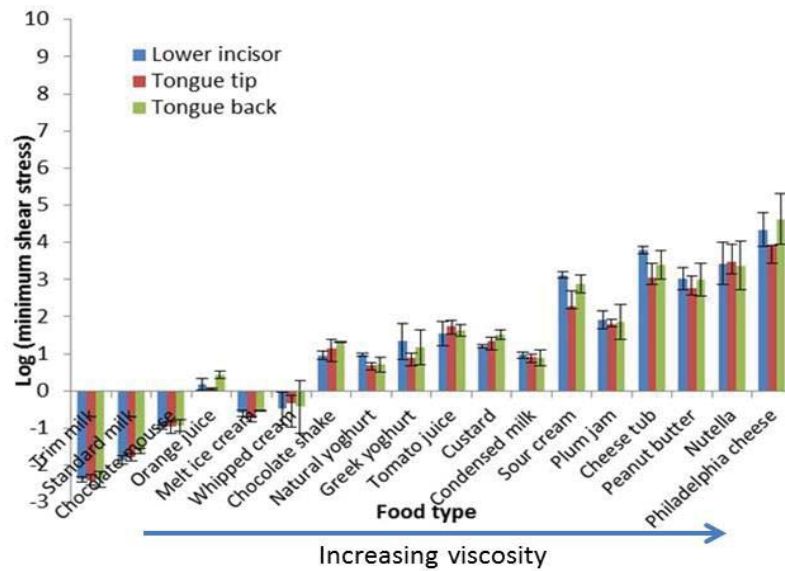
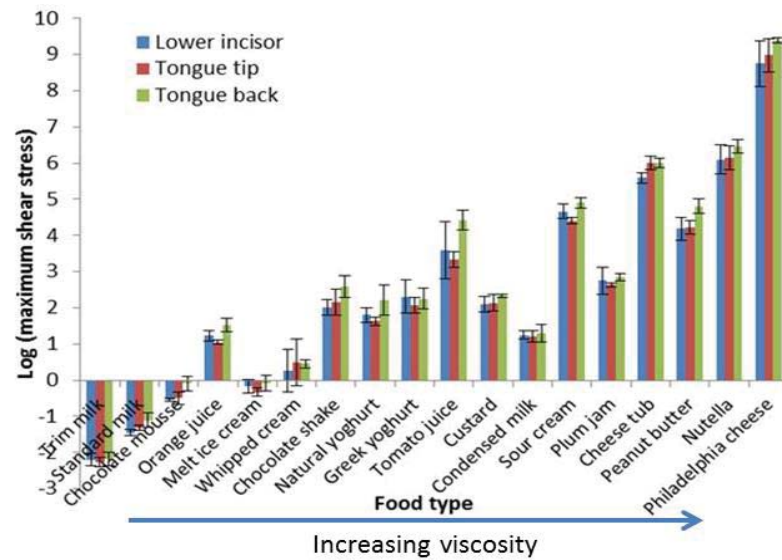


Figure 7-9a. The logarithmic value of maximum, minimum and average shear stress during oral processing of food samples (from top to bottom) for subject 1.

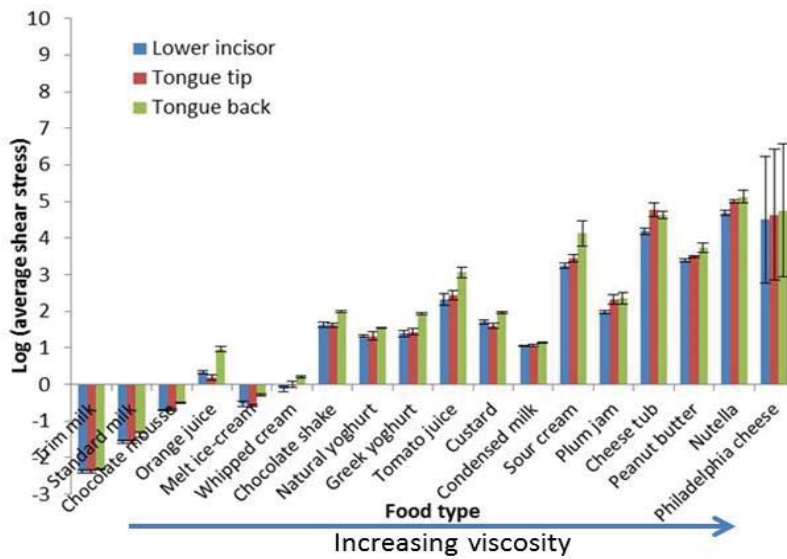
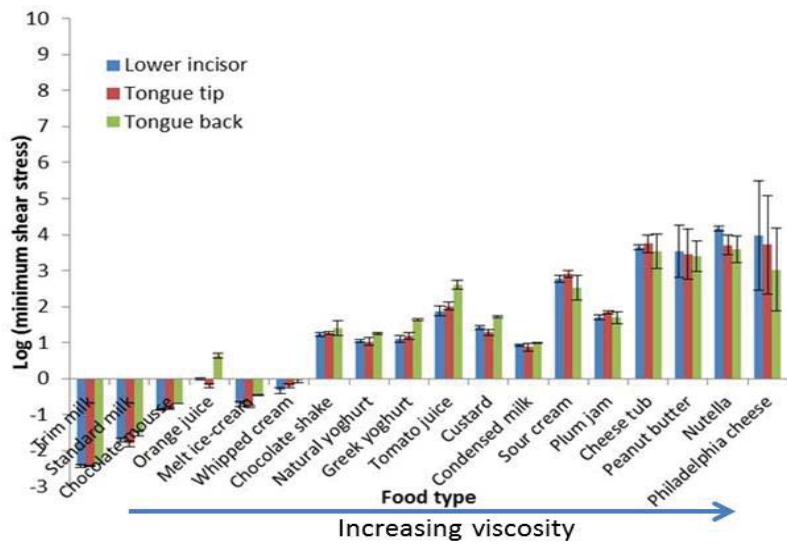
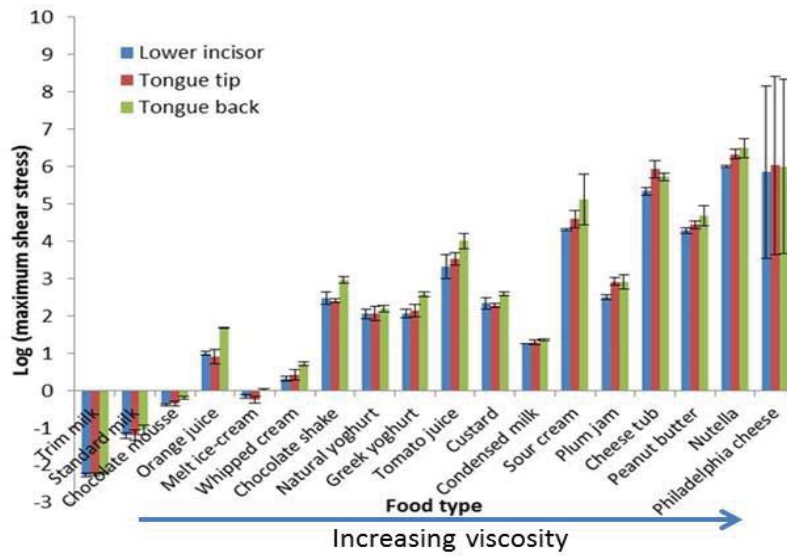


Figure 7-9b. The logarithmic value of maximum, minimum and average shear stress during oral processing for subject 2.

7.4. Discussion

7.4.1. *Dynamic parameters of tongue and lower jaw movement during oral food processing*

7.4.1.1. **Tongue and lower jaw displacement**

Ultrasound, x-ray microbeam (XRMB), magnetic resonance imaging (MRI) and articulograph (EMA) have been used by researchers over the past decade to measure tongue displacement and velocity during speech (Funatsu & Fujimoto, 2013; Goozee, Lapointe & Murdoch, 2003; Murdoch, Goozee, Theodoros & Stokes, 2000; Murdoch, Kuruvilla & Goozee, 2012) and swallowing (Cheng, Butler, Gandevia & Bilston, 2008; Gao et al., 2012; Green & Wang, 2003; Ostry & Munhall, 1985; Vazquez-Alvarez & Hewlett, 2007).

Previous EMA data showed the distance and velocity of tongue movement during speech and consumption of liquid/semi-solid. The vertical displacement of the tongue was within 20 mm, and the antero-posterior displacement was within 40 mm during the speech test; the tongue speed was 0 ~ 0.700 m/s (Dromey, Nissen, Nohr, & Fletcher, 2006). The EMA data presented in this thesis showed that the vertical displacement of the tongue tip, lower incisor and tongue back was within 60 mm, and the antero-posterior displacement was within 40 mm (both excluding cheese tub). The vertical displacement was larger than speech data, which indicates that the lower jaw opened wider and the range of tongue movement was larger in the vertical dimension during oral processing of foods. The antero-posterior displacement of the tongue was similar during speech and oral processing. The maximum displacement of the tongue tip and tongue back generally increased with food viscosity in three different dimensions. The data also showed that the lateral displacement of tongue was within 80 mm for subject 1 and within 60 mm for subject 2.

The EMA data showed that all of the maximum displacement changes (Δ_{\max} Dis) of the lower incisor, tongue tip and tongue back were within the accurate measurement range in the centre of the EMA cube. The Δ_{\max} Dis ranged from 0.82 mm (tongue tip, X-axis) during consumption of standard milk to 119.44 mm (tongue tip, Y-axis) during consumption of cheese tub. The lateral Δ_{\max} Dis was slightly higher than the

anteroposterior and vertical dimensions, especially for subject 1. Tongue tip and tongue back were much more active during consumption of high viscosity samples (Figure 7-4). It is assumed that those food samples increased the delivery time between the tongue tip and tongue back (Goldfield, Smith, Buonomo, Perez, & Larson, 2013) during the end of oral processing and swallowing.

The tongue tip Δ_{\max} Dis for subject 1 was significantly higher during consumption of cheese tub than other food samples. Individual differences might also contribute to this apparent anomaly, as the sudden increased values were apparent in all three dimensions, not only in one dimension. The tongue tip is the most flexible part of the tongue; has a large range of movements during oral processing, especially when processing high viscosity foods. Other unknown reasons for this greater activity could not be excluded. Accuracy measurement deviation can be excluded as an explanation for this result because a previous speech study, the maximum deviation ranged between 1-2 mm (Yunusova, Green & Mefferd, 2009).

The displacement of the tongue tip and back tended to decrease with decreasing food viscosity in the anteroposterior and vertical dimensions. These data indicated that food properties affected the displacement range of the tongue and lower jaw. In other words, the normal tongue movement in spatial oral processing tended to increase with increasing original food viscosity during oral processing, which was different from Steel and Van Lieshout's findings on swallowing (Steele & Van Lieshout, 2004). These new findings should be useful in choosing and designing foods for certain groups of people who cannot open the lower jaw widely, such as those with temporomandibular joint dysfunction (TMJD).

The total displacement of the tongue/lower incisor during the entire oral process data has not been reported before. The EMA data in this research showed the total displacement of the lower incisor was 95 - 1840mm, the total displacement of the tongue tip was 94 mm - 2803 mm, and the total displacement of the tongue back was 77mm - 2828 mm. The column plots (Figure 7-5) indicate that the total displacement increased with increasing food viscosity for both subjects.

EMA data were collected from two subjects in this study; it was a very small sample size for general studies. Food oral processing is a dynamic and variable process which is

affected by many factors. Therefore, a small size sample was a good choice for a detailed examination of a new method. Hasegawa et al. (2008) found that the velocity data on a specific subject was more suitable for understanding the dependence of the velocity on the thickener viscosity than those on many subjects.

7.4.1.2. Tongue and lower jaw velocity

Most previous tongue velocity data were published by speech researchers (Ostry & Munhall, 1985; Dromey, et al., 2006; Mays & Stone, 2011). There are few published studies on tongue velocity during food oral processing. Recently, Sonomura et al. (2011) investigated water swallowing and found that the swallowing velocity of water was slowed by high viscosity. The velocity of the water bolus reached its maximum when it was near the posterior of the tongue. The maximum velocity of the water bolus was approximately 0.9 m/s for 10 cc and 0.8 m/s for 5 cc. In the current study, the maximum velocity at the tongue back was 0.21 m/s (0.16, 0.15 and 0.13 m/s in antero-posterior (X), lateral (Y) and vertical (Z) dimensions) during drinking water for subject 2; for subject 1, the maximum velocity at the tongue back was 0.23 m/s (0.13, 0.16, 0.15 m/s in X, Y, and Z dimensions). The difference in findings between the two studies is understandable, because Sonomura et al. studied the velocity of the water bolus, but the current study recorded the velocity of the tongue back. Obviously, the velocity of the top layer of the water bolus is faster than the tongue surface movement. Sensor coils' position on the tongue back and individual difference may also contribute to the differences.

Hasegawa et al. (2005) reported that the averaged velocity range for water bolus have a wider distribution than that of the gel bolus, and the peak velocity reached 0.8 m/s for a water bolus of 6 cc. The wide distribution of velocity spectra is thought to induce the scattering of the bolus. Takahashi et al. (2002) measured the bolus velocities for thickeners using X-ray videofluorography. The measured bolus head velocity was 0.368 ~ 0.161 m/s for this thickener ($n = 0.49$, $K = 24$) at a pharynx.

This research showed the maximum velocity of the tongue back ($V_{\max\text{TB}}$) during consumption of 5.3g trim milk was $0.18 \pm 0.04 - 0.31 \pm 0.20$ m/s. The maximum velocity of the tongue tip ($V_{\max\text{TT}}$) was $0.17 \pm 0.01 - 0.28 \pm 0.20$ m/s; tongue tip and tongue back have similar maximum velocity (V_{\max}). The $V_{\max\text{TB}}$ of natural yoghurt was

0.21 ± 0.03 - 3.20 ± 0.40 m/s, the $V_{\max\text{TT}}$ was 0.24±0.01 ~ 0.35±0.06 m/s. The $V_{\max\text{TB}}$ of Greek yoghurt was 0.13 ± 0.02 - 0.21 ± 0.02 m/s, $V_{\max\text{TT}}$ was 0.12 ± 0.00 - 0.32 ± 0.04 m/s. The $V_{\max\text{TB}}$ value of natural yoghurt was quite close to previous studies on swallowing (Hasegawa, Ootoguro, Kumagai, & Nakazawa, 2005; Takahashi, Nitou, Tayama, Kawano, & Ogoshi, 2002). The V_{\max} value of Greek yoghurt was also similar to Rauh et al. (2012). They used a neuro-numerical approach to determine water and yoghurt velocities. Their results were 0.00 - 0.16 m/s in the frontal plane for water, and 0.00 - 0.13 m/s for yoghurt.

The results showed that the maximum velocity tended to increase with food viscosity in three dimensions for both subjects, but the average tongue velocity (V_{ave}) tended to decrease with increasing food viscosity in the vertical dimension. However, not all foods followed this trend. This trend was different from that reported by Hasegawa et al. (2005). They measured the velocity distribution of water, yogurt, jelly of gelatin and gellan during swallowing. Their data showed that the velocity distribution of the food bolus was different among different subjects, but the maximum velocity of all subjects decreased with increasing thickener concentration (Hasegawa, et al., 2005; Kumagai, Tashiro, Hasegawa, Kohyama, & Kumagai, 2009). They measured the maximum velocity of water to be about 0.5 m/s through the pharynx and that of yoghurt was about 0.2 m/s. They monitored the velocity of the food bolus during swallowing, whereas the current study recorded the tongue velocity during the whole oral residence time. This study showed the maximum velocity during consumption of water and Greek yoghurt was about 0.2 m/s and 0.17 m/s, respectively, which corresponded with Hasegawa's result. The maximum velocity also occurs during swallowing time at the tongue tip (water) or tongue back (Greek yoghurt) in this study. The data presented in this thesis was for three different dimensions and in the different dimensions, the $V_{\max\text{TB}}$ was found to be even higher during consumption of Greek yoghurt (Appendix A8: Table 3a).

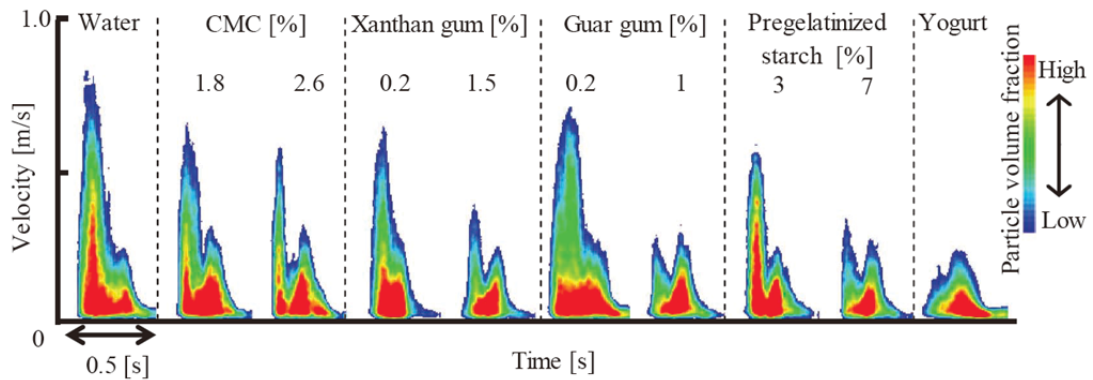


Figure 7-10. Representative colour spectra showed velocity of thickener solutions through the pharynx. The velocity spectra for water, which dysphagic patients often aspirate into their trachea, and yogurt, which they rarely aspirate, are also shown for comparison (Kumagai, et al., 2009).

The velocity of low viscosity food boluses is not equal to the tongue velocity due to the flow properties of liquids where the bottom layer of the bolus (next to the tongue surface) is equal or very close to the tongue velocity (Lamb, 1932; Batchelor, 1967) but the bolus which is further away from the tongue surface moves with a higher/lower velocity (Pomeau, 2002). For high viscosity and solid boluses, the top layer and the bottom layer of the food bolus move with a similar velocity due to higher cohesive force in food bolus; therefore, the tongue velocity is used to represent the food bolus velocity in this research; for liquid and low viscosity bolus, only the bottom layer of bolus is equal to the tongue velocity. The data presented in this thesis was the calculated tongue velocity not the food bolus velocity. This was considered to be one of the main reasons for the difference of water velocity from previous data. The higher contraction velocities of muscles and pressure gradients in the upper levels are consistent with the bolus velocities required for efficient swallowing (Kim, McCulloch, & Rim, 2000).

Tongue velocity is more important than food bolus velocity in this study, because the shear generated between tongue and food bolus is more related to the velocity of the tongue surface.

7.4.1.3. Tongue and lower jaw shear stress

The mixing and shearing by flow in the oral cavity have not been fully understood during oral processing. In the oral cavity, normal and shear forces are both applied to foods during oral processing, and complex flow profiles are generated (Chung, Olson, Degner & McClements, 2013; Le Reverend, Norton, Cox & Spyropoulos, 2010). Normal force of lower jaw and tongue is perpendicular to shear stress, which was

investigated when applied to foods using devices (Turker, Brinkworth, Abolfathi, Linke & Nazeran, 2004) or numerical models (Mathmann et al., 2007). However, shear force is hard to record using current techniques, so there are few studies on shear force between tongue/teeth and food bolus. Shear rate was investigated more than shear stress in the oral cavity in the last decades.

Shama and Sherman (1973) found that the average shear rate in the mouth was between $10 - 1,000\text{s}^{-1}$, according to the apparent viscosity of the non-Newtonian foods using indirect methods. It was hard to measure the flow *in vivo* in that era. Houska et al. (1998) found that the apparent shear rate and the equivalent viscosity of non-Newtonian food samples had a very good correlation: the higher the viscosity, the lower the shear rate. Kutter et al. (2011) used a Posthumus funnel method to mimic the liquid flow during oral processing in order to predict mouth feel properties. In this model, the shear rates were higher than estimated, as these values represented the maximum value and decreased with time. But it was similar to the liquid flow in the oral cavity, including shear flow. However, the Posthumus funnel was not designed to simulate flow in mouth, so the geometry was different from the effective area in the oral cavity. Mizunuma et al. (2004) found a correlation between viscosity (shear rate at 100 s^{-1}) and liquid bolus flow during swallowing using a 3D throat model. They stated that the relationship between the time that the bolus front moved from the middle to the hypopharynx and the viscosity of non-Newtonian fluids was approximate to that of Newtonian fluids, from 10 to 1000 mPa.s when the shear rate was 100 s^{-1} . However, Kumagai et al. (2009) reported that $10 - 30\text{ s}^{-1}$ was the best shear rate to rank viscosity in the oral cavity. Yamagata et al. (2012) investigated the best viscosity for easy swallowing for elderly people. They found that diluted solutions containing $> 2\%$ xanthan gum-based product were significantly more difficult to swallow than solutions containing $< 2\%$. They also found that the optimal shear rate was about 100 s^{-1} for sensory evaluation viscosity of these liquids. They found that when the shear rate of oral viscosity was $50 - 130\text{ s}^{-1}$ the liquid could be easily swallowed by the elderly. Young people and elderly did not tend to perceive viscosity at the same shear rate. Previous studies showed that the best shear rate varies in oral evaluation viscosity during food processing.

Shear rate is tightly linked to viscosity in oral processing. It represents the rate of shearing deformation. But the shear stress is more about force and pressure. It is useful to understand the food bolus formation and food transport during food oral processing.

Nicosia and Robbins (2001) modelled the contraction of tongue muscles as a spatially uniform pressure applied to the tongue. Rauh et al. (2012) used a hybrid neuro-numerical approach to determine water and yoghurt velocity and oral cavity wall shear stress. The wall shear stress of water was 0.39 - 100Pa, and for yoghurt was 30 - 178 Pa. The Greek yoghurt data presented in this thesis was 7.69 ± 1.46 Pa - 190.72 ± 66.74 Pa (subject 1) and 42.38 ± 2.69 Pa - 385.61 ± 50.65 Pa (subject 2), which was similar to Rauh et al. (2012). Terpstra et al. (2005) used both a decreasing-height model and constant-height model to calculate the shear stress on the tongue during oral processing of mayonnaise and custard. It was 50 - 300 Pa when the shear rate was at 30 s^{-1} for mayonnaise; and 10 - 50 Pa when the shear rate was at 1 s^{-1} for custard (values estimated from plots). This research showed the maximum shear stress of custard to be 32.88 ± 5.32 Pa (subject 1, shear rate $0.04 \pm 0.01 \text{ s}^{-1}$) and 51.37 ± 3.09 Pa (subject 2, shear rate $0.02 \pm 0.00 \text{ s}^{-1}$). The tongue shear stress had a similar range in both studies even though the shear rate was different.

The logarithmic plots (Figure 7-9) showed a significant increasing trend with growing food viscosity on both subjects. The trend was even more regular than the absolute value, which indicates that an exponential relationship may exist between tongue/teeth shear stress and food viscosity in oral processing.

7.4.2. Validity of the shear stress method

This method was somewhat similar in certain respects to Terpstra's (2005) constant-height model. When calculating shear stress, the maximum displacement of tongue movement in the vertical dimension (Z-axis) was used as a constant-height. In practice, the height in Equation (4) kept changing with tongue movement due to the deformation of liquid and semi-solid foods. However, the dynamic height continues to be difficult to determine during oral processing. Therefore, an appropriate constant-height is a practical means to calculate dynamic shear stress with real time tongue velocity. The constant-height is the only estimated parameter in this study and is based on the maximum displacement data. Results showed that the maximum shear stress of the

tongue back on the Greek yoghurt and custard bolus was similar to previously published data. This indicates the feasibility of this method. The results also showed that the real time velocity and shear on foods can be derived from the tongue upper surface. The velocity and shear of tongue upper surface may not present the real time velocity of top layer of thin semi-solids or liquids, but it can represent the real time velocity of the bottom layer of these foods (the layer that contacts with the upper tongue surface). Therefore, the data should be more reliable than a purely mathematical model.

The greatest strength of this method is the collection of dynamic data. The dynamic data is not presented in the current study due to the huge volume of data. However, this is a practical way to reproduce sensor coils movement in the oral cavity.

7.4.3. Application of oral shear stress measurements

Shear stress comes from the force vector component parallel to the cross section, so shear stress exists between two materials which are in contact. In the oral cavity, shear stress is generated between the tongue and food material, teeth and food, palate and food, oral wall and food during oral processing. Among them, the former two are the main source of shear stress. Because of the anatomy of the oral cavity and the oral motor pattern, teeth and food generate more normal force than shear stress. However, the tongue and food mainly generate shear stress, especially during food transport and mixing phases. This kind of force parallels the contact surface (tongue, palate and/or oral wall), assists with food fragmentation and mashes or pushes food into the pharynx. Therefore, shear stress is believed to be the main source of power to move food into the pharynx in this study. Shear stress also plays an important role in swallowing, alongside oral pressure.

Shear stress measurement in the oral cavity has attracted researchers attention recently, because: 1) Shear stress is one of the power sources in oral movement; 2) it is involved in the transportation, fragmentation, mixing and swallowing phases in the oral process; 3) shear stress dynamically changes with the changing food bolus, and vice versa. Therefore, shear stress is another way to investigate oral processing of various foods by different groups of people. At the same time, the shear stress information may be useful for designing appropriate foods or devices for special groups of people (*e.g.* people with temporomandibular joint dysfunction, or dysphagia, or people who wear dentures).

7.5. Conclusions

This chapter elaborated the potential relationship between the velocity of tongue and lower jaw and food viscosity, and the shear stress of the tongue and lower jaw and food viscosity for two subjects. The maximum velocity of the tongue and lower jaw tended to increase with increasing food viscosity in three dimensions. For subject 2, the maximum velocity of the tongue and lower jaw increased before the viscosity reached a certain point, then decreased. The average velocity of the tongue and lower jaw tended to decrease in the vertical dimension with increasing food viscosity. The shear stress between the tongue and lower jaw and food samples tended to increase with increasing food viscosity, whether the (maximum, minimum or average) shear stress was, it is very likely that they have an exponential relationship.

For test samples, the maximum total displacement of the tongue tip, tongue back and lower incisor occurred while consuming Nutella, tongue tip: 2580.11 ± 957.63 mm (subject 1) or 1459.27 ± 235.82 mm (subject 2); tongue back: 2828.55 ± 395.33 mm (subject 1) or 1371.53 ± 295.23 mm (subject 2); lower incisor: 2284.41 ± 139.94 mm (subject 1) or 926.75 ± 152.74 mm (subject 2). The minimum total displacement of the tongue tip, tongue back and lower incisor occurred while consuming melt ice-cream (subject 1) or orange juice (subject 2), tongue tip: 85.91 ± 9.50 mm or 94.24 ± 7.21 mm; tongue back: 86.33 ± 12.82 mm or 77.63 ± 5.44 mm; lower incisor: 89.88 ± 16.04 mm or 83.18 ± 9.08 mm (Appendices A8: Table 2). This demonstrates that the viscous food moved a longer distance than thin food.

The maximum velocity of tongue tip in antero-posterior (X) dimension was 0.09 ± 0.01 m/s - 17.54 ± 20.79 m/s (subject 1) or 0.07 ± 0.01 m/s - 1.15 ± 1.31 m/s (subject 2); it was 0.08 ± 0.01 - 14.07 ± 8.35 m/s or 0.1 ± 0.01 m/s - 4.72 ± 6.38 m/s in lateral dimension (Y); it was 0.08 ± 0.02 m/s - 19.23 ± 17.68 m/s or 0.09 ± 0.01 m/s - 2.32 ± 3.08 m/s in vertical dimension (Z). The maximum velocity of tongue back in X dimension was 0.10 ± 0.01 m/s - 4.78 ± 7.38 m/s or 0.07 ± 0.01 m/s - 2.57 ± 3.37 m/s; it was 0.07 ± 0.02 m/s - 10.99 ± 7.63 m/s or 0.08 ± 0.02 m/s - 1.58 ± 1.88 m/s in Y dimension; it was 0.08 ± 0.02 m/s - 15.06 ± 13.14 m/s or 0.10 ± 0.01 m/s - 4.3 ± 5.83 m/s in Z dimension. The maximum velocity of lower incisor in X dimension was 0.08 ± 0.02 - 8.55 ± 7.38 m/s or 0.09 ± 0.01 - 0.21 ± 0.06 m/s; it was 0.06 ± 0.02 - 13.53 ± 9.53 m/s or 0.10 ± 0.01 - 0.14 ± 0.04 m/s in Y axis; it was 0.10 ± 0.02 - 19.27 ± 17.67 m/s or 0.04 ± 0.00 - 0.19 ± 0.07

m/s in Z dimension (Appendices A8: Table 3a). The velocity range between two subjects was large.

The maximum shear stress of the tongue tip, tongue back and lower incisor was $0.01 \pm 0 - 2225354.37 \pm 611158.43$ Pa, $0.01 \pm 0 - 3798052.88 \pm 2372357.87$ Pa, $0.01 \pm 0 - 1704864.18 \pm 1080193.08$ Pa; The minimum shear stress of the tongue tip, tongue back and lower incisor was $0.00 \pm 0.00 - 6153.21 \pm 3007.72$ Pa, $0.00 \pm 0.00 - 5793.5 \pm 5122.92$ Pa, $0.00 \pm 0.00 - 14866.17 \pm 2669.25$ Pa; The average shear stress of the tongue tip, tongue back and lower incisor was $0.00 \pm 0.00 - 102341.87 \pm 8279.21$ Pa, $0.00 \pm 0.00 - 146520.4 \pm 55778.73$ Pa, $0.00 \pm 0.00 - 49781.98 \pm 8862.6$ Pa (Appendices A8: Table 4b). Data showed that the shear stress of processing viscous food was extremely large in the oral cavity, but there was minimal shear stress during the oral processing of liquids.

The shear results in this thesis are believed to be closer to reality than mathematical modelling methods. At the same time, the oral movement data also was obtained. These results will help further understanding of oral processing mechanisms and changing food properties during oral processing.

Chapter 8: Conclusions and recommendations

8.1. Conclusions

A series of studies have been completed for liquid, semi-solid and soft-solid foods to investigate relationships between food properties and oral processing behaviour. The shear stress and shear rate in the oral cavity and tongue movement have also been studied during oral processing of food samples.

A method for accurately recording oral residence time (ORT) during the oral processing of liquid, semi-solid and soft-solid foods was developed. EMA and EMG were both able to measure ORT correctly, with the former tracking the tongue and lower jaw movements dynamically, and the latter recording muscle activities.

The results showed that the original food properties, such as rheological properties, stretch-ability, moisture content and pH, affect oral processing behaviours. For example, the shear stress applied by the tongue and lower jaw tends to increase with increasing viscosity. Oral processing behaviours also affect final food bolus properties at the swallowing point. The expectorated bolus moisture content correlates with the rheological properties of the original food, however for the foods tested, pH was shown to have little effect on the expectorated bolus moisture content.

Chapter 7 focused on investigating shear stress and shear rate. The maximum shear stresses in the oral cavity during consumption of different food samples were presented and compared with previous research.

Various tongue behaviours dominate oral processing of semi-solid and soft-solid foods. Shear stress between the tongue and lower jaw, the tongue and the palate, the tongue and the wall of the oral cavity is the main power source during oral processing of semi-solid and soft-solid foods; because the dynamic velocity and shear stress are extremely large for viscous food samples, but minimal for thin liquids in the oral cavity.

8.2. Recommendations for future study

A more comprehensive understanding of tongue behaviour during oral processing of semi-solid and soft-solid foods is required. Basic patterns of the tongue movement during oral processing of different foods need to be established in future research. The shear stress between the tongue (different parts) and palate (or teeth, or other oral surfaces) needs to be calculated, as this is an essential factor of the dynamic breakdown of food structure. Therefore, more subjects' data are required to extend and develop these data presented in this thesis.

Above all, the tongue movement and the dynamic shear stress of tongue in oral cavity are the key aspects during oral processing of semi-solid and soft-solid foods. A comprehensive understanding of these would provide opportunities to fully understand the oral processing mechanism and swallowing threshold triggers.

It would be meaningful to measure the rheological and tribological parameters, cohesion and adhesion, and sensory perception of semi-solid and soft-solid foods. Such work has the potential to provide information on how bolus changes and the concurrent sensory experiences of semi-solid and soft-solid foods during oral processing assist in determining swallowing threshold triggers.

Sensory perception plays an important role in oral processing. However, the relationships between sensory perception and oral processing behaviour of semi-solid and soft-solid foods have not been fully understood. Dynamic sensory perception information is useful to connect the feedback regulation of the central nervous system to oral processing behaviour.

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Appendices

A1: Primary questionnaire

Primary Questionnaire

All information you provide will be treated as confidential.
May I keep your details on file for future studies, if for some reason you are unable to participate in this one? Yes/No

Personal Details

Name:
Date of Birth (day/ mth/ yr):
Gender:

Contact Details

Address:
.....
Telephone: Home: Mobile:
Email:

Availability

Please indicate all availability by circling times below. (You will only be required to attend about one hour per day.)

Monday	Tuesday	Wednesday	Thursday	Friday
9-10am	9-10am	9-10am	9-10am	9-10am
10-11am	10-11am	10-11am	10-11am	10-11am
11-12noon	11-12noon	11-12noon	11-12noon	11-12noon
12-1pm	12-1pm	12-1pm	12-1pm	12-1pm
1-2pm	1-2pm	1-2pm	1-2pm	1-2pm
2-3pm	2-3pm	2-3pm	2-3pm	2-3pm
3-4pm	3-4pm	3-4pm	3-4pm	3-4pm
4-5pm	4-5pm	4-5pm	4-5pm	4-5pm

Any time when you are unavailable due to holidays/work/exams:

General Health

Please circle the appropriate answer to the following questions, and add any details where necessary.

Please describe your overall general health.

.....

Are you taking any medication which affects muscle function or saliva flow? YES NO

Do you have allergies of any kind? YES NO
If yes, please detail

Oral Health and Habits

Please circle the appropriate answer to the following questions, and add any details where necessary.

Do you wear dentures or have any prosthetic teeth? YES NO

Do you have any milk teeth (baby teeth)? YES NO

Do you have any knowledge of you having caries or gum disease? YES NO

Do you have any teeth missing or loose? YES NO
How many? Tooth type? MOLAR INCISOR

Have you had any major dental work carried out in the last six months? YES NO

Do you feel any pain when eating foods? YES NO

Are there any foods you have difficulty chewing? YES NO

Do you chew chewing gum? YES NO
How often?

Do you generally chew on one side of the mouth? YES NO
If yes, which side? RIGHT LEFT
Are you right or left handed when writing? RIGHT LEFT

Do you grind your teeth? YES NO

Do you have the history of clicking or discomfort in jaw when it moves? YES NO

Do you have the history of restriction in jaw Movement? YES NO

Do you have a history of dysphonia (speech problem) or dysphagia (swallowing impaired)? YES NO

Have you had dental/oral ulcer in the last one Month?	YES	NO
Have you had any tongue problem which may restrict tongue movement in the last three months?	YES	NO
Have you had any disease or accident that may affect swallowing in the last six months?	YES	NO

Food to be Investigated

The following foods may be presented to you at different times over the sessions. Please indicate in the boxes provided if you are willing /able to eat these foods, and if you have any known allergies to ingredients in the foods. (A complete list of ingredients of each food will be given to you before you undertake the study.)

Food type	Allergies	Willing to consume
Water		
Tea		
Skim milk		
Full-fat milk		
Original yoghurt		
Cold coffee		
Orange juice		
Tomato juice		
Orange juice with fruit particles		
Liquid honey		
Soft cheese (Brie)		
Mashed potato		
Sponge cake		
Whipped cream		
Shakes		
Semi-solid honey		
Melted ice-cream		
Yoghurt with small fruit particles		
Smooth peanut butter		
Fruit jam (no particles)		
Fruit jam with fruit particles		
Cheese (feta)		
Mayonnaise		
Butter		
Jelly without fruit particles		
Custard		
White sauce		

Comments:

A2: The EMG traces of subject B

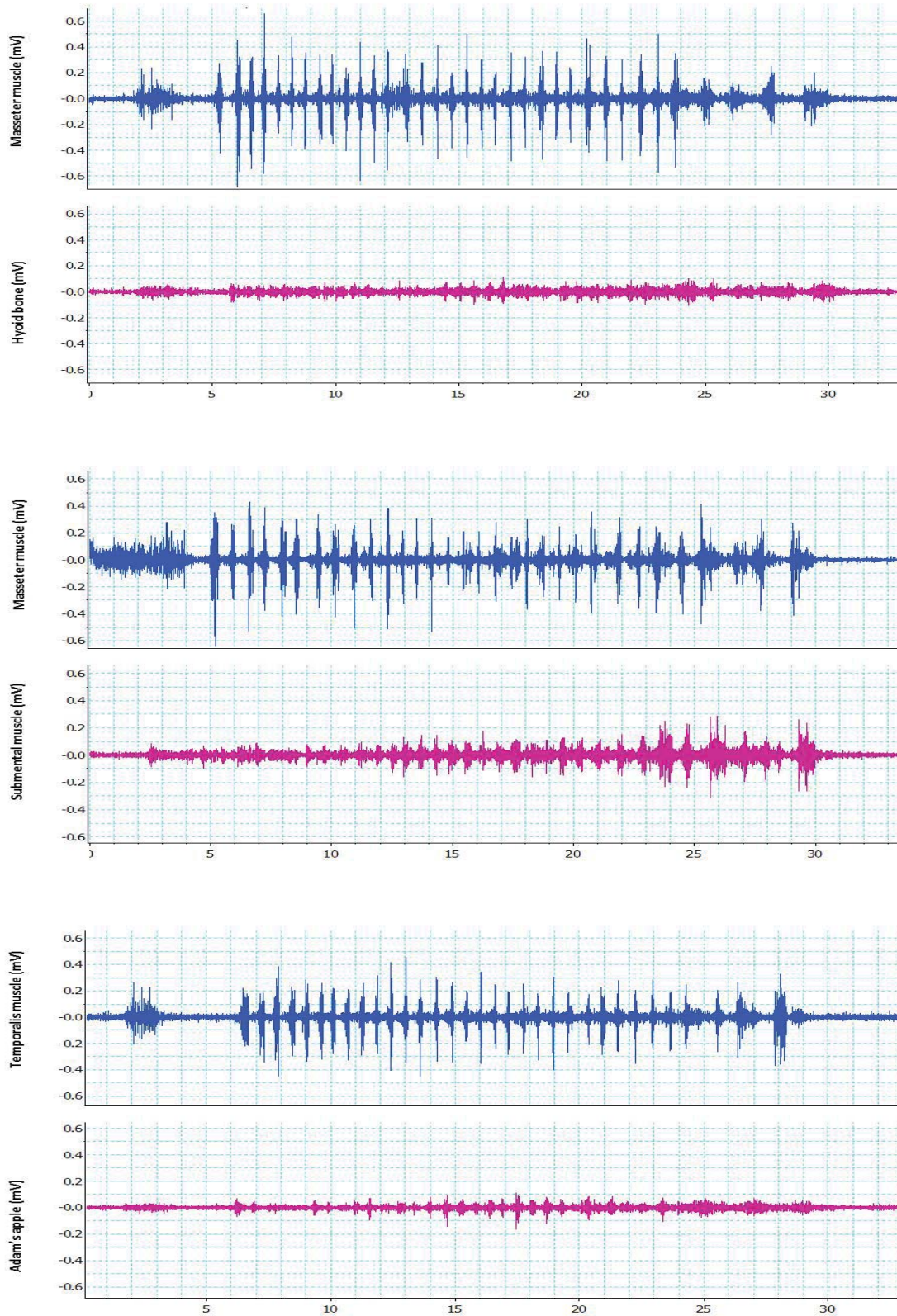


Figure A2-1. The EMG traces of right masseter, submental muscle, temporalis, hyoid bone, and Adam's apple during consumption of 1 cashew nut for subject B in 3 sessions.

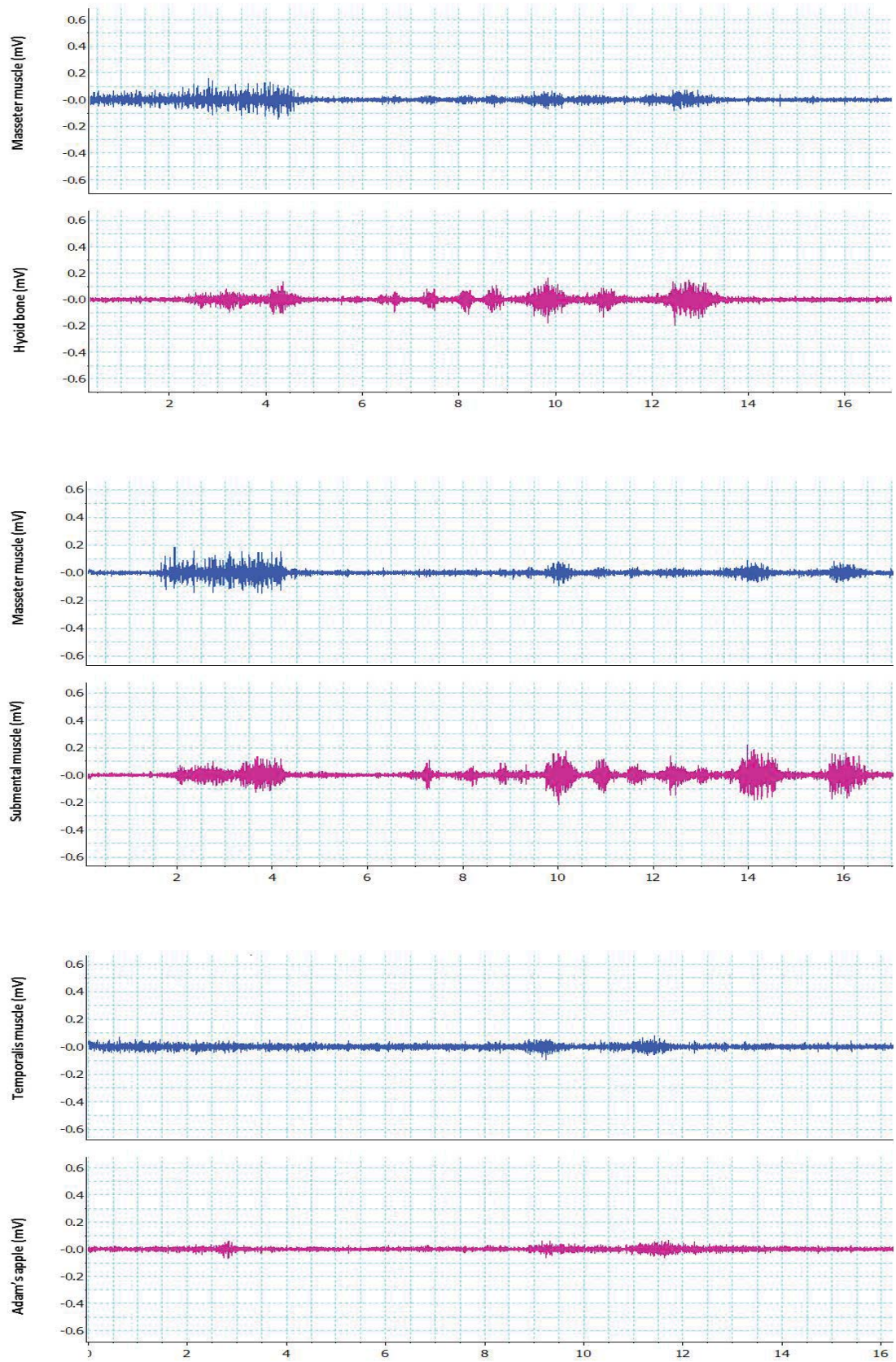


Figure A2-2. The EMG traces of right masseter, submental muscle, temporalis, hyoid bone, and Adam's apple during consumption of Greek yoghurt for subject B in 3 sessions.

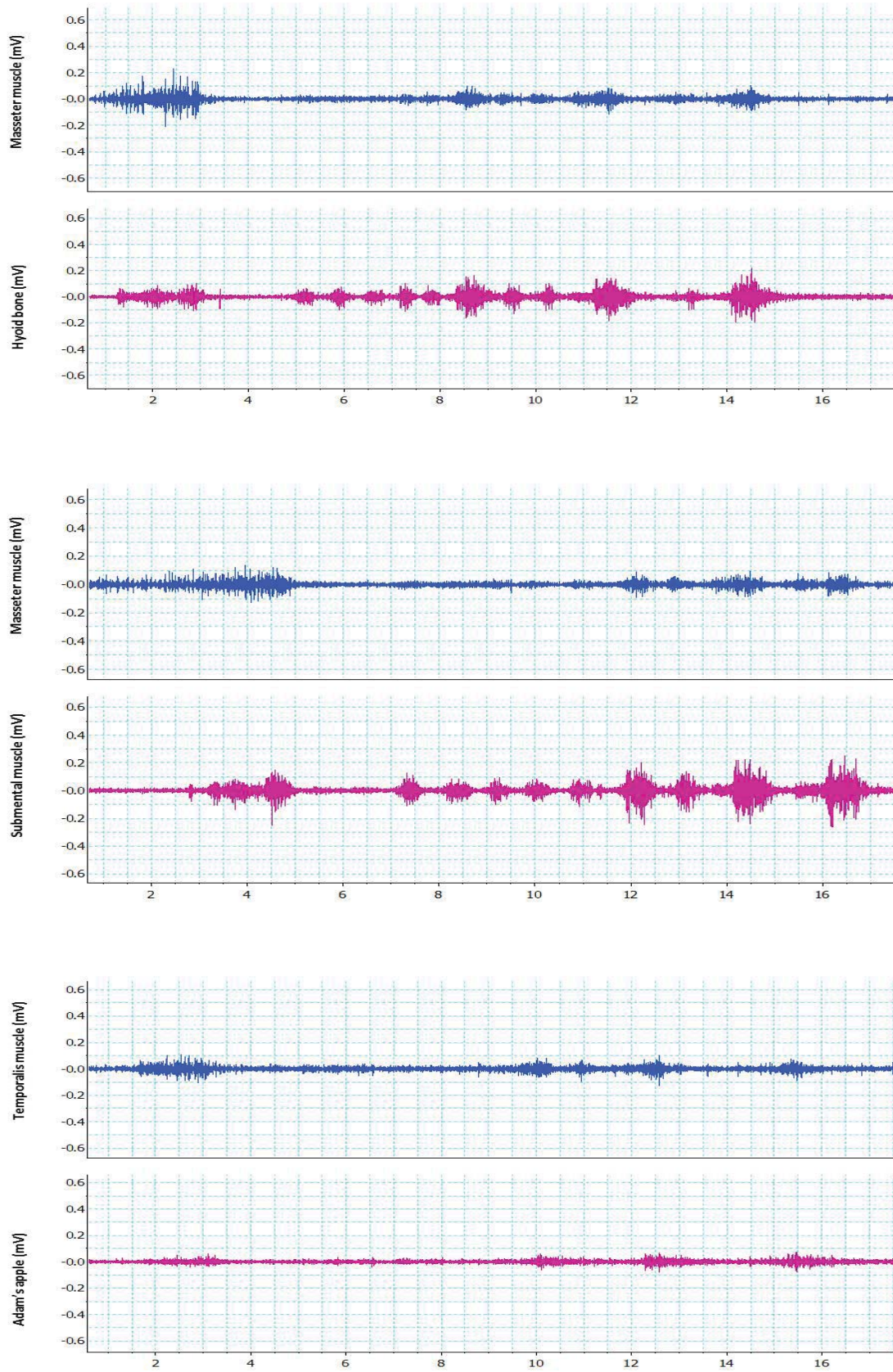


Figure A2-3. The EMG traces of right masseter, submental muscle, temporalis, hyoid bone, and Adam's apple during consumption of plum jam for subject B in 3 sessions.

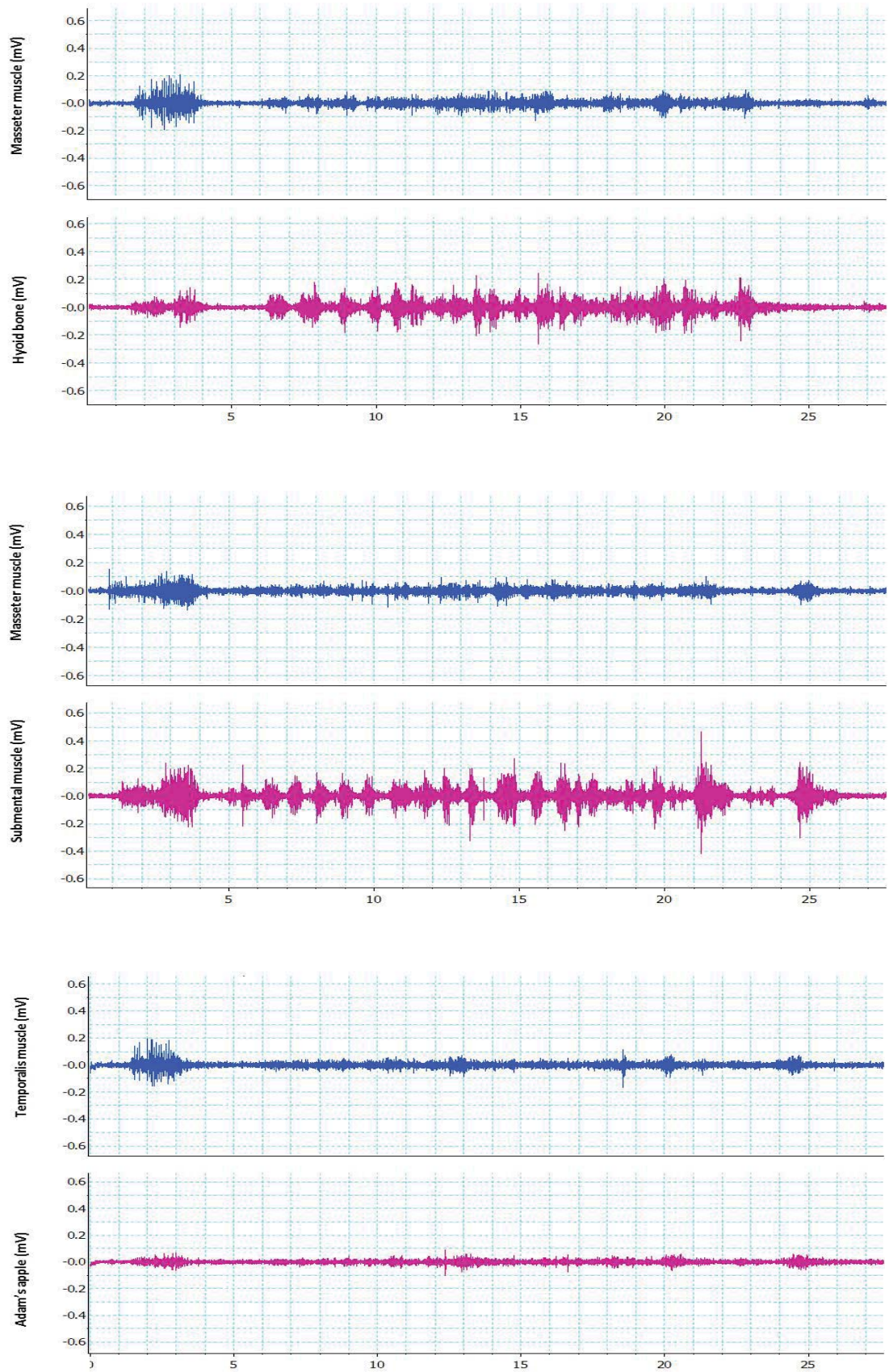


Figure A2-4. The EMG traces of right masseter, submental muscle, temporalis, hyoid bone, and Adam's apple during consumption of Nutella for subject B in 3 sessions.

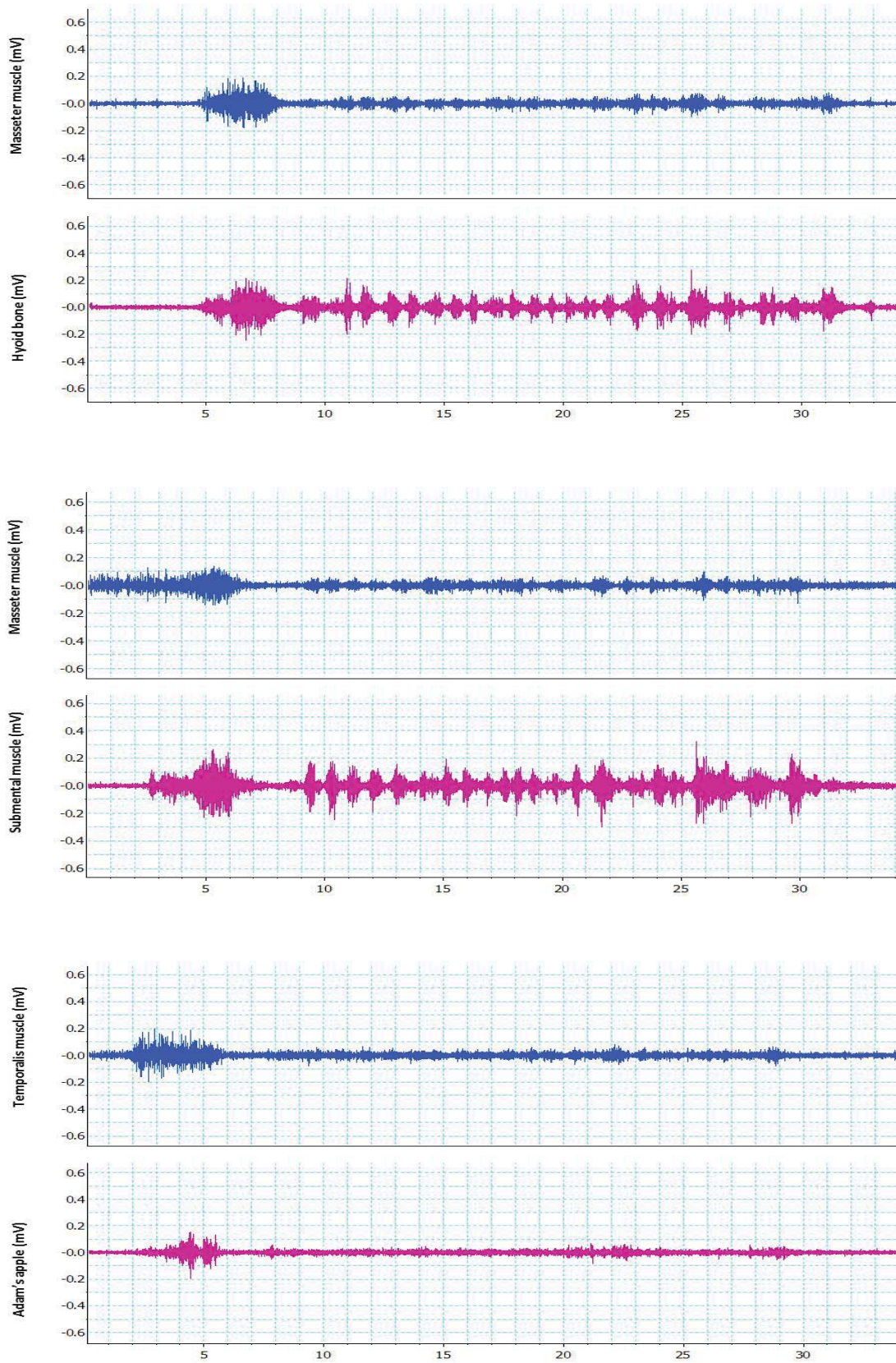


Figure A2-5. The EMG traces of right masseter, submental muscle, temporalis, hyoid bone, and Adam's apple during consumption of cream cheese for subject B in 3 sessions.

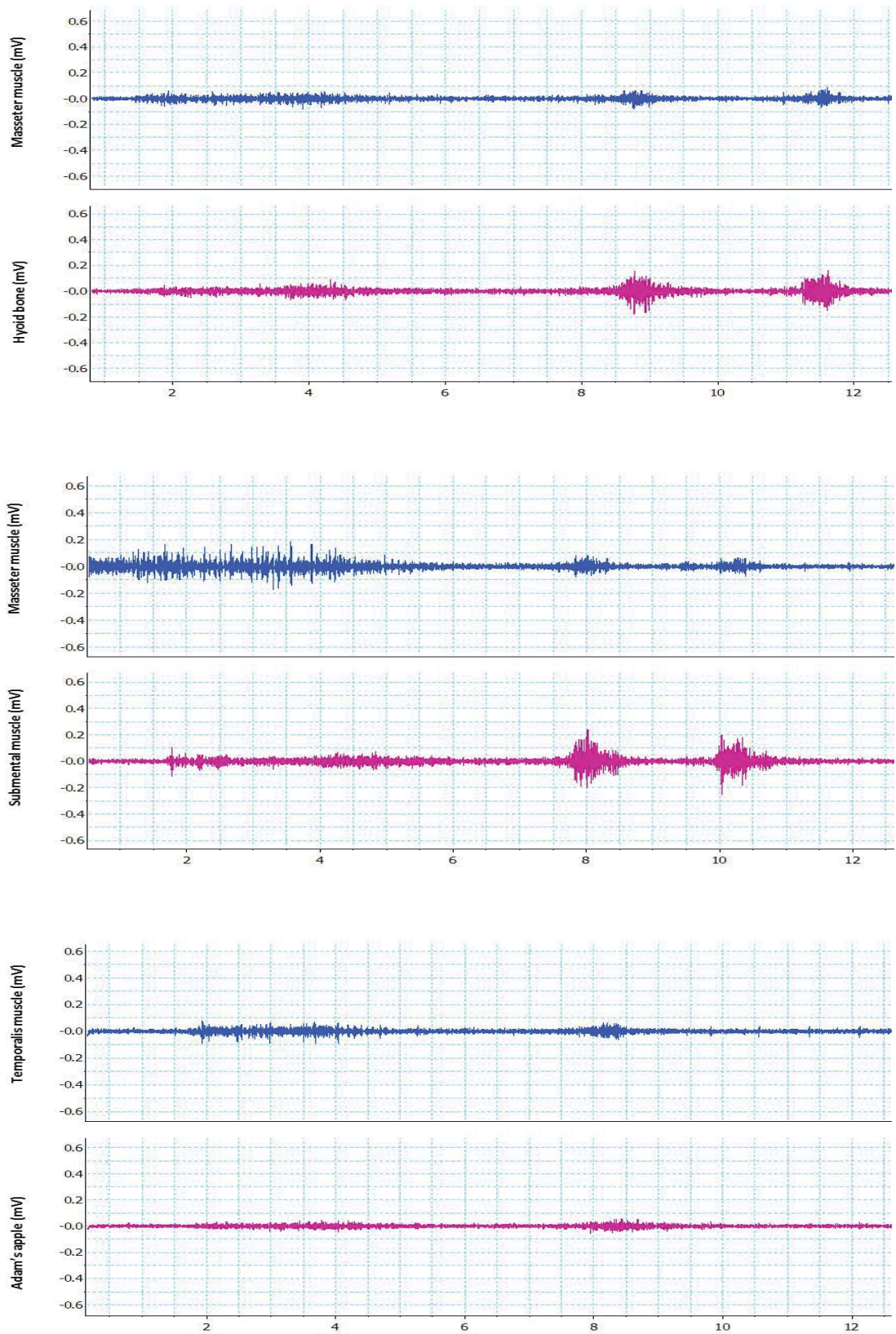
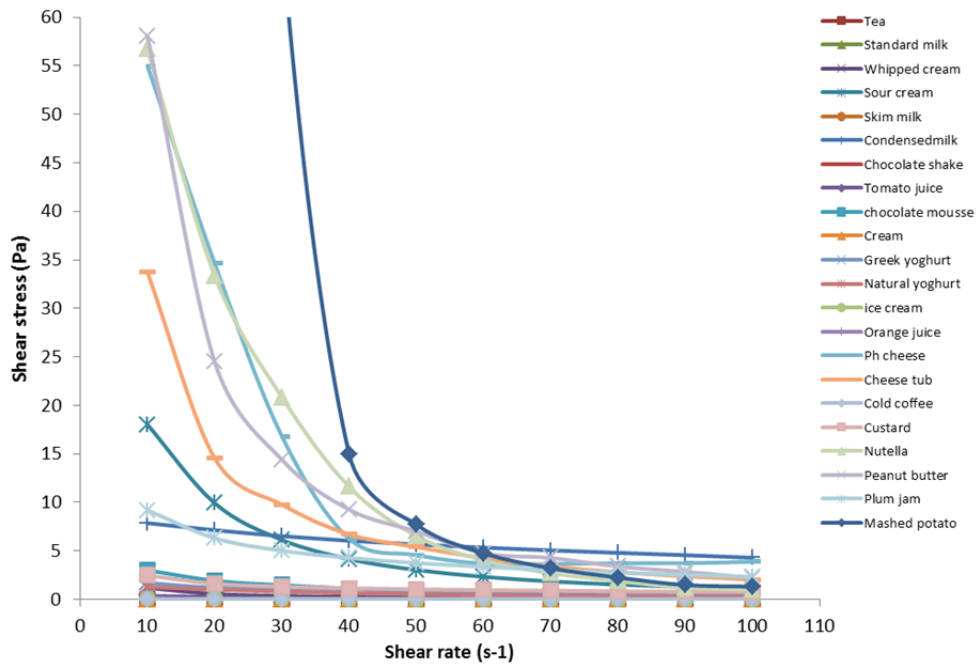
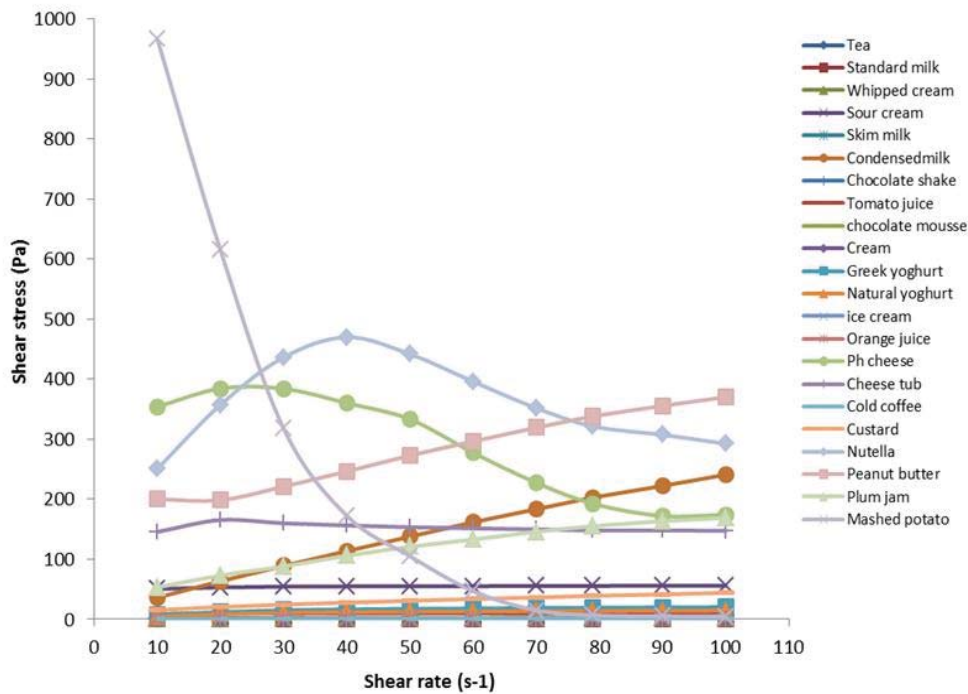


Figure A2-6. The EMG traces of right masseter, submental muscle, temporalis, hyoid bone, and Adam's apple during consumption of standard milk for subject B in 3 sessions.

A3: Shear stress – shear rate plots at 20 °C

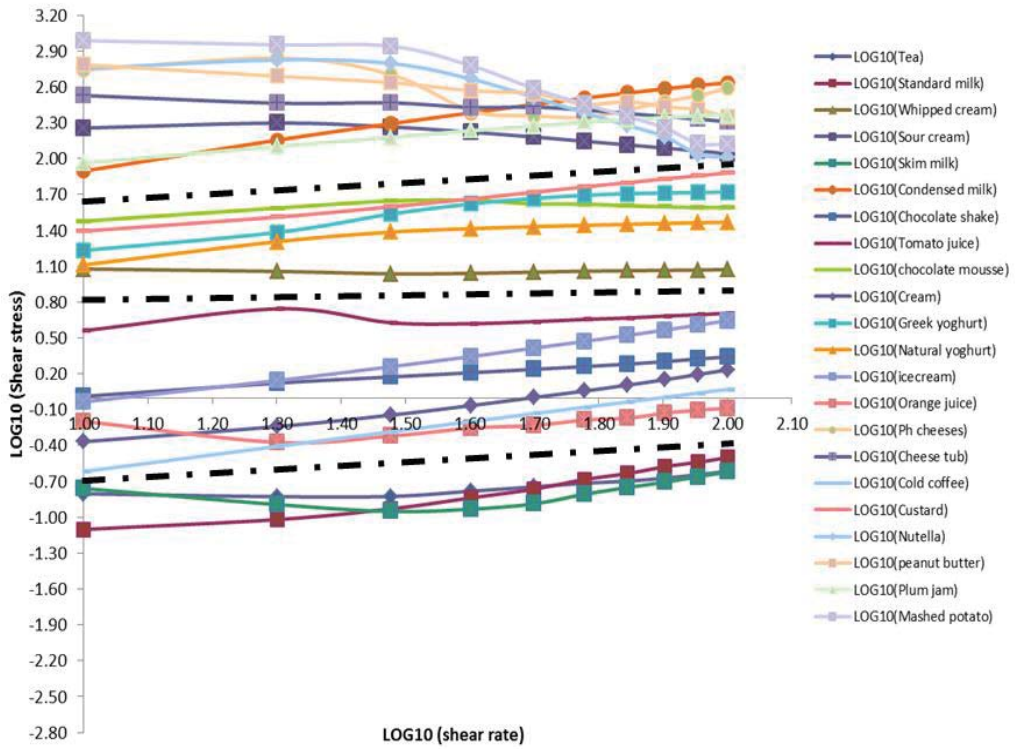


A4: Shear stress – shear rate plots at 37 °C

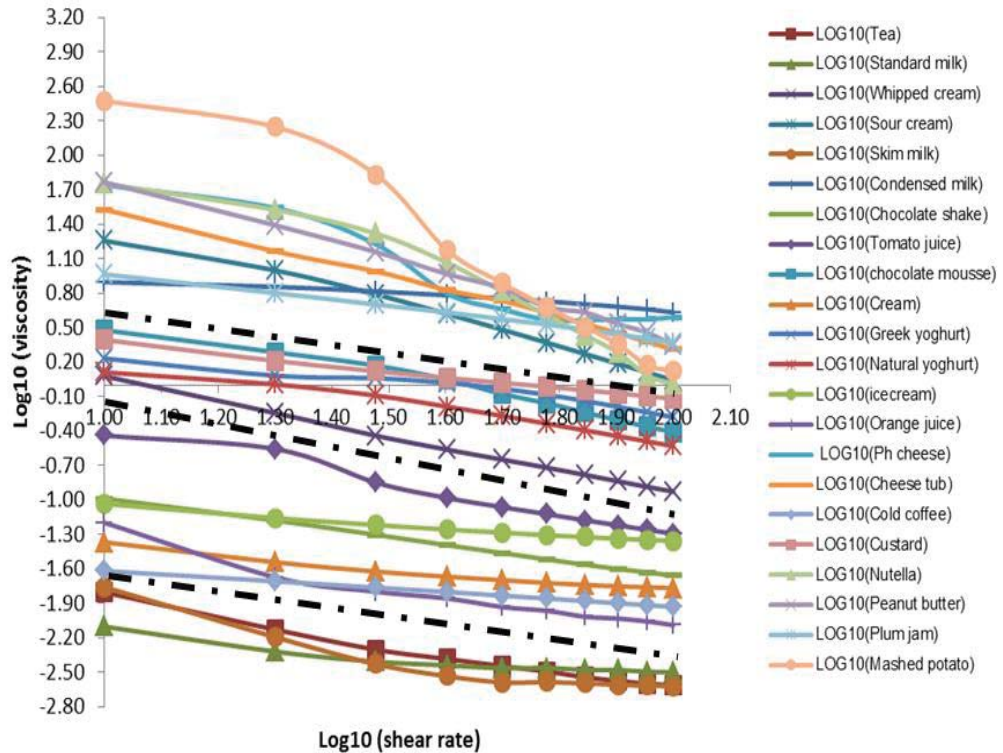


Note: The flow curves of some test foods are not very smooth because of low viscosity (breakfast tea) or fruit particles suspended in fluids (orange juice and tomato juice).

A5: Shear stress – shear rate logarithmic plots at 20 °C



A6: Viscosity – shear rate logarithmic plots at 20 °C



A7: Expecterated food bolus images of subjects

Subject 4



Subject 5



Subject 6



Subject 7



Subject 8




A8: Summary of data used in Chapter 7

Table 1. Maximum displacement change ($\Delta_{max} Dis$) of tongue tip, tongue back and lower incisor in three dimensions (mean \pm SD)

Samples	Sub	Δ_{max} displacement of lower incisor (mm)			Δ_{max} displacement of tongue tip (mm)			Δ_{max} displacement of tongue back (mm)		
		Antero-postior	lateral	vertical	Antero-postior	lateral	vertical	Antero-postior	lateral	vertical
Trim milk	1	3.25±0.5	2.35±0.46	4.31±0.63	2.36±1.01	1.71±0.24	2.43±0.96	5.42±0.63	4.51±1.37	7.32±1.02
	2	2.54±1.52	2.19±0.77	2.13±1.36	5.42±5.71	3.26±3.18	2.92±2.79	6.97±4.16	3.64±1.1	8.36±2.39
Standard milk	1	1.23±0.12	1.3±0.05	1.16±0.19	0.82±0.1	1.29±0.06	1.91±0.42	5.03±0.53	4.64±1.05	8.66±1.6
	2	2.18±0.58	1.75±0.48	2.57±0.7	3.01±2.15	4.61±4.59	4.43±3.39	4.02±0.76	3.68±0.38	11.8±5.29
Chocolate mousse	1	1.7±0.29	1.7±0.59	1.51±0.72	2.7±1.28	1.36±0.3	2.03±1.13	28.04±9.45	19.61±5.42	34.15±19.26
	2	4.27±0.63	3.39±1.29	3.66±0.64	1.67±0.05	2.79±0.87	3.04±0.87	5.97±1.04	5.2±0.68	13.8±1.55
Orange juice	1	2.67±0.79	1.54±0.33	3.87±0.91	1.22±0.09	1.61±0.49	2.38±0.39	5.02±1.28	2.77±0.47	8.64±2.86
	2	1.26±0.09	0.86±0.14	1.51±0.27	1.12±0.31	0.98±0.17	1.05±0.22	3.43±0.75	2.79±1.26	10.3±2.51
Melt ice-cream	1	2.9±0.34	1.48±0.31	3.77±0.62	1.52±0.17	1.65±0.16	1.16±0.05	3.46±0.4	2.34±0.21	5.67±0.72
	2	3.04±0.03	2.05±0.66	2.27±0.74	2.03±1.07	2.66±1.56	1.83±1.19	5.04±1.78	4.09±1.63	11.82±2.47
Whipped cream	1	5.83±6.25	15.13±18.75	3.82±3.23	12.44±13.76	9.21±8.25	19.69±24.06	13.02±3.69	20.94±9.16	9.48±0.98
	2	3.5±1.29	2.64±0.41	1.77±0.61	2.46±0.83	3.56±0.52	3.69±1.75	9.48±6	6.58±1.83	11.35±1.71
Chocolate shake	1	1.34±0.16	1.92±0.39	1.7±0.4	2.14±1.52	12.66±15.43	6.29±6.18	4.42±0.27	4.97±0.25	7.31±0.34
	2	3.97±1.72	3.11±1.16	5.03±0.71	3.25±2.26	2.88±1.39	3.7±0.88	6.7±3.3	6.48±1.7	12.18±0.99
Natural yoghurt	1	3.13±0.97	2.44±1.46	3.05±1.15	2.92±1.15	1.6±1.02	1.67±0.36	16.43±2.17	15.99±6.95	18.74±9.04
	2	2±0.49	1.2±0.21	4.07±0.62	5.09±3.18	2.53±0.81	5.53±2.57	7.4±2.67	7.6±2.32	11.59±2.1
Greek yoghurt	1	10.19±4.89	7.98±3.93	3.39±0.87	2.73±0.52	1.59±0.05	1.8±0.49	9.05±0.87	2.48±0.31	9.74±1.23
	2	2.46±0.78	1.6±0.35	1.18±0.4	1.89±0.43	2.21±0.81	1.48±0.51	4.88±0.71	6.3±0.94	8.78±1.35
Tomato juice	1	2.78±1.3	40.74±51.02	15.93±18.67	3.3±1.12	0.95±0.27	2.76±1.26	34.08±28.1	22.97±9.08	42.72±29.12
	2	1.6±0.35	1.08±0.37	1.38±0.42	1.27±0.53	1.61±0.27	1.98±0.69	4.26±1.23	3.77±1.05	8.26±3.06
Custard	1	1.36±0.13	2.06±0.68	1.53±0.17	1.31±0.44	1.99±0.5	2.53±0.8	8.6±0.14	9.2±0.65	7.21±0.89
	2	2.19±0.18	1.69±0.42	3.35±0.71	2.77±0.41	2.58±1.03	2.79±0.66	7.78±0.38	7.28±2.56	10.77±1.3
Condense milk	1	3.56±0.3	3.65±0.4	4.99±1.05	2.49±0.77	6.16±3.89	3.72±1.08	12.42±2.68	9.83±2.34	13.03±6.13
	2	4.75±0.95	3.2±1.57	5.06±0.91	12.7±10.82	39.23±49.3	8.66±4.73	12.87±0.48	9.58±1.48	13.89±2.73
Sour cream	1	4.56±0.48	2.53±0.28	5.85±1.02	10.01±6.24	26.49±17.03	4.25±0.78	10.71±1.77	6.29±1.8	10.45±3.91
	2	2.3±1.26	2.17±1.33	2±0.31	3.89±0.23	5.72±2.24	3.84±0.49	18.29±8.28	54.51±32.26	50.9±32.61
Plum jam	1	3.37±0.38	5.1±1.9	6.96±3	4.72±1.07	5.67±1.36	5.05±0.92	19.23±6.81	28.56±9.38	15.47±2.64
	2	2.67±0.36	1.35±0.24	1.96±0.43	8.12±4.06	17.79±12.28	17.2±12.03	12.74±6.44	40.52±27.83	29.12±25.58
Cheese tub	1	8.29±1.23	10.21±1.9	12.02±2.41	116.28±87.35	119.44±44.51	71.99±33.26	34.99±3.77	44.05±16.55	24.88±2.22
	2	3.51±0.65	3.91±1.63	5.32±1.48	25.34±14.08	34.28±8.63	27.56±15.56	19.59±3.68	10.2±0.58	21.73±7.37
Peanut butter	1	8.36±0.96	4.46±1.52	8.86±5.23	11.14±3.26	12.43±8.04	7.35±3.58	30.82±14.8	17.72±5.27	32.06±14.06
	2	5.23±1.75	4.5±2.27	6.15±0.38	15.81±4.84	18.87±4.09	10.67±0.47	31.03±16.68	26.04±16.51	30.14±18.99
Nutella	1	7.99±2.52	10.38±3.85	10.6±3.64	11.89±0.45	22.19±4.06	16.03±7.12	40.31±15.2	51.05±32.02	31.74±11.67
	2	5.2±0.77	7.31±3.8	9.02±1.44	20.29±3.06	23.64±9.18	30.03±2.92	42.46±25.3	34.71±20.32	41.06±16.64
Philadelphia cheese	1	29.63±21.15	50.72±54.3	40.02±40.44	33.49±18.74	76.35±69.43	45.58±41.86	35.73±6.69	61.6±40.18	53.91±33.81
	2	5.29±0.28	4.39±0.25	11.07±2.2	25.1±1.99	32.68±1.32	23.97±4.5	24.58±5.3	26.67±1.31	25.82±2.65

Table 2. The total displacement of tongue tip, tongue back and lower incisor during oral residence time (mean \pm SD)



Samples	Sub.	Total displacement (mm)		
		Lower incisor	Tongue tip	Tongue back
Trim milk	1	149.4 \pm 31.67	150.37 \pm 14.43	153.67 \pm 9.7
	2	216.48 \pm 69.18	190.91 \pm 67.47	192.43 \pm 51.93
Standard milk	1	130.42 \pm 10.47	120.11 \pm 6.73	135.73 \pm 12.07
	2	96.87 \pm 11.29	152.05 \pm 48.23	97.98 \pm 17.2
Chocolate mousse	1	206.75 \pm 100.25	218.78 \pm 90.01	498.43 \pm 57.68
	2	213.53 \pm 25.36	163.75 \pm 43.42	179.13 \pm 25.93
Orange juice	1	99.43 \pm 23.67	95.07 \pm 27.80	90.99 \pm 22.13
	2	83.18 \pm 9.08	94.24 \pm 7.21	77.63 \pm 5.44
Melt ice-cream	1	89.88 \pm 16.04	85.91 \pm 9.50	86.33 \pm 12.82
	2	208.57 \pm 16.35	220.16 \pm 58.89	178.03 \pm 17.42
Whipped cream	1	190.02 \pm 68.63	219.09 \pm 98.67	232.52 \pm 54.76
	2	299.81 \pm 109.55	267.21 \pm 64.57	285.16 \pm 78.1
Chocolate shake	1	106.81 \pm 6.13	133.62 \pm 47.78	119.55 \pm 8.31
	2	221.57 \pm 74.22	164.19 \pm 47.45	181.35 \pm 53.41
Natural yoghurt	1	132.19 \pm 41.1	181.68 \pm 14.7	299.52 \pm 79.1
	2	270.89 \pm 40.41	337.43 \pm 49.74	306.52 \pm 54.35
Greek yoghurt	1	500.17 \pm 175.12	208.88 \pm 62.68	139.79 \pm 29.23
	2	153.7 \pm 3.45	161.03 \pm 1.24	153.31 \pm 4.62
Tomato juice	1	183.98 \pm 36.44	154.49 \pm 3.50	287.02 \pm 84.44
	2	103.45 \pm 15.41	113.21 \pm 21.90	102.67 \pm 10.58
Custard	1	173.1 \pm 13.51	164.89 \pm 16.91	202.27 \pm 28.44
	2	298.23 \pm 58.22	382.27 \pm 48.19	324.67 \pm 58.91
Condensed milk	1	289.54 \pm 38.03	338.07 \pm 22.49	363.54 \pm 57.57
	2	640.12 \pm 97.66	849.12 \pm 291.77	617.41 \pm 88.18
Sour cream	1	312.92 \pm 54.41	497.94 \pm 143.06	356 \pm 95.91
	2	184.23 \pm 30.96	212.84 \pm 34.83	363.55 \pm 111.3
Plum jam	1	428.77 \pm 77.31	532.82 \pm 94.14	535.69 \pm 89.63
	2	242.06 \pm 16.21	309.43 \pm 25.40	394.78 \pm 66.19
Cheese tub	1	1158.82 \pm 214.19	2803.72 \pm 165.07	1236.26 \pm 290.27
	2	485.17 \pm 89.41	733.72 \pm 218.38	588.13 \pm 82.98
Peanut butter	1	712.21 \pm 102.14	1151.76 \pm 652.20	976.92 \pm 431.9
	2	430.12 \pm 43.26	535.87 \pm 44.04	593.09 \pm 151.4
Nutella	1	2284.41 \pm 139.94	2580.11 \pm 957.63	2828.55 \pm 395.33
	2	926.75 \pm 152.74	1459.27 \pm 235.82	1371.53 \pm 295.23
Philadelphia cheese	1	1840.5 \pm 662.07	2419.57 \pm 928.80	1960.68 \pm 765.31
	2	661.52 \pm 381.98	1037.12 \pm 599.75	839.19 \pm 491.32

Table 3a Maximum velocity of tongue tip, tongue back and lower incisor in three dimensions (mean \pm SD)

Samples	Sub	Maximum velocity of lower incisor (m/s)			Maximum velocity of tongue tip (m/s)			Maximum velocity of tongue back (m/s)		
		Antero-posterior	lateral	vertical	Antero-posterior	lateral	vertical	Antero-posterior	lateral	vertical
Trim milk	1	0.09 \pm 0.01	0.07 \pm 0.01	0.13 \pm 0.02	0.1 \pm 0.02	0.11 \pm 0	0.11 \pm 0.02	0.13 \pm 0.05	0.12 \pm 0.03	0.22 \pm 0.2
	2	0.12 \pm 0.07	0.16 \pm 0.05	0.11 \pm 0.04	0.12 \pm 0.03	0.27 \pm 0.21	0.1 \pm 0.01	0.1 \pm 0.02	0.12 \pm 0.02	0.13 \pm 0.01
Standard milk	1	0.17 \pm 0.01	0.15 \pm 0.02	0.13 \pm 0.02	0.1 \pm 0.01	0.14 \pm 0.01	0.14 \pm 0.01	0.14 \pm 0	0.16 \pm 0.01	0.22 \pm 0.03
	2	0.1 \pm 0.01	0.1 \pm 0.01	0.05 \pm 0	0.29 \pm 0.28	0.56 \pm 0.63	0.47 \pm 0.52	0.08 \pm 0.02	0.11 \pm 0.01	0.11 \pm 0.02
Chocolate mousse	1	0.17 \pm 0.07	0.12 \pm 0.07	0.14 \pm 0.03	0.19 \pm 0.08	0.08 \pm 0.01	0.16 \pm 0.04	1.73 \pm 0.38	1.07 \pm 0.11	2.35 \pm 0.52
	2	0.16 \pm 0	0.14 \pm 0.01	0.08 \pm 0.01	0.1 \pm 0	0.13 \pm 0.03	0.09 \pm 0.01	0.1 \pm 0.01	0.18 \pm 0.04	0.11 \pm 0.02
Orange juice	1	0.12 \pm 0.02	0.07 \pm 0.01	0.15 \pm 0.04	0.1 \pm 0.02	0.15 \pm 0.03	0.09 \pm 0.02	0.1 \pm 0.01	0.11 \pm 0.01	0.14 \pm 0.03
	2	0.1 \pm 0.01	0.1 \pm 0.02	0.05 \pm 0.01	0.08 \pm 0	0.12 \pm 0.01	0.1 \pm 0	0.08 \pm 0.01	0.08 \pm 0.02	0.1 \pm 0.01
Melt ice-cream	1	0.08 \pm 0.02	0.06 \pm 0.02	0.13 \pm 0.02	0.1 \pm 0.01	0.11 \pm 0.01	0.08 \pm 0.02	0.1 \pm 0.01	0.1 \pm 0.01	0.08 \pm 0.02
	2	0.17 \pm 0.04	0.14 \pm 0.03	0.07 \pm 0.01	0.15 \pm 0.09	0.18 \pm 0.1	0.15 \pm 0.1	0.09 \pm 0	0.13 \pm 0.02	0.14 \pm 0
Whipped cream	1	0.99 \pm 1.16	2.39 \pm 3.17	0.37 \pm 0.41	2.24 \pm 2.93	1.43 \pm 1.89	3.06 \pm 4.1	1.04 \pm 0.9	2.06 \pm 2.18	0.36 \pm 0.24
	2	0.16 \pm 0.03	0.13 \pm 0.03	0.08 \pm 0.01	0.09 \pm 0	0.13 \pm 0.04	0.12 \pm 0.02	0.11 \pm 0.01	0.14 \pm 0.04	0.15 \pm 0.05
Chocolate shake	1	0.14 \pm 0.01	0.12 \pm 0.03	0.11 \pm 0.02	0.15 \pm 0.06	0.18 \pm 0.1	0.17 \pm 0.06	0.17 \pm 0.01	0.17 \pm 0.03	0.19 \pm 0.01
	2	0.16 \pm 0.03	0.17 \pm 0.03	0.06 \pm 0	0.11 \pm 0.02	0.1 \pm 0.01	0.09 \pm 0.01	0.11 \pm 0.02	0.25 \pm 0.06	0.14 \pm 0.02
Natural yoghurt	1	0.13 \pm 0.05	0.11 \pm 0.03	0.11 \pm 0.03	0.28 \pm 0.06	0.12 \pm 0.04	0.14 \pm 0.02	0.83 \pm 0.37	1.62 \pm 0.79	1.24 \pm 0.76
	2	0.13 \pm 0.01	0.12 \pm 0.02	0.1 \pm 0.01	0.19 \pm 0.02	0.13 \pm 0.02	0.13 \pm 0.03	0.13 \pm 0.01	0.17 \pm 0.04	0.17 \pm 0.05
Greek yoghurt	1	0.61 \pm 0.18	0.55 \pm 0.03	0.17 \pm 0.02	0.25 \pm 0.03	0.09 \pm 0.01	0.17 \pm 0.05	0.14 \pm 0	0.07 \pm 0.02	0.19 \pm 0.02
	2	0.09 \pm 0.01	0.1 \pm 0	0.06 \pm 0.02	0.07 \pm 0	0.1 \pm 0.01	0.1 \pm 0.01	0.07 \pm 0.01	0.12 \pm 0.01	0.1 \pm 0
Tomato juice	1	0.17 \pm 0.07	7.69 \pm 10.47	0.13 \pm 0.04	0.27 \pm 0.03	0.08 \pm 0.03	0.17 \pm 0.02	1.26 \pm 0.26	2.24 \pm 0.88	1.9 \pm 0.86
	2	0.1 \pm 0.01	0.1 \pm 0.02	0.04 \pm 0	0.07 \pm 0.01	0.1 \pm 0.02	0.1 \pm 0.02	0.08 \pm 0.01	0.11 \pm 0.01	0.1 \pm 0.01
Custard	1	0.16 \pm 0.01	0.14 \pm 0.04	0.1 \pm 0.02	0.09 \pm 0.01	0.14 \pm 0.03	0.14 \pm 0.02	0.13 \pm 0.01	0.24 \pm 0.09	0.16 \pm 0.02
	2	0.15 \pm 0.01	0.1 \pm 0.01	0.09 \pm 0.01	0.19 \pm 0.02	0.12 \pm 0.02	0.15 \pm 0.03	0.13 \pm 0.01	0.12 \pm 0.01	0.15 \pm 0.02
Condense milk	1	0.12 \pm 0.02	0.15 \pm 0.02	0.11 \pm 0.01	0.16 \pm 0.03	0.17 \pm 0.05	0.11 \pm 0	0.96 \pm 0.54	0.14 \pm 0.01	1.29 \pm 0.79
	2	0.21 \pm 0.06	0.14 \pm 0.04	0.19 \pm 0.07	0.99 \pm 1.11	4.72 \pm 6.38	0.41 \pm 0.35	0.19 \pm 0.06	0.22 \pm 0.08	0.23 \pm 0.05
Sour cream	1	0.13 \pm 0.01	0.11 \pm 0.02	0.13 \pm 0.01	0.42 \pm 0.29	1.12 \pm 0.7	0.14 \pm 0.03	0.43 \pm 0.33	0.11 \pm 0.01	0.65 \pm 0.64
	2	0.1 \pm 0.01	0.13 \pm 0	0.07 \pm 0.03	0.1 \pm 0.03	0.14 \pm 0.02	0.13 \pm 0.01	0.66 \pm 0.76	1.58 \pm 1.88	7.8 5 \pm 5.49
Plum jam	1	0.14 \pm 0.01	0.11 \pm 0.05	0.15 \pm 0	0.16 \pm 0.07	0.22 \pm 0.02	0.14 \pm 0.02	0.84 \pm 0.96	1.2 \pm 1.36	0.19 \pm 0.02
	2	0.12 \pm 0.01	0.12 \pm 0.01	0.06 \pm 0.01	0.21 \pm 0.1	0.42 \pm 0.36	0.6 \pm 0.54	0.27 \pm 0.11	0.7 \pm 0.42	4.3 \pm 5.83
Cheese tube	1	0.28 \pm 0.01	0.15 \pm 0.01	0.17 \pm 0.05	17.54 \pm 20.79	6.51 \pm 4.19	5.85 \pm 4.26	1.51 \pm 0.85	1.2 \pm 0.82	0.94 \pm 0.89
	2	0.15 \pm 0.04	0.14 \pm 0.04	0.1 \pm 0.03	1.15 \pm 1.31	0.99 \pm 0.87	2.32 \pm 3.08	0.38 \pm 0.34	0.18 \pm 0.08	1.06 \pm 1.18
Peanut butter	1	1.02 \pm 1.21	0.31 \pm 0.3	0.29 \pm 0.23	0.71 \pm 0.21	0.55 \pm 0.14	0.71 \pm 0.6	0.76 \pm 0.83	0.68 \pm 0.83	1.11 \pm 1.26
	2	0.14 \pm 0.03	0.13 \pm 0.02	0.09 \pm 0.01	0.28 \pm 0.08	0.31 \pm 0.11	0.17 \pm 0.02	2.57 \pm 3.37	0.56 \pm 0.57	0.5 \pm 0.21
Nutella	1	6.04 \pm 10.07	6.32 \pm 10.01	0.89 \pm 0.92	5.61 \pm 8.84	5.95 \pm 8.82	0.61 \pm 0.42	4.78 \pm 7.38	3.73 \pm 5.31	2.9 \pm 2.49
	2	0.12 \pm 0	0.11 \pm 0.01	0.11 \pm 0.02	1.08 \pm 1.18	0.97 \pm 0.99	1.78 \pm 1.59	1.78 \pm 1.34	0.49 \pm 0.21	1.2 \pm 0.7
Philadelphia cheese	1	8.55 \pm 7.38	13.53 \pm 9.53	19.27 \pm 17.67	8 \pm 5.81	14.07 \pm 8.35	19.23 \pm 17.68	4.27 \pm 2.85	10.99 \pm 7.63	15.06 \pm 13.14
	2	0.14 \pm 0.01	0.12 \pm 0.02	0.12 \pm 0	0.42 \pm 0.11	0.38 \pm 0.05	0.38 \pm 0.07	0.36 \pm 0.18	0.31 \pm 0.05	0.8 \pm 0.48

Increasing viscosity

Table 3b Minimum velocity of tongue tip, tongue back and lower incisor in three dimensions (mean ± SD)

Samples	Sub	Minimum velocity of lower incisor (m/s)			Minimum velocity of tongue tip (m/s)			Minimum velocity of tongue back (m/s)		
		Antero-posterior	lateral	vertical	Antero-posterior	lateral	vertical	Antero-posterior	lateral	vertical
Trim milk	1	-0.1±0.02	-0.07±0.01	-0.16±0.04	-0.1±0.02	-0.12±0.02	-0.12±0.04	-0.13±0.05	-0.13±0.04	-0.24±0.22
	2	-0.14±0.09	-0.16±0.04	-0.11±0.02	-0.15±0.04	-0.2±0.12	-0.1±0.01	-0.11±0.03	-0.13±0.01	-0.14±0.02
Standard milk	1	-0.17±0.02	-0.13±0.02	-0.11±0.01	-0.11±0.01	-0.14±0.01	-0.16±0.01	-0.14±0.02	-0.17±0.02	-0.14±0.01
	2	-0.12±0	-0.11±0.01	-0.05±0	-0.28±0.28	-0.6±0.68	-0.49±0.51	-0.07±0.01	-0.1±0	-0.1±0.01
Chocolate mousse	1	-0.18±0.07	-0.12±0.05	-0.13±0.04	-0.2±0.08	-0.1±0.01	-0.14±0.04	-1.19±0.34	-1.71±0.75	-1.46±0.49
	2	-0.17±0.01	-0.18±0.03	-0.08±0.02	-0.1±0	-0.13±0.01	-0.1±0.03	-0.1±0.01	-0.19±0.01	-0.09±0
Orange juice	1	-0.1±0.02	-0.08±0.01	-0.16±0.03	-0.08±0.01	-0.14±0.02	-0.09±0.01	-0.12±0.02	-0.11±0.01	-0.1±0.03
	2	-0.11±0.01	-0.1±0.01	-0.05±0	-0.07±0.01	-0.13±0.01	-0.12±0.02	-0.06±0.01	-0.07±0.01	-0.07±0.02
Melt ice-cream	1	-0.08±0.02	-0.07±0.02	-0.16±0.02	-0.1±0.01	-0.11±0.01	-0.07±0.02	-0.1±0.02	-0.11±0.01	-0.08±0.01
	2	-0.15±0.01	-0.13±0.03	-0.07±0.01	-0.16±0.06	-0.19±0.09	-0.15±0.09	-0.1±0.02	-0.13±0.03	-0.12±0.02
Whipped cream	1	-0.87±0.97	-2.83±3.84	-0.62±0.74	-1.65±2.11	-1.16±1.49	-3.22±4.32	-1.73±1.28	-3.36±2.48	-0.5±0.41
	2	-0.16±0.03	-0.13±0.03	-0.07±0.01	-0.1±0.03	-0.13±0.04	-0.12±0.03	-0.15±0.05	-0.19±0.11	-0.12±0.03
Chocolate shake	1	-0.15±0.01	-0.11±0.02	-0.11±0.02	-0.13±0.03	-0.21±0.13	-0.14±0.04	-0.13±0.02	-0.17±0.05	-0.15±0.03
	2	-0.16±0.04	-0.18±0.03	-0.06±0.01	-0.11±0.02	-0.11±0.03	-0.08±0	-0.13±0.05	-0.36±0.2	-0.09±0.02
Natural yoghurt	1	-0.13±0.04	-0.11±0.04	-0.11±0.03	-0.25±0.02	-0.11±0.03	-0.14±0.01	-1.74±0.33	-1.11±0.74	-2.03±0.61
	2	-0.13±0.01	-0.13±0.02	-0.11±0.01	-0.19±0.01	-0.13±0.01	-0.13±0.02	-0.15±0.02	-0.15±0.01	-0.13±0.04
Greek yoghurt	1	-0.65±0.03	-0.51±0.13	-0.17±0.04	-0.26±0.02	-0.08±0.01	-0.17±0.04	-0.17±0.01	-0.07±0.01	-0.12±0.03
	2	-0.09±0.01	-0.12±0.01	-0.06±0.03	-0.08±0.01	-0.09±0	-0.09±0.01	-0.07±0.01	-0.1±0.02	-0.09±0.01
Tomato juice	1	-0.19±0.08	-0.18±0.11	-2.83±3.81	-0.25±0.05	-0.07±0.01	-0.19±0.03	-5.85±5.79	-1.82±0.57	-6.49±5.47
	2	-0.1±0.01	-0.09±0.02	-0.04±0.01	-0.07±0	-0.11±0.01	-0.11±0.02	-0.08±0.01	-0.12±0.02	-0.07±0
Custard	1	-0.19±0.01	-0.13±0.02	-0.09±0	-0.08±0.01	-0.12±0.01	-0.16±0.03	-0.12±0	-0.22±0.05	-0.12±0
	2	-0.14±0.01	-0.1±0.01	-0.1±0.01	-0.21±0.03	-0.11±0.01	-0.14±0.02	-0.12±0.01	-0.13±0.01	-0.14±0.01
Condense milk	1	-0.11±0.02	-0.12±0.02	-0.11±0	-0.15±0.02	-0.23±0.14	-0.13±0.01	-0.62±0.29	-0.13±0.01	-0.77±0.39
	2	-0.17±0.01	-0.15±0.06	-0.2±0.09	-1.04±1.26	-2.5±3.2	-0.32±0.24	-0.17±0.03	-0.17±0.06	-0.2±0.01
Sour cream	1	-0.14±0.01	-0.11±0.01	-0.14±0.02	-0.44±0.32	-1.35±1.23	-0.21±0.1	-0.42±0.33	-0.1±0.01	-0.59±0.45
	2	-0.11±0.02	-0.11±0.02	-0.06±0.03	-0.1±0.02	-0.16±0.03	-0.12±0.01	-2.28±1.55	-7.6±5.32	-1.77±2.12
Plum jam	1	-0.12±0.01	-0.12±0.04	-0.15±0.02	-0.14±0.04	-0.24±0.04	-0.14±0.02	-0.63±0.68	-0.91±1.03	-0.18±0.02
	2	-0.12±0	-0.12±0.01	-0.05±0	-0.3±0.22	-0.5±0.4	-0.55±0.34	-0.5±0.38	-4.66±5.93	-0.51±0.5
Cheese tub	1	-0.25±0.01	-0.15±0.02	-0.17±0.04	-17.33±20.94	-6.17±4.49	-5.62±4.47	-0.77±0.22	-1.94±1.48	-0.66±0.48
	2	-0.15±0.02	-0.12±0.01	-0.1±0.02	-0.34±0.09	-2.5±3.06	-2.39±3.04	-0.25±0.1	-0.27±0.21	-1.38±1.67
Peanut butter	1	-0.84±0.95	-0.42±0.46	-0.58±0.62	-1.3±1.15	-11.69±15.78	-0.67±0.59	-0.57±0.51	-1.14±1.45	-0.63±0.6
	2	-0.13±0.01	-0.13±0.02	-0.09±0.01	-0.25±0.02	-0.31±0.21	-0.16±0.01	-0.29±0.14	-1.62±2.02	-3.81±5.1
Nutella	1	-6.59±11.05	-5.14±8.2	-1.01±1.12	-6.54±10.45	-4.99±7.67	-1.42±1.74	-6.46±6.98	-7.14±6.37	-1.91±2.05
	2	-0.13±0.01	-0.11±0.01	-0.12±0	-0.65±0.39	-0.58±0.52	-0.98±0.27	-0.42±0.2	-1.14±1.37	-3.92±4.21
Philadelphia cheese	1	-9.87±7.72	-13.68±9.83	-13.45±10.17	-10.39±6.06	-13.84±9.35	-13.24±9.78	-6.56±4.58	-10.61±7.74	-11±7.67
	2	-0.15±0	-0.11±0.01	-0.11±0.01	-0.37±0.16	-0.28±0.06	-0.47±0.19	-0.74±0.27	-0.65±0.34	-0.99±0.86

Increasing viscosity



Table 4a. Shear rate of tongue tip, tongue back and lower incisor (mean \pm SD) Constant height= ΔZ_{max}

Samples	Sub	Average shear rate (S ⁻¹)			Maximum shear rate (S ⁻¹)			Minimum shear rate (S ⁻¹)		
		Lower incisor	Tongue tip	Tongue back	Lower incisor	Tongue tip	Tongue back	Lower incisor	Tongue tip	Tongue back
Trim milk	1	0.01±0	0.03±0.01	0.01±0	0.04±0.01	0.08±0.03	0.04±0.02	0±0	0±0	0±0
	2	0.05±0.03	0.04±0.02	0.01±0	0.15±0.09	0.13±0.04	0.02±0	0±0	0±0	0±0
Standard milk	1	0.07±0.01	0.04±0.01	0.01±0	0.17±0.04	0.11±0.03	0.03±0	0.01±0	0±0	0±0
	2	0.02±0.01	0.02±0.01	0.01±0	0.06±0.02	0.13±0.07	0.02±0.01	0±0	0±0	0±0
Chocolate mousse	1	0.05±0.01	0.04±0.01	0.01±0	0.16±0.02	0.15±0.04	0.12±0.04	0.01±0	0±0	0±0
	2	0.02±0	0.02±0	0±0	0.07±0.01	0.05±0.01	0.02±0	0±0	0±0	0±0
Orange juice	1	0.02±0	0.03±0	0.01±0	0.05±0.02	0.07±0	0.02±0.01	0±0	0±0	0±0
	2	0.03±0	0.05±0.01	0±0	0.09±0.01	0.16±0.03	0.01±0	0±0	0.01±0	0±0
Melt ice-cream	1	0.02±0	0.05±0	0.01±0	0.05±0.01	0.12±0.01	0.03±0	0±0	0.01±0	0±0
	2	0.03±0.02	0.04±0.01	0±0	0.12±0.07	0.17±0.04	0.02±0	0±0	0±0	0±0
Whipped cream	1	0.04±0.03	0.02±0.01	0.01±0	0.45±0.42	0.13±0.07	0.45±0.32	0.01±0	0±0	0±0
	2	0.04±0.01	0.02±0.01	0±0	0.13±0.05	0.06±0.02	0.03±0.01	0±0	0±0	0±0
Chocolate shake	1	0.04±0.01	0.02±0.01	0.01±0	0.11±0.03	0.07±0.03	0.04±0	0±0	0±0	0±0
	2	0.01±0	0.01±0	0±0	0.05±0.01	0.04±0	0.03±0.02	0±0	0±0	0±0
Natural yoghurt	1	0.02±0	0.06±0.01	0.01±0	0.06±0.01	0.22±0.04	0.21±0.08	0±0	0±0	0±0
	2	0.01±0	0.02±0.01	0.01±0	0.05±0.01	0.05±0.02	0.02±0	0±0	0±0	0±0
Greek yoghurt	1	0.02±0.02	0.07±0.01	0.03±0.02	0.09±0.09	0.29±0.09	0.13±0.09	0±0	0±0	0±0
	2	0.04±0.01	0.03±0.01	0±0	0.12±0.04	0.09±0.03	0.02±0	0±0	0±0	0±0
Tomato juice	1	0.03±0.02	0.04±0.01	0±0	0.29±0.2	0.15±0.05	0.19±0.06	0±0	0±0	0±0
	2	0.03±0.01	0.03±0.01	0.01±0	0.1±0.04	0.07±0.02	0.02±0	0±0	0±0	0±0
Custard	1	0.04±0	0.03±0.01	0.01±0	0.14±0.02	0.08±0.02	0.04±0.01	0±0	0±0	0±0
	2	0.02±0	0.03±0.01	0.01±0	0.06±0.01	0.1±0.03	0.02±0	0±0	0±0	0±0
Condense milk	1	0.01±0	0.02±0	0.01±0	0.04±0.01	0.08±0.01	0.11±0.04	0±0	0±0	0±0
	2	0.01±0	0.01±0	0±0	0.06±0.02	0.34±0.41	0.02±0	0±0	0±0	0±0
Sour cream	1	0.01±0	0.02±0	0.01±0	0.03±0.01	0.33±0.24	0.06±0.04	0±0	0±0	0±0
	2	0.02±0	0.01±0	0±0	0.07±0.02	0.05±0.01	0.17±0.09	0±0	0±0	0±0
Plum jam	1	0.01±0	0.02±0	0±0	0.04±0.02	0.06±0.02	0.08±0.08	0±0	0±0	0±0
	2	0.02±0.01	0.01±0	0±0	0.09±0.03	0.05±0.01	0.13±0.11	0±0	0±0	0±0
Cheese tub	1	0.01±0	0±0	0±0	0.03±0.01	0.24±0.22	0.09±0.06	0±0	0±0	0±0
	2	0.01±0	0±0	0±0	0.04±0.01	0.03±0.02	0.09±0.10	0±0	0±0	0±0
Peanut butter	1	0.01±0.01	0.02±0.01	0±0	0.04±0.03	0.09±0.07	0.05±0.05	0±0	0±0	0±0
	2	0.01±0	0.01±0	0±0	0.02±0.01	0.02±0.02	0.02±0.01	0±0	0±0	0±0
Nutella	1	0.01±0.01	0.01±0	0±0	0.27±0.36	0.19±0.24	0.27±0.22	0±0	0±0	0±0
	2	0.01±0	0±0	0±0	0.02±0	0.07±0.05	0.1±0.06	0±0	0±0	0±0
Philadelphia cheese	1	0±0	0±0	0±0	0.17±0.1	0.24±0.02	0.14±0.1	0±0	0±0	0±0
	2	0±0	0±0	0±0	0.02±0	0.03±0	0.28±0.2	0±0	0±0	0±0

Increasing viscosity

Table 4b. Shear stress of tongue tip, tongue back and lower incisor (mean \pm SD) Constant height = ΔZ_{max}

Samples	Sub	Average shear stress (Pa)			Minimum shear stress (Pa)			Maximum shear stress (Pa)		
		Lower incisor	Tongue tip	Tongue back	Lower incisor	Tongue tip	Tongue back	Lower incisor	Tongue tip	Tongue back
Trim milk	1	0±0	0±0	0±0	0±0	0±0	0±0	0.01±0	0.01±0	0.01±0
	2	0±0	0±0	0±0	0±0	0±0	0±0	0.01±0	0.01±0	0.01±0
Standard milk	1	0.02±0	0.02±0	0.03±0	0.01±0	0.02±0	0.02±0	0.04±0	0.05±0	0.08±0.01
	2	0.03±0	0.03±0	0.04±0.01	0.02±0	0.02±0	0.03±0	0.06±0.01	0.07±0.02	0.09±0.03
Chocolate mousse	1	0.15±0.01	0.16±0.02	0.28±0.04	0.1±0	0.11±0.01	0.12±0.01	0.29±0.01	0.32±0.04	0.81±0.11
	2	0.2±0.01	0.2±0.01	0.31±0.01	0.14±0.01	0.15±0.01	0.2±0	0.42±0.03	0.45±0.06	0.63±0.06
Orange juice	1	3.36±0.5	2.47±0.19	6.42±1.48	1.55±0.44	1.18±0.02	2.76±0.5	17.23±4.11	11.16±1.12	35.27±10.2
	2	2.17±0.2	1.52±0.25	9.21±1.6	0.99±0.08	0.65±0.1	4.41±0.75	9.91±0.99	9.01±4.3	47.62±2.33
Melt ice-cream	1	0.35±0.04	0.25±0	0.4±0.01	0.25±0.01	0.19±0	0.29±0	0.69±0.09	0.46±0.04	0.82±0.13
	2	0.29±0.04	0.26±0.02	0.5±0.03	0.2±0.03	0.17±0.01	0.35±0.02	0.7±0.09	0.58±0.11	1.06±0.07
Whipped cream	1	0.8±0.22	1.22±0.6	1.17±0.15	0.35±0.12	0.47±0.08	0.46±0.31	2.09±1.19	3.76±2.28	2.85±0.29
	2	0.76±0.12	1.02±0.2	1.61±0.07	0.47±0.08	0.64±0.09	0.87±0.12	2.1±0.31	2.79±0.91	5.19±0.57
Chocolate shake	1	19.56±3.46	36.32±19.23	54.79±0.7	9.16±1.86	15.27±7.19	21.06±0.68	113.07±45.33	173.99±112.13	445.96±199.31
	2	43.07±5.97	41.67±4.45	97.09±5.11	17.04±2.19	18.48±1.26	28.54±13.06	314±115.47	255.68±28.38	936.8±198.74
Natural yoghurt	1	16.61±1.53	10.03±0.94	28.25±5.14	9.48±0.63	4.79±0.49	5.22±1.32	65.18±17.86	42.49±5.28	193.86±105.28
	2	21.08±1.78	21.55±5.4	34.91±2.08	11.17±1.23	11.04±2.93	18.28±1.01	120.02±31.33	126.18±47.54	161.06±59.23
Greek yoghurt	1	54.5±24.38	17.94±1.98	39.85±25.59	25.52±12.35	7.69±1.46	18.41±12.44	240.41±111.35	122.59±31.18	190.72±66.74
	2	25.26±5.24	27.97±5.52	84.95±7.33	13.06±3.02	15.36±3.17	42.38±2.69	118.44±33.03	150.74±38.93	385.61±50.65
Tomato juice	1	966.52±1089.37	210.29±70.99	1453.12±446.1	44.59±29.13	57.41±21.79	44.72±16.39	15700.3±20535.67	2389.22±135.44	31298.36±19915.63
	2	227.39±71.19	289.63±85.28	1219.64±380.61	78.85±22.56	106.55±24.32	424.03±118.39	2664.94±1693.17	3621.49±1534.95	11097.8±4157.36
Custard	1	30.3±1.52	40.45±6.12	65.57±5.64	15.87±1	22.26±2.5	32.88±5.32	128.7±34.03	144.45±46.35	212.35±14.33
	2	50.96±6.37	40.11±6.76	92.73±7.1	26.41±2.93	19.84±0.9	51.37±3.09	230.12±78.13	191.53±19.58	385.14±49.13
Condense milk	1	11.9±0.44	10.33±0.34	12.49±1.11	9.2±0.29	8.23±0.22	7.88±0.66	17.62±0.83	16.07±1	19.78±1.82
	2	11.23±0.44	11.57±0.69	13.39±0.42	8.6±0.49	7.7±1.74	10.04±0.25	17.91±0.29	19.92±3.04	22.59±1.32
Sour cream	1	3738.9±013.77	1781.9±152.53	5706.02±1475.06	1324.94±236.43	295.5±258.95	847.49±362.85	51855.01±25598.44	25576.05±4479.46	83419.94±24685.05
	2	1768.41±306.7	2925.01±644.2	17123.23±9055.02	604.42±132.09	832.02±177.99	452.96±363.37	20391.7±10201.93	44221.99±18148.28	223319.49±296627.55
Plum jam	1	153.39±34.03	120.6±16.17	204.54±12.54	85.69±23.06	61.64±9.01	80.37±34.16	402.75±342.14	427.77±22.25	719.71±79.48
	2	95.53±10.95	222.5±66.91	243.42±88.66	52.18±7.91	70.44±6.96	52.1±16.42	323.61±48.34	858.75±199.54	909.75±418.21
Cheese tub	1	202.14±91±1715.81	42502.52±12416.84	38798.36±0185.46	6295±1381.65	1479.44±806.66	410448.33±141069.32	410448.33±141069.32	10480210.53±314060.09	5516566.8±132427
	2	15438.65±2705.63	64840.13±28399.99	44250.19±10818.33	4485.09±776.01	6371.37±3181.41	56256.86±4440.55	227196.7±58805.26	998096.6±573085.8	5516566.8±132427
Peanut butter	1	2679.6±1041.31	1938.24±618.96	5538.54±1550.74	1151.26±456.66	658.16±274.76	1212.87±635.79	16956.87±7145.33	17364.56±4552.28	67202.51±19712.03
	2	2464.49±253.03	3094.33±122.57	5604.26±1792.94	13077±16935.42	9799.58±12549.07	4045.1±3833.56	19678.43±3470.71	28356.56±64435.75	58685.86±38900.33
Nutella	1	55422.57±310936.17	66349.42±40395.67	103167.38±15340.03	4728.44±4083.98	6153.21±3007.72	6902.99±9318.91	1704864.18±108193.08	1834495.54±1168907.82	3062121.97±1050412.73
	2	49781.98±8862.6	102341.87±8279.21	146520.4±55778.73	14866.16±2669.25	6153.21±3007.72	5795.5±5122.92	671785.16±476359.47	22252543.37±611158.43	3798052.88±237357.87
Philadelphia cheese	1	9717128.83±637706.39	8749633.12±585790.21	11673094.89±2096542	59211.63±7384.45	7881.81±740.44	291791.55±399413.4	1561779366.31±116035696.47	1902049397.83±1621150058.12	244806026±52423230.71
	2	1787147.98±497526.95	2715035.11±517174.76	3676544.93±330208.4	323654.06±109730.41	123800.48±6495.83	20802.48±17820.4	149799956.35±40317554.83	268146063.12±68199122.89	23598858.76±106518464.74

Increasing viscosity

Table 5. Logarithm value of shear stress of tongue tip, tongue back and lower incisor (Constant height= ΔZ_{max})

Samples	Sub	Log (average shear stress)			Log (minimum shear stress)			Log (maximum shear stress)		
		Lower incisor	Tongue tip	Tongue back	Lower incisor	Tongue tip	Tongue back	Lower incisor	Tongue tip	Tongue back
Trim milk	1	-2.34±0.01	-2.36±0.02	-2.31±0	-2.38±0.01	-2.41±0.02	-2.38±0.02	-2.21±0.02	-2.26±0.01	-2.18±0.02
	2	-2.38±0.03	-2.37±0.04	-2.31±0.01	-2.43±0.03	-2.43±0.01	-2.36±0.01	-2.27±0.05	-2.25±0.05	-2.21±0.02
Standard milk	1	-1.73±0.02	-1.66±0.04	-1.47±0.03	-1.86±0.03	-1.8±0.03	-1.62±0.02	-1.46±0.03	-1.33±0.02	-1.11±0.06
	2	-1.56±0.04	-1.57±0.04	-1.37±0.08	-1.71±0.05	-1.8±0.08	-1.52±0.07	-1.2±0.07	-1.2±0.13	-1.05±0.13
Chocolate mousse	1	-0.83±0.03	-0.81±0.04	-0.56±0.07	-0.98±0.02	-0.96±0.04	-0.94±0.05	-0.54±0.02	-0.5±0.05	-0.1±0.06
	2	-0.7±0.02	-0.69±0.03	-0.51±0.01	-0.87±0.02	-0.83±0.03	-0.69±0.01	-0.38±0.03	-0.36±0.06	-0.2±0.04
Orange juice	1	0.52±0.06	0.39±0.03	0.8±0.09	0.17±0.12	0.07±0.01	0.43±0.08	1.22±0.11	1.05±0.04	1.53±0.14
	2	0.33±0.04	0.18±0.07	0.96±0.08	-0.01±0.04	-0.19±0.06	0.64±0.08	0.99±0.05	0.91±0.19	1.68±0.02
Melt ice-cream	1	-0.46±0.03	-0.61±0.01	-0.4±0.01	-0.6±0.02	-0.73±0.01	-0.54±0.01	-0.17±0.05	-0.34±0.04	-0.09±0.06
	2	-0.54±0.07	-0.59±0.03	-0.3±0.03	-0.7±0.08	-0.77±0.03	-0.46±0.02	-0.16±0.05	-0.24±0.08	0.02±0.03
Whipped cream	1	-0.12±0.12	0.04±0.2	0.06±0.06	-0.48±0.17	-0.33±0.08	-0.43±0.27	0.25±0.23	0.5±0.25	0.45±0.04
	2	-0.12±0.07	0±0.09	0.21±0.02	-0.33±0.07	-0.2±0.06	-0.07±0.06	0.32±0.06	0.42±0.14	0.71±0.05
Chocolate shake	1	1.29±0.07	1.5±0.21	1.74±0.01	0.95±0.08	1.14±0.19	1.32±0.01	2.02±0.16	2.15±0.27	2.59±0.23
	2	1.63±0.06	1.62±0.05	1.99±0.02	1.23±0.05	1.27±0.03	1.41±0.2	2.4±0.16	2.4±0.05	2.96±0.1
Natural yoghurt	1	1.22±0.04	1±0.04	1.44±0.08	0.98±0.03	0.68±0.04	0.7±0.1	1.8±0.11	1.62±0.06	2.23±0.23
	2	1.32±0.04	1.32±0.11	1.54±0.03	1.05±0.05	1.03±0.11	1.26±0.02	2.06±0.13	2.06±0.2	2.2±0.1
Greek yoghurt	1	1.67±0.26	1.25±0.05	1.52±0.26	1.33±0.28	0.88±0.08	1.17±0.28	2.31±0.27	2.07±0.12	2.25±0.17
	2	1.39±0.09	1.44±0.09	1.93±0.04	1.11±0.1	1.18±0.09	1.63±0.03	2.06±0.12	2.14±0.18	2.58±0.06
Tomato juice	1	2.65±0.54	2.3±0.14	3.14±0.13	1.54±0.32	1.73±0.15	1.62±0.15	3.6±0.75	3.33±0.19	4.41±0.26
	2	2.33±0.16	2.44±0.13	3.06±0.15	1.88±0.14	2.02±0.1	2.61±0.12	3.32±0.32	3.52±0.17	4±0.2
Custard	1	1.48±0.02	1.6±0.06	1.82±0.04	1.2±0.03	1.34±0.05	1.51±0.07	2.09±0.12	2.14±0.13	2.33±0.03
	2	1.7±0.06	1.6±0.07	1.97±0.03	1.42±0.05	1.29±0.08	1.71±0.03	2.33±0.16	2.28±0.05	2.58±0.05
Condense milk	1	1.05±0.02	1.01±0.01	1.09±0.04	0.96±0.01	0.92±0.01	0.89±0.04	1.25±0.02	1.21±0.03	1.29±0.04
	2	1.05±0.02	1.06±0.03	1.13±0.01	0.93±0.02	0.87±0.11	1±0.01	1.25±0.01	1.29±0.06	1.35±0.03
Sour cream	1	3.57±0.07	3.25±0.04	3.74±0.11	3.12±0.07	2.29±0.4	2.88±0.22	4.67±0.2	4.4±0.08	4.9±0.14
	2	3.24±0.07	3.46±0.1	4.13±0.34	2.77±0.09	2.91±0.1	2.52±0.33	4.31±0.02	4.59±0.23	5.12±0.68
Plum jam	1	2.18±0.09	2.08±0.06	2.31±0.03	1.92±0.12	1.79±0.06	1.85±0.23	2.75±0.18	2.63±0.02	2.85±0.05
	2	1.98±0.05	2.33±0.13	2.36±0.15	1.71±0.07	1.85±0.04	1.69±0.16	2.51±0.06	2.92±0.1	2.92±0.19
Cheese tub	1	4.3±0.04	4.61±0.14	4.58±0.07	3.79±0.09	3.06±0.36	3.39±0.35	5.59±0.14	5.99±0.17	6±0.13
	2	4.18±0.08	4.77±0.19	4.63±0.11	3.64±0.08	3.74±0.24	3.54±0.48	5.34±0.11	5.93±0.23	5.73±0.1
Peanut butter	1	3.38±0.21	3.26±0.16	3.72±0.14	3.02±0.21	2.77±0.23	2.99±0.31	4.18±0.22	4.22±0.13	4.8±0.15
	2	3.39±0.04	3.49±0.02	3.75±0.13	3.55±0.73	3.46±0.7	3.39±0.43	4.29±0.07	4.44±0.1	4.68±0.27
Nutella	1	4.66±0.29	4.74±0.27	5.01±0.07	3.43±0.55	3.47±0.46	3.38±0.64	6.1±0.39	6.15±0.33	6.45±0.18
	2	4.69±0.08	5.01±0.03	5.13±0.18	4.17±0.07	3.71±0.28	3.59±0.37	6±0.02	6.33±0.13	6.5±0.26
Philadelphia cheese	1	6.77±0.54	6.76±0.46	7.06±0.08	4.33±0.62	3.89±0.04	4.62±0.92	8.75±0.86	8.97±0.62	9.38±0.09
	2	4.51±1.73	4.64±1.79	4.76±1.81	3.98±1.51	3.72±1.37	3.03±1.15	5.85±2.31	6.03±2.39	6±2.34

Increasing viscosity

A9: Abbreviations

Antero-posterior dimension (X-axis)

Average masseter muscle voltage (AV_{masseter})

Average submental muscle voltage ($AV_{\text{submental}}$)

Average tongue velocity (V_{ave})

Average voltage (AV)

Blood-oxygenation-level-dependent (BOLD)

Central nervous system (CNS)

Central pattern generator (CPG)

Digastric short burst (DSB)

Dried foil container weight (W_{con})

Dried food sample and foil container (W_{dry})

Dry mass of food sample or bolus based moisture content (MC_{DMB})

Dynamic velocity (v)

Echo-planar imaging (EPI)

Electromagnetic Articulography (EMA)

Electromyography (EMG)

EMA recorded ORT (ORT_{EMA})

EMG recorded ORT (ORT_{EMG})

Epidermal growth factor (EGF)

Expectorated bolus moisture content (MC_{exp})

Functional MRI (fMRI)

Genioglossus short burst (GgSB)

Hypopharyngeal transit time (HTT)

Initial food sample mass based moisture content (MC_{IMB})

Initial food sample weight (W_{ini}),

Lateral dimension (Y-axis)

Loss modulus (G'')

Magnetic resonance imaging (MRI)

Maximum master muscle voltage (MV_{masseter})

Maximum submental muscle voltage ($MV_{\text{submental}}$)

Maximum voltage (MV)

Mean maximum tensile force (MF_{max})

Mean work till maximum force (MW_{max})

Moisture content (MC)

Oral residence time (ORT)

Original food sample moisture content (MC_{ori})

Parafilm stimulated saliva (Para-SFR)

Primary motor area (MI)

Primary somatosensory cortex (SI)

Saliva flow rate (SFR)

Secondary somatosensory cortex presentation (SII)

Small amplitude oscillatory shear (SAOS)

Storage modulus (G')

Temporomandibular joint (TMJ)

Temporomandibular joint dysfunction (TMJD)

Texture Profile Analysis (TPA)

The average SFR during consumption of 9 different food (SFR_{food})

The height of the food bolus between the hard palate and the tongue (h)

The maximum displacement change in the vertical dimension (ΔZ_{max})

the maximum displacement changes ($\Delta_{\text{max}} \text{Dis}$)

The maximum tensile force (F_{max})

The maximum velocity (V_{max})

The maximum velocity of the tongue back ($V_{\max\text{TB}}$)

The maximum velocity of the tongue tip ($V_{\max\text{TT}}$)

The maximum voltage (Voltage_{\max})

The square root of the mean of squares (RMS)

The total area under masseter muscle curve ($\text{TA}_{\text{masseter}}$)

The total area under submental muscle curve ($\text{TA}_{\text{submental}}$)

The voltage of the rectified RMS EMG data of masseter muscle ($\text{Voltage}_{\text{mas}}$)

The work till the maximum force (W_{\max})

Thermal Scanning Rigidity Monitor (TSRM)

Total area under EMG curve (TA)

Unstimulated saliva (Rest SFR)

Vertical dimension (Z-axis)

Videofluorography (VFG)

Weight of bolus and foil container ($W_{\text{b\&c}}$)

Weight of moisture in food sample (W_{moi})

X-ray microbeam (XRMB)