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An Evaluation of the Tekscan I-Scan System for the Assessment of Tongue Movement during Oral Processing of Semi-solid Foods

By

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Abstract

The main objective of this dissertation is to evaluate the scope of a commercial pressure sensor device, the Tekscan I-Scan System (Tekscan, South Boston, MA, USA), to study tongue movement whilst eating foods that are predominantly manipulated with the tongue during oral processing. Initially, methodology to use the sensor sheet in mouth had to be developed as this application of the system was novel. To measure tongue pressures the approach of fixing the sensory sheet, wrapped into cling film to protect it from saliva and food residues, to the upper palate was taken. Ten subjects were then asked to consume seven selected semi-liquid / semi-solid commercial food products with the sensor fixed in place. The foods ranged from liquid to gel-like and their textural attributes were analyzed instrumentally. The data sets obtained with the Tekscan I-Scan System included pressure, area and force data over sampling time. Initial and final values, mean values and peak values as well as average values were provided. Area data referred to the pressure cells that had been activated by the probe (attached on the tongue). To assess the scope of the Tekscan I-Scan system relationships between the results from texture analysis and in-vivo measurement were explored through principle component analysis.

The tongue pressure distribution during whole eating process is available as movie recordings. This revealed higher pressure distributed near the gums of two sides of molars at the time of maximum contact pressure between tongue and palate while pressure was distributed in the middle region of the palate in other periods. Also, the

time of maximum tongue variables attained was close to 70% of whole eating duration and it was interpreted as the moment the subject swallowed. The frequency of tongue moving rhythm was one per second and tongue pressures were produced evenly whether food was consumed in oral cavity or no sample was present in mouth. Total contact pressure and number of contact pressure peaks showed linear correlations to finish time as well as the textural properties.

This research shows that the behavior of tongue movement was comparatively stable during eating process independent of subjects and the kinds of semi-solid foods, except for the moment that maximum contact pressure was recorded which implied swallow was happening. The textures of the selected products are not all differentiated obviously but there are close correlative PCA results with some tongue variables. Linear relationships between texture data and tongue variables reveal the high interaction between food texture and tongue manipulation. The capacity of Tekscan I-Scan System on the study of tongue movement is proved. However, the shape of sensor sheet and the sensory assessment of food texture are the two main works in the future for further study of tongue movement.

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Content

1. Introduction

The essential role of food is to provide energy and nutrients as well as to have pleasure in life (Chen, 2009). Various kinds of foods are produced and sold in the supermarkets for consumers' choices. When consumers choose products, they consider food quality and food texture is one of the major criteria of food quality (Schmitt et al., 1998). Quality of food texture therefore forms an important part of product development. It is usually studied through texture analysis and sensory evaluation (Drake, 2007; Duizer, 2001; Agrawal *et al.*, 1997; Cardarelli *et al.*, 2008). For some time now, researchers have been interested in the effect of food texture (including the mechanical properties and sensory attributes) on the human eating behavior (Dan and Kohyama, 2007; Malone *et al.*, 2003; Piancino *et al.*, 2008; Chen and Lolivret, 2011; Hiiemae *et al.*, 1995; Hiiemae *et al.*, 1996; Hiiemae and Palmer, 1999). No matter what kind of the texture it is, during consumption food is manipulated, deformed or moved across the oral receptors (Engelen and Van Der Bilt, 2008, Bourne, 2004). Oral perception of food texture is sensed by the contact of eating behavior on food (Christensen and Casper, 1987; Guinard and Mazzucchelli, 1996; Lucas *et al.*, 2002; Takahashi *et al.*, 2002). Further, this food-quality sense influences the way people select their food (Zheng *et al.*, 2006; Cayot, 2007; Sorensen *et al.*, 2003; Lucas and Luke, 1984; Buschang *et al.*, 1997; Mioche and Peyron, 1995). Eating behavior analysis as conducted by a new tool in this research could potentially be of great value for the knowledge of Human physiology and exploration into how the interaction between eating behavior and food quality allows development of advanced design rules for high quality foods for daily food purchases.

Therefore, this dissertation is to investigate whether the Tekscan I-Scan System (Tekscan, Inc., South Boston, USA), a pressure sensor sheet system not previously used for oral in-vivo application, can be adapted for the evaluation of tongue pressures during eating foods that are mostly manipulated with the tongue. In terms of application to the human body over and above technical applications such as Force Sensitive Insole, the system has previously been used to study the pressure in human Muscle Activity (Tekscan, 2011b). A particular objective is to establish whether statistically sound data can be obtained to discriminate variable texture across a range of semi-solid foods of variable texture. If this is successful, will the data correlate to results from classical food texture analysis using the Texture Analyzer (Stable Micro Systems Ltd., Surrey, UK)? The question will be explored in this dissertation.

This dissertation is organized as follows: previous texture study of semi-solid foods and the human tongue physiology are introduced in Chapter 1 along with major achievements to date in quantifying the behavior of the tongue during eating. The Tekscan I-Scan System is also introduced in Chapter 1. Chapter 2 comprises the food materials and the methods applied in this research. In Chapter 3 the main study results are presented including the analyses of interactions between variables acquired with the sensor sheet during eating as well as between these and instrumentally acquired texture data. In Chapter 4 a brief overall discussion of the evaluation of Tekscan I-Scan

System on tongue measurement combined with Texture Analysis is given. In Chapter 5, the findings of this project are summarized, and the gaps and suggestions for the future work are described.

1.1 Texture study of semi-solid foods

Food texture is defined as all the attributes of the product including physical (rheological and structural) properties and those perceived by the senses of touch (kinesthesia and mouthfeel), sight and hearing (Brennan, 1989; Lawless and Heymann, 1998). It is an important property considered in the food industry for quality evaluation and inspection (Zheng *et al.*, 2006). This research is concerned with semi-solid foods which are characteristically manipulated mostly with the tongue during the eating process and not by the teeth. Thus they represent an ideal class of foods to evaluate a new tool for quantifying the role of the tongue during manipulation of food.

Specifically, cheese spread, jelly, crème fraîche, crème caramel, custard and stirred yogurt were chosen for this study to cover thin or more liquid-like semi-solid foods all the way through to highly structured or thick semi-solid foods. The composition of these foods varies and for each type itself a range of textures can be found, for example set yogurt and stirred yogurt have very different textures.

Yogurt, crème fraîche and cheese spread are dairy products made through fermentation during which the proteins and the casein in base milk or cream conjunct with calcium phosphate to form colloidal particles (Buchheim and Welsch, 1973). The content of milk proteins is an important factor affecting the physical properties of yogurt. An increasing protein content increases the amount of bound water and, consequently, the firmness of the resulting gel (Snoeren *et al.*, 1982). Different from the undisturbed gel structure in set yogurt, the formed gel of stirred yogurt is broken by stirring to obtain a smooth and highly viscous but pourable product (Walstra *et al.*, 1999; Horne, 1999). The viscosity of stirred yogurt depends on the firmness of the gel before stirring, the higher firmness of the gel the higher viscosity and smoother the product (Rohm, 2003). Based on the manufacture process of stirred yogurt, yogurt drink is produced from skimmed milk mixed with whey or water. Crème fraîche is a soured cream with a pH of around 4.5 containing about 28% butter fat. It is a comparatively high viscosity and fat content. Cheese spread is made from skim milk or from a mixture of milk and cream is a soft, rich, spreadable cheese with mildly acid flavor and a smooth consistency (Sainani *et al.*, 2004). The fat content of a cream cheese spread is up to 40% (Elenbogen and Baron, 1964) with 44% - 60% moisture (Prow and Metzger, 2005). Both the fat content and moisture content contribute to the texture quality of cheese spread. High moisture with relatively low fat content gives a mealy texture while increasing fat results in a butter-like consistency (Templeton and Sommer, 1932).

Custard and crème caramel were also included in this study and these are non-fermented dairy products. Custard is a cooked mixture of milk or cream and egg yolk, including sugar, modified starch, gelling agents like carrageenans, and colorants and flavors (De Wijk *et al.*, 2003). The consistency of custard depends on the level of eggs or thickener. Crème caramel is a kind of stand-up custard-based dessert. Gelling agents such as agar or carrageenan rather than eggs contribute to the texture of crème caramel. Its thickness and melting attributes are related to viscosity whereas its creaminess is affected by fat content (De Wijk *et al.*, 2003). Jelly is another semi-solid food included in this study. It is prepared from citric acid, sweetener and gelling agents such as gellan gum, xanthan gum and locust bean gum while traditionally gelatin is used. Not only does the concentration of the gelling agents influence the texture of jelly but the content of citric acid also has a significant effect on its sensory hardness and smoothness through contribution to the gelation of gellan gum (Moritaka *et al.*, 1999). Jellies with a high proportion of citric acid and a low proportion of gellan gum are soft while those with a low proportion of citric acid and a high proportion of gellan gum are more solid. However, the smoothness of jellies during eating increases with decreasing proportions of gellan gum and citric acid. Harder jellies are less smooth than softer jellies. Except for the ingredients, conditions of production (Haque *et al.*, 2001; Cerning, 1995; Yu *et al.*, 2007) and storage environment (Coggins *et al.*, 2010; Beal *et al.*, 1999; Raffo *et al.*, 2006) are the extra oral factors that affect the texture properties of foods.

1.1.1 Instrumental measure of food texture

In food texture study, there are two principally different ways of measuring texture: by physical measurement and sensory analysis. Researchers then hope to link the result of a physical measurement with the result of sensory analysis. One of the reasons is because the acquisition of statistically sound sensory data is time consuming and expensive while statistically sound physical data can be acquired quicker given appropriate measurement protocols (Janssen *et al.*, 2007; Brighenti *et al.*, 2008; Foegeding and Drake, 2007). Therefore, this study was planned to adopt an instrumental measure of food texture to link the outcome from tongue sensory data.

In 1861 Lipowitz introduced the first instrument and puncture test for measuring the firmness and consistency of jellies (Bourne, 2001). Since then, different instruments and physical tests have been developed for understanding the multifaceted nature of texture, such as a deformation apparatus with torsion test for viscosity of jelly (Schwedoff, 1889), the Tarr–Baker Jelly Tester with a puncture test for firmness of pectin jellies (Tarr, 1926), and the Bostwick Consistometer with imitative test for thickness of tomato purees (Mc Carthy and Seymour, 1993). After that, Universal Testing Machines were developed to configure different kinds of tests for the physical measurement of food texture. The TA.XT2 Texture Analyzer (Stable Micro Systems Ltd., Surrey, UK) is one of them and was used in this research. It consists of a drive system, test cells and force measuring and recording system, the same as other universal testing machines. In terms of semi-solid foods amongst others it has been applied to evaluate the consistency of milk sweets and caramel jam based on a compression test (Corradini and Peleg, 2000); Barigou *et al.* (2003) determined the elastic properties of the alginate particles (Barigou *et al.*, 2003); Cunha and Viotto (2010) observed the values for springiness, gumminess, adhesiveness and hardness measured in a compression–decompression cycle test to compare different emulsifying salts for preparation of processed cheese samples. Texture parameters such as firmness, viscosity, cohesiveness, springiness, stickiness, stretchiness, gel strength and other properties of semi-solids are able to be analyzed by the Texture Analyzer through different types of tests. Here the so called Back Extrusion test is used in which a probe is forced into the semi-solid food contained in a sample holder that is only slightly larger in diameter than the probe. Compression velocity is pre-selected and once the maximum travel distance is reached, typically chosen to be a few millimeter of the bottom of the sample holder, the probe is retracted from the sample at the same velocity. A typical force–distance curve is obtained from this test interpreted as firmness, cohesiveness, consistence and viscosity. These details are illustrated in Section 2.3.

Parameters obtained from texture analysis measured by Texture Analyzer on semi-solid foods have been compared with data obtained through sensory assessment in some previous studies. In Kealy's study (2006), a strong correlation was found between the taste panel and physical results of hardness and adhesiveness of cream cheese. Correlations were also observed between values determined by instrumental texture and the sensory attributes of cream cheeses in Brighenti's work (2008). Illustrated in Table 1.1, high positive correlations ($p<0.001$) were obtained between the hardness values (determined by penetration and spreadability tests) and sensory firmness, stickiness and cohesiveness of mass (Brighenti *et al.*, 2008). However, few studies in literature concern the relationship between physical texture data and the pressure/force data during oral processing. There is one study reported by Taniguchi *et al.* (2008) who quantified behavior of the tongue using liquid, syrup, thin and thick pastes for oral manipulation. The detailed method is described in Section 1.4.5. They found that posterior tongue activities with thin and thick pastes eating were larger than the activities with liquid and syrup eating.

Table 1.1 Pearson correlation coefficients between the instrumental (rheological and textural) parameters and sensory properties (Brighenti *et al.*, 2008).

	Instrumental texture	
Sensory	Penetration hardness	Spreadability hardness
Firmness	0.89***	0.88***
Stickness	-0.85***	-0.83***
Gumminess	0.51*	0.55*
Cohesiveness of mass	0.85***	0.86***

*P < 0.05; **P < 0.01; ***P < 0.001

Briefly summarized, the TA.XT2 Texture Analyzer is been universally used to reveal the mechanical nature of a food. It is also a machine allowing easy manipulation on the semi-solid samples and therefore, it was adopted for the texture measurement in this thesis.

Sensations experienced during oral processing may reflect food quality though the effects of oral manipulation on food texture. In order to better understand the oral processing and especially the role of tongue, the physiology of the tongue and the manipulations of the tongue during eating are reviewed in the following two sections.

1.2 Physiology of the tongue

The human tongue, attached to the floor of the mouth, is a highly mobile and deformable muscular organ with a virtually infinite number of degrees of mechanical freedom and without bony supports. It depends on the extrinsic muscles to anchor it firmly to the surroundings bones. The approximately anterior two-thirds of the tongue mostly lie in the mouth while the approximately posterior one-thirds of the tongue faces back to the oropharynx (Sanguineti *et al.*, 1997; Chen, 2009). The average length of the human tongue from the oropharynx to the tip is 10 cm (Kerrod, 1997) with the longest one (from the tip to the middle of the closed top lip) is 9.8 cm (Taylor, 2009) and the widest tongue is 7.9 cm (Sloot, 2010).

The muscles of tongue are the soft components able to move its body for oral behavior. They can be divided into two groups, extrinsic and intrinsic muscles. There are four paired extrinsic muscles (Figure 1.1) attaching the tongue to other structures in the role of tongue reposition during movement. Genioglossus is responsible for tongue protrusion, the hyoglossus is responsible for tongue depression, styloglossus is responsible for tongue elevating and retracting, and the pallatoglossus enables elevating the back of the tongue and depressing the soft palate. The four paired intrinsic muscles are the superior longitudinal muscle, the inferior longitudinal muscle, the verticals and transverses (Figure 1.2). These intrinsic muscles are arranged along the length of the tongue, in control of the lengthening and shortening of the tongue, the curling and uncurling of its apex and edges, and the flattening and rounding of its surface. (Dubrul, 1988; Huang *et al.*, 1999; Chen, 2009)

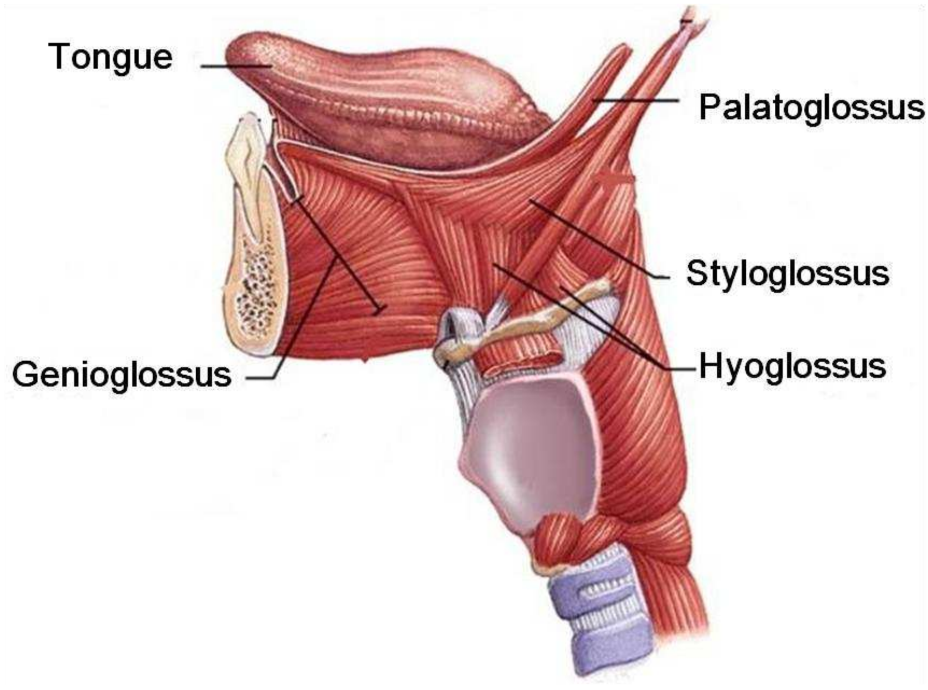


Figure 1.1 Extrinsic muscles of tongue (The McGraw-Hill Companies, 2012)

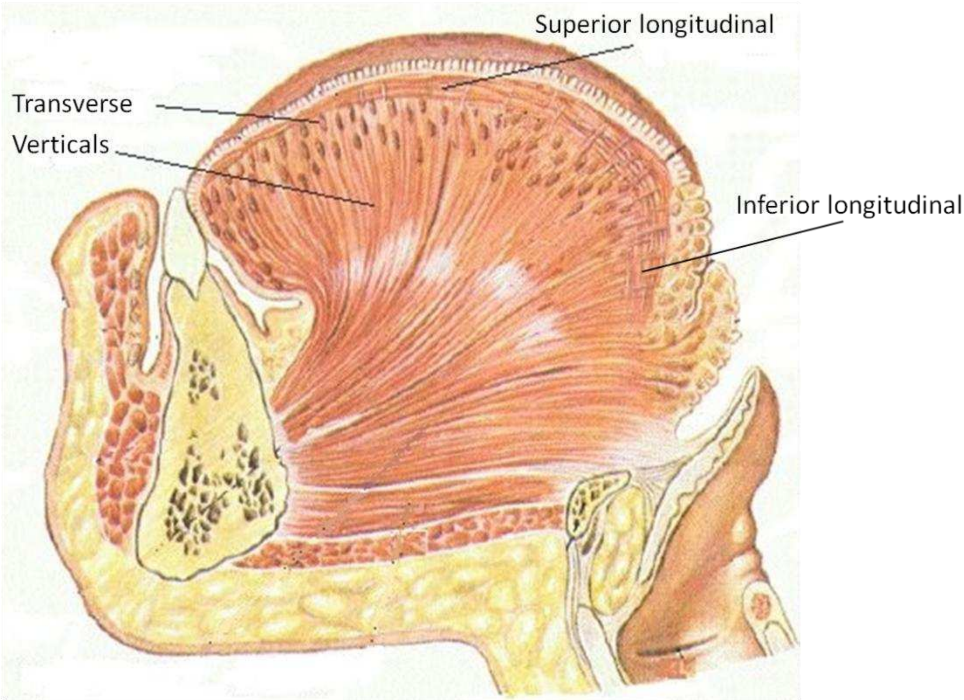


Figure1.2 Intrinsic muscles of tongue (Armstrong, 1998)

The muscles enabling actions such as speech, swallowing, licking and kissing, initially, are manipulated by the nervous system. The nerve distribution within the tongue is presented in Figure 1.3 (Mu and Sanders, 2010). The hypoglossal nerve (XII) with its branches is located between the lingual (LN) and glossopharyngeal (IX) nerves in the posterior tongue.

Two extrinsic (hyoglossus and styloglossus) and one intrinsic (inferior longitudinal) muscles receive their nerve supplies from the I-XII (the lateral branch of hypoglossal nerve), whereas the genioglossus and the other three paired intrinsic (superior longitudinal, transverse, and vertical) muscles receive their innervations from the m-XII (the medial branche of hypoglossal nerve) (Abd-El-Malek, 1938; Mu & Sanders, 2010).

The hypoglossal nerve is one of the 12 pairs of cranial nerves (XII). It enters the tongue from each side at the ventrolateral aspect of the posterior tongue and gives off its first branch to supply the geniohyoid muscle. Then it is divided into l-XII and m-XII branches. The hypoglossal nerve provides the muscles of the tongue with signals from the brain, playing an essential role as a motor in the movements of speech, food manipulation and swallowing (Alves, 2010; Lin and Barkhaus, 2009; Smith, 2011). Differently, the palatoglossus muscle is the only muscle of the tongue that is not innervated by the hypoglossal nerve but innervated by the vagus nerve (cranial nerve X) (Tachimura *et al.*, 2005).

The lingual nerve (LN) is a branch of cranial nerves travelling from the mandibular nerve of the trigeminal nerve to the inner space between the inferior longitudinal and the genioglossus muscles. The branches of the lingual nerve give their supplies to the superior and the inferior longitudinal muscles. Numerous communications are between the lingual and hypoglossal nerves in the tongue. Actually, the lingual nerve is a sensory nerve which innervates the sensation of taste buds from the fungiform papillae of the anterior two thirds of the tongue. (Saigusa *et al.*, 2006; Mu and Sanders, 2010)

Although the glossopharyngeal nerve (IX) does not innervate the extrinsic and intrinsic tongue muscles, the mucosa of the tongue is supplied by the glossopharyngeal and lingual nerves. The main trunk of the glossopharyngeal nerve enters the mucosa at the most posterior lateral portions of the tongue. It receives general sensation from the posterior regions of the tongue and some tastes function within the middle one-thirds of the tongue. (Doty *et al.*, 2009; Tomita *et al.*, 1986)

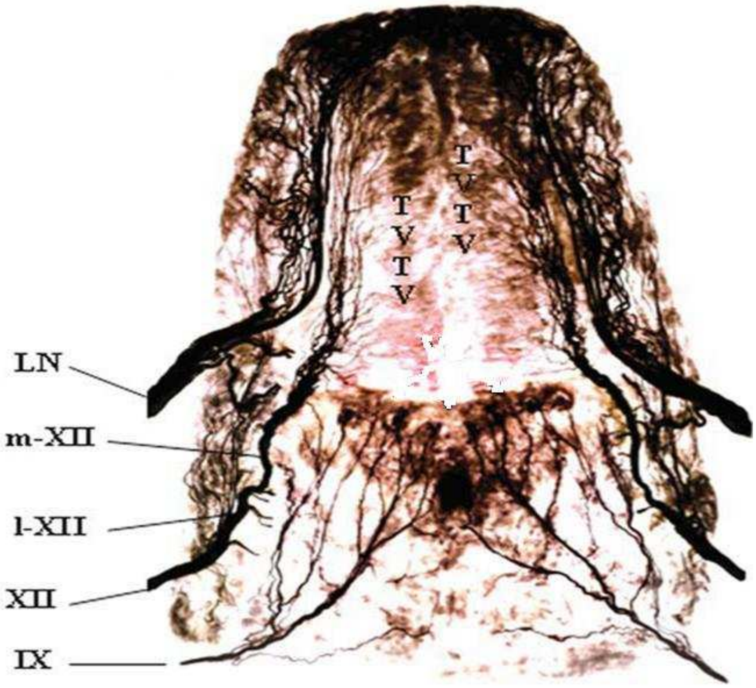


Figure 1.3 Entire nerve map of the adult human tongue demonstrated by Sihler's stain. LN: lingual nerve; XII: hypoglossal nerve; l-XII: the lateral branch of hypoglossal nerve; m-XII: the medial branche of hypoglossal nerve; IX: glossopharyngeal nerve. T: posterior transverse muscles; V: vertical muscles. (Mu and Sanders, 2010)

The branches of cranial nerves are responsible for different muscles of the tongue with numerous communications which work in coordination to produce movements. A rich blood supply, mainly provided by the lingual branch of the external carotid artery supports the tongue activities (Blissett *et al.*, 2006). This dissertation focuses on tongue movements that occur during oral manipulation of semi-solid foods.

1.3 Operation of the tongue during oral processing

In addition to gustatory sensation, the primary role of the tongue is aiding the oral processing of food.

Oral processing encompasses the coordination of teeth, jaw, tongue, saliva and pharynx with a series of physiological, physical, chemical and biochemical reactions taking place. For solid foods, oral processing involves five operations: bite, mastication, bolus formation, food transportation and swallowing. For semi-solid or liquid foods, bite, mastication and other work of teeth may not be required. Their bolus formation and transportation is mainly the result of cooperated operations of tongue and saliva, and swallowing is facilitated by tongue and pharynx.

The main purpose of oral processing is to form a suitable food bolus for easy swallowing (Prinz and Lucas, 1997). As soon as the mouth is opened for food intake, movement of the tongue starts. The tongue moves forwards and backwards to introduce the food into the mouth (Okada *et al.*, 2007), then compresses the food against the upper palate and breaks it down into smaller fragments (Blissett *et al.*, 2006, Salles *et al.*, 2011). Food size reduction is a crucial requirement for bolus formation. It also increases the food surface area for exposure to enzyme digestion (Alexander, 1998). During food size reduction and regardless of food type, increased food hardness was found to significantly relate to increased tongue muscle activity (Foster *et al.*, 2006). During oral processing, saliva gradually flows into the gaps between the food particles dissolving the components of the food and enhancing the viscous cohesion of the bolus (Prinz and Lucas, 1997). For all the vegitable and nut samples it was found that when swallowable boluses were formed, the weight of the food boluses lost 60% of their initial weight, which might result from the liberation of liquid content and soluble nutrients and the transportation of food particales (Peyron *et al.*, 2004). Mishellany *et al.* (2006) have claimed that different bolus structures and different individual oral strategies may contribute to the formation of various granularities of bolus particles.

Oral processing is generalized into two stages of food transportation by Hiiemae and Palmer (1999). The first stage is transport of food from the incisal region to the molar area in the oral cavity where a swallowable food bolus is formed. Either solid or semi-solid or liquid food is carried from the canine region to the last molars by a fast retraction of the tongue when the jaws are held at a wide gap coordinated with the retraction of the hyoid in the first stage. The second stage is the transport of the swallowable food bolus from the oral cavity to the oropharyngeal surface of the tongue for pharyngeal swallow (Hiiemae and Palmer, 1999). The tongue squeezes and propels the bolus with the palate toward the oropharynx through the fauces (Okada *et al.*, 2007). In contrast to solid foods, semi-solid foods resembling boluses require little mastication (de Wijk *et al.*, 2011). Hiiemae *et al.* (1995) found that all parts of the tongue and hyoid had anteroposterior and vertical movement in high-amplitude synchrony when eating semi-solid foods. Bolus transportation is through the beginning to the end of eating process.

As soon as a food bolus is formed, swallowing is initiated voluntarily. Some studies claimed that the trigger to swallowing depends on food type (Prinz and Lucas, 1997; Hoebler *et al.*, 2000) whereas some found it was by bolus size (Lucas and Luke, 1984; Buschang *et al.*, 1997). Swallowing can be seen as the final stage of the eating process (Chen and Lolivret, 2011). Okada *et al.* (2007) discovered that in case of humans at least two swallows are involved to clear the oral cavity of a food. Each swallow is composed of three continuous phases: an oral phase, a pharyngeal phase, and an esophageal phase (Chen, 2009). The first phase is a voluntary movement of saliva, liquid or a prepared food bolus passed to the back of the oral cavity by the tongue sweeping (Pedersen *et al.*, 2002). When swallowing is initiated, the bolus is moved beneath the anterior part of the tongue where the tongue tip is able to elevate the bolus (properties: e.g. size or viscosity) and judgment whether it is ready to be swallowed occurs (Dodds *et al.*, 1989). Then the bolus is pulled into a supralingual position by the tip of the tongue pressing against the incisors. Meanwhile, the lateral edges of the tongue forms a groove on the tongue dorsum through which the bolus can pass to the entrance of the oropharynx. The palatoglossus muscle is the primary muscle for the tongue elevation (Tachimura *et al.*, 2005). Both pharyngeal and oesophageal phases are entirely based on reflex occurring in the pharynx and oesophagus, respectively, and are much shorter than the oral phase (Chen, 2009). During swallowing, the activity pattern of the anterior tongue is shifted from a decrementing discharge pattern to an incrementing discharge pattern by altering from the upright to the horizontal supine position (Inagaki *et al.*, 2009). The extrinsic tongue muscles, especially the genioglossus muscle, blend with the intrinsic muscles make the greatest contribution to swallowing (Yoleri and Mavioglu, 2000). Although the activity taken by geniohyoid muscles lags behind the genioglossus muscles, both pairs of muscles appear to remain active until the bolus has passed the area of the laryngopharynx (Cunningham and Basmajian, 1969). The activities of swallowing and tongue movement are cooperated well, which may be because they share the same brain regions (the left lateral pericentral and anterior parietal cortex, the anterior cingulate cortex and adjacent supplementary motor area) (Martin *et al.*, 2004). Jack and Gibbon (1995) used the technique of electropalatography (EPG) to find that semi-solid foods require three rolling tongue motions to clear the food from the mouth and jelly require up to six rolling cycles while liquid milk requires two of these, some of which did not give full contact between the tongue and upper palate.

It is clear that the tongue plays a major role in eating process. A large body of knowledge on its biology and the general role during eating is available. Less well established though are the interactions with specific types of foods. These may be established by quantifying the mechanical response of the tongue during the eating process. The following section provides a review of the relevant literature of tongue. It has been found that mechanical studies on the tongue including the design and application of measurement techniques have predominantly been developed in the context of medicinal research or treatment such as for patients with dysphagia will be reviewed in the following section (1.4). As mentioned before, correlations between physical data on food texture and in-vivo tongue pressure data are scarce but the one study is included in Section 1.4.5.

1.4 Tool development for tongue movement in previous studies

As the technology development, the tools applied on the studies of tongue movement for human physiology, medical application and clinical issues are invented. Some advanced imaging techniques such as cinefluorography, ultrasound, electro-palatography and NMRI, have been used to support the sophisticated analyses of tongue movement (Hiiemae and Palmer, 2003). For example, the extraction and tracking of tongue surface movements during speech (Akgul *et al.*, 1999; Stone and Vatikiotis-Bateson, 1995) or during feeding (Imai *et al.*, 1995; Stone and Shawker, 1986) were recorded by ultrasound image sequences. Further, cinefluorography and videofluorography are able to record a continuous video of the oral movements close to actual speeds. In addition, some devices were designed to attain physical data, e.g. pressure, of the moving tongue.

The six types of pressure devices that have been applied to measurements on the tongue are introduced below.

1.4.1 Strain gauge pressure transducer

The strain gauge pressure transducer (Figure 1.4) is one of the early pressure devices designed by Proffit *et al.* in the 1960s to establish the range of tongue pressure against the teeth in normal adults during swallowing (Proffit *et al.*, 1964). It consisted of a 4 mm X 8 mm stainless steel deflection beam with a thickness of 0.127 mm insulated with a thin covering of epoxy resin, then covered by two resistance strain gauges on each side. Pressure data was measured when 25 subjects made 5 involuntary swallows with two pressure transducers placed on the upper palate toward incisors and molars at the same time, respectively. Proffit *et al.* (1964) found that during swallowing the tongue exerted a relatively consistent pattern of pressure onto the upper palate where the incisors and the molars were located and tended to occur simultaneously in the two areas for each individual. A wide range in maximum tongue pressures occurred in subjects with similar dentitions.

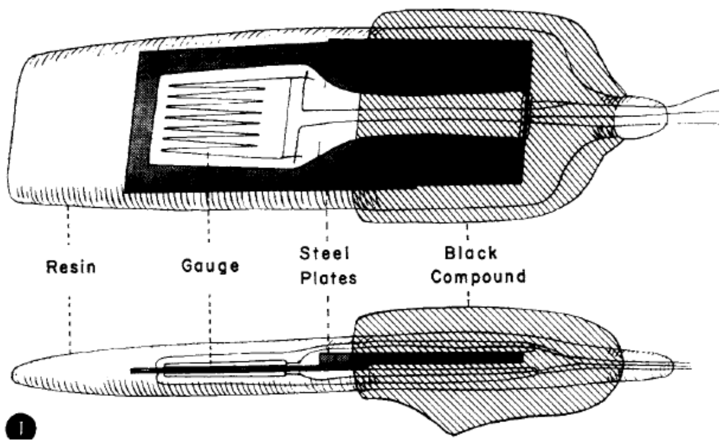
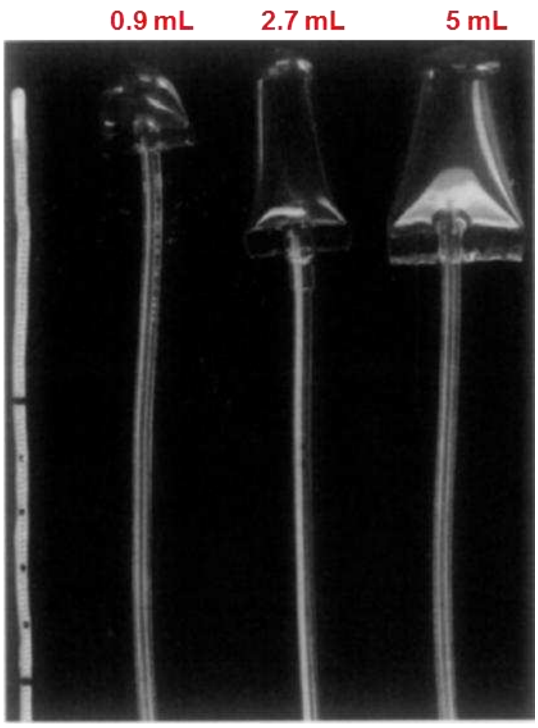


Figure 1.4 Strain gauge pressure transducer (Proffit *et al.*, 1964)

1.4.2 Iowa Oral Performance Instrument

The Iowa Oral Performance Instrument (IOPI) (Breakthrough, Oakdale, IA) with sensing bulbs (Medex Inc., Hilliard, OH) has traditionally been used to study tongue strength in varied swallowing conditions (Clark *et al.*, 2003; Robin *et al.*, 1991; Robin and Luschei, 1991). In Pouderoux and Kahrilas's study, the IPOI was worked by introducing a sensing bulb into a subject's mouth (Figure 1.5 C). Subjects were asked to perform a hard swallow with water samples using different volumes of bulbs (Figure 1.5 B). They also took in different viscous samples (water, chocolate pudding and mashed potato) with the same volume of bulb. The results showed that the pressure exerted by the tongue during swallowing depended on bolus viscosity and it could be reproduced by volitional control. The anterior two thirds of the tongue showed both greater forces and modulation than the tongue base root (Pouderoux and Kahrilas, 1995).

(A)



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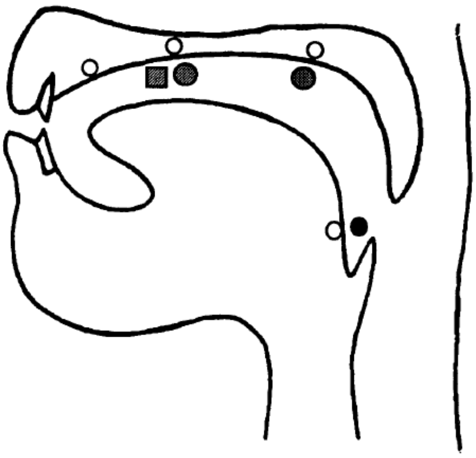


(c)

Figure 1.5 IOPI measurement. (A) IOPI. (B) Strain-gauge sensor with the three volume sizes (small size 0.9 mL, middle size 2.7 mL and large size 5 mL) of IOPI sensing bulbs; (C) Locations of the recording sites within the oral cavity (■, large bulb; ●, medium bulb; •, small bulb; O, strain gauge (Pouderoux and Kahrilas, 1995).

Another application of the IOPI was to measure the strength and endurance of tongue function in a group of individuals with normal and impaired swallowing (Stierwalt and Youmans, 2007). Strength and maximal pressures were measured by the subjects pushing the bulb against the roof of the mouth as hard as possible. Endurance of the tongue was collected immediately following the strength task by asking the subjects to sustain 50% of their maximum pressure for as long as possible. Comparing the swallowing between normal and impaired subjects, Stierwalt and Youmans (2007) found that tongue weakness related to signs of dysphagia.

1.4.3 Disposable oral probes

Hayashi and co-workers (2002) developed a disposable probe assembled using a small balloon, a stainless pipe, and a 1 mL disposable tuberculin-test syringe cylinder for measuring tongue pressure. To record maximal voluntary tongue pressure, the probe was pressurized to set the balloon diameter at approximately 18 mm. Subjects were then to press the balloon onto their palates as strongly as possible. To record tongue pressure during swallow, 5 mL of water were administered with a scaled 10 mL syringe and swallowed with the balloon in the mouth. A negative correlation to age was found both for maximal voluntary tongue pressure and tongue pressure during swallow (Hayashi *et al.*, 2002).

Assembled with Hayashi and co-workers' disposable oral probe, an infusion tube as a connector, and a recording device (Prototype device PS-03, ALNIC), a tongue pressure measurement device (Figure 1.6) was composed to measure the maximum tongue pressure in Utanohara *et al.*'s study (2008) where subjects were asked to raise the tongue and compress the small balloon probe onto the palate. Tongue strength was found to decline with aging and a progressive decrease in male subjects aging faster than female subjects (Utanohara *et al.*, 2008)

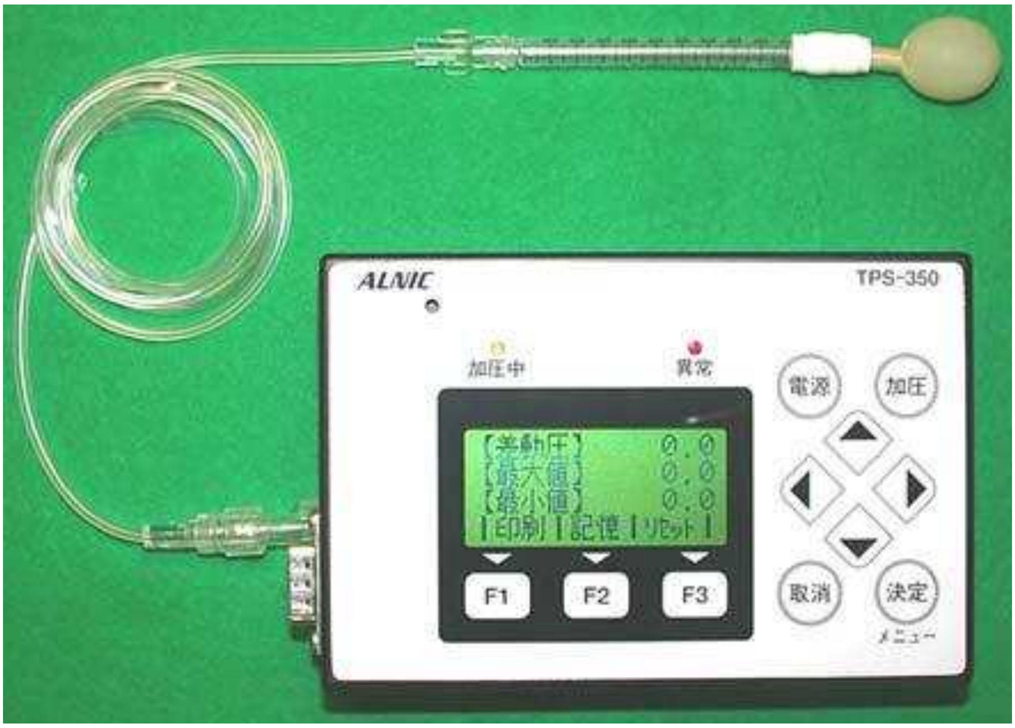


Figure 1.6 Tongue pressure measurement device. This device consists of a disposable oral probe and a recording device (Prototype device PS-03, ALNIC)

1.4.4 The transpalatal arch

In the report of Chiba *et al.* (2003), a transpalatal arch (TPA) was made with a 0.9 mm stainless steel wire and 3-dimensional transfer inserts (Figure .7 D) for tongue pressure measurements. To fix the TPA in the oral cavity, the 0.9-mm stainless steel wire had been welded to the 3D transfer inserts which were set on the first molar at each side. The loop of the TPA for sensors clinging to the contour of the palatal mucous membrane was placed at the level of the middle of the second premolars (P), first molars (M1), or second molars (M2) (Figure 1.7) respectively. The maximum recorded tongue pressures were taken from different positions at each act of swallowing for comparison. Significant differences were observed in comparisons between the positions P and M1, M1 and M2, and P and M2 (Chiba *et al.*, 2003).

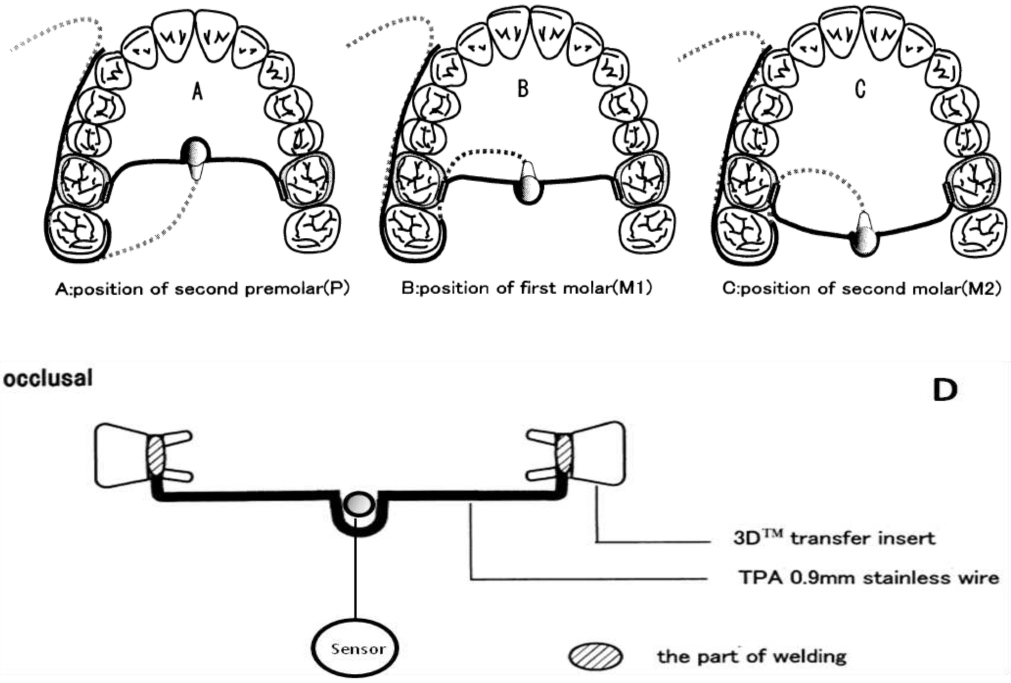


Figure 1.7 Positions (A, B, C) and Design (D) of pressure sensor.

1.4.5 A midline disk-shaped pressure sensor

A midline disk-shaped pressure sensor (Flexi Force Sensor model A101-1, Tekscan) (Figure 1.8) was applied to measure the tongue pressure against the hard palate with the two sensors positioned at the anterior tongue pressure (AT) and the posterior tongue pressure (PT) fixed using ethyl cyanoacrylate (super glue), respectively in Taniguchi *et al.*'s study (2008). 5 mL of samples (liquid, syrup, 0.5% agar and 1.0% agar) with different consistency were swallowed by eleven normal adults. The hardness, adhesiveness and cohesiveness of the foods were measured as physical properties using a creep meter (RE2-3305, Yamaden, Tokyo, Japan) and the viscosity was measured using a viscometer (TV-22, Toki Industry). The Kruskal-Wallis ANOVA on ranks and the coefficient of variation were performed to clarify the effects of food consistency on different tongue variables (Figure 1.9). The peak amplitude, area and time duration of the anterior and posterior tongue pressure all were found to increase with increasing hardness of the bolus (Taniguchi *et al.*, 2008).

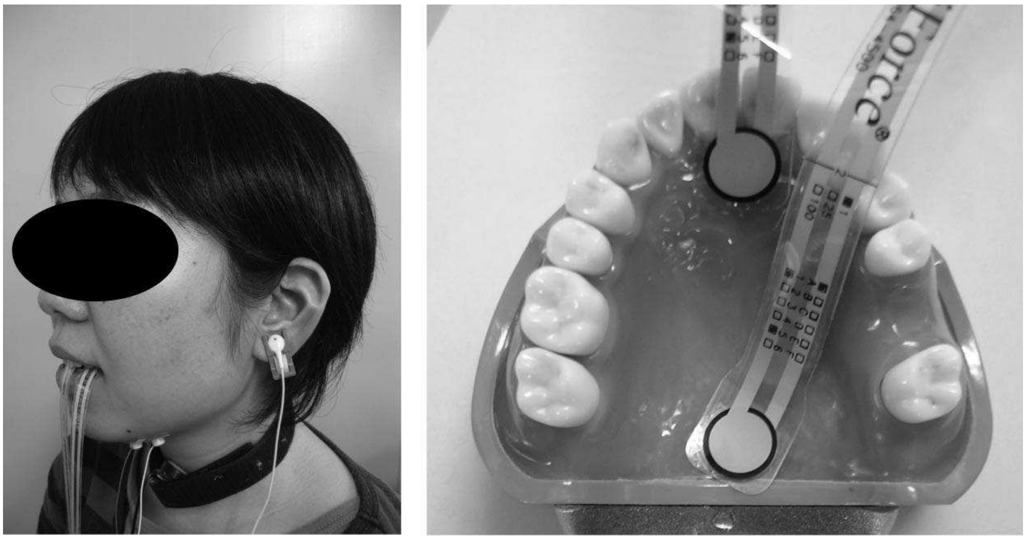


Figure 1.8 Positions of the midline disk-shaped pressure sensor

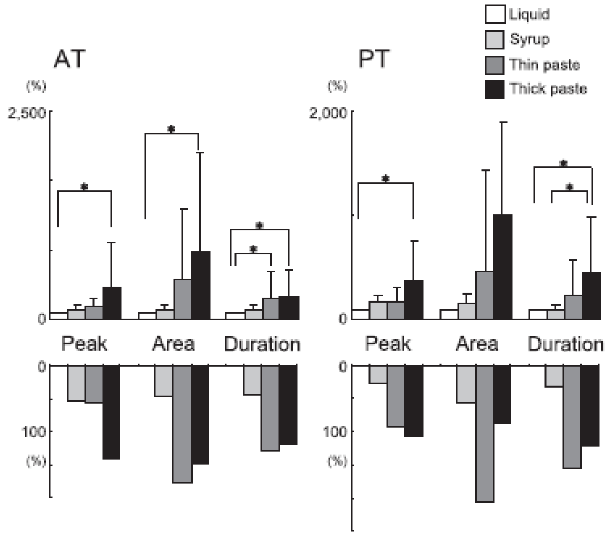


Figure 1.9 Effects of food consistency on the anterior (AT) and posterior (PT) tongue pressures. The top graphs show the mean values of the peak amplitude, area, and duration of each activity, which were normalized to the activity during swallowing of the liquid. The bottom graphs show the coefficient of variation of these values. *P <0.05. Thin paste: 0.5% agar; Thick paste: 1.0% agar.

1.4.6 An advanced pressure sensor system

An advanced pressure sensor system (I-SCAN, Nitta, Osaka, Japan) with five 0.1 mm thick sensor sheets (Nitta, Osaka, Japan) was designed to measure pressure. Five measuring points (Chs1-5) were attached on the palate with a sheet-type denture adhesive (Touch Correct II, Shionogi, Tokyo, Japan) shown in Figure 1.10 (Tamine *et al.*, 2010). The system was calibrated by applying negative pressure using a vacuum pump through an air duct in the cable of the sensor sheet. 15 mL of water were swallowed by young and elderly individuals in Tamine *et al.*'s (2010) study, which found the duration of tongue pressure was significantly longer in the elderly at all measuring points and the maximal magnitude of tongue pressure in the anterior-median part of the hard palate lower than in the young.

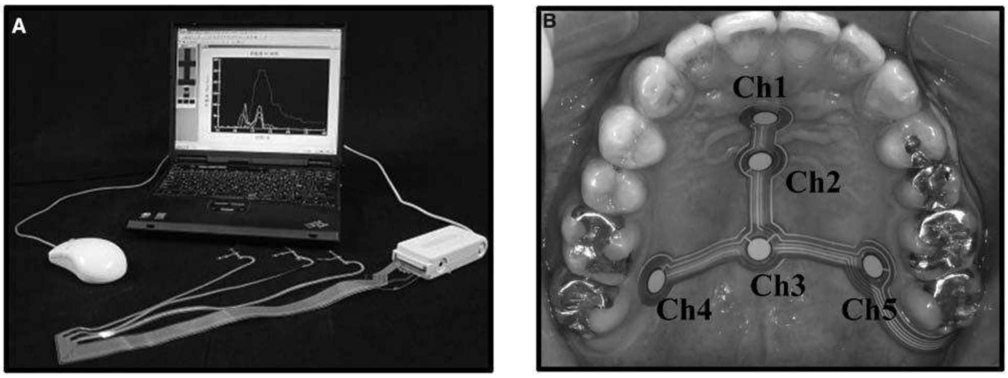


Figure 1.10 System used for measuring tongue pressure with a sensor sheet. (A) Complete view of measuring system. (B) The sensor sheet with 5 measuring points attached to the hard palate directly with denture adhesive. Ch1, anterior median part; Ch2, mid-median part; Ch3, posterior median part; Ch4, right lateral part; Ch5, left lateral part.

1.5 Tekscan I-Scan System

The Tekscan Industrial Sensing (I-Scan) System (Tekscan, Inc., South Boston, USA) equipped with the I-Scan sensor sheet model 4201 was chosen for the measurement of tongue movement in this dissertation (Figure 1.11). There has been no indication that this device has previously been used for in-mouth application. It is typically applied in human barefoot pressure analysis (Tekscan, 2011b).

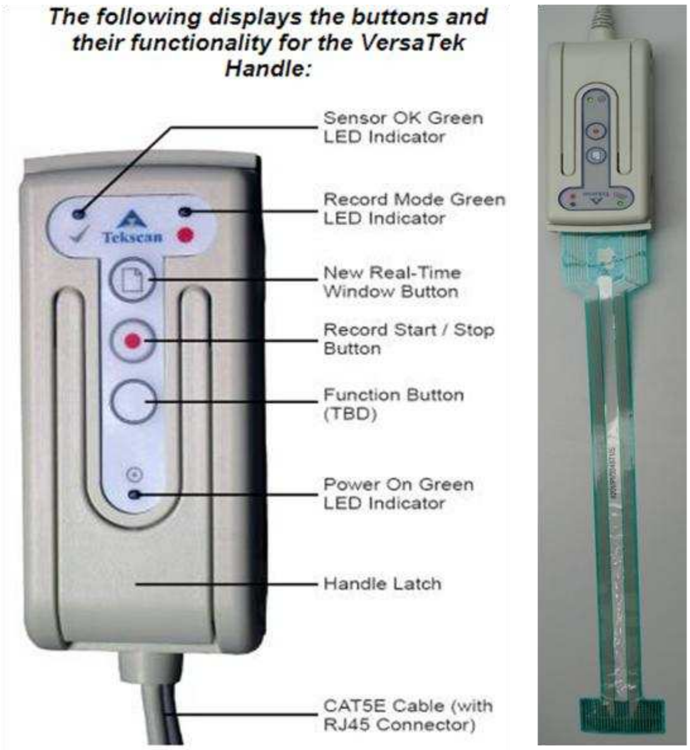
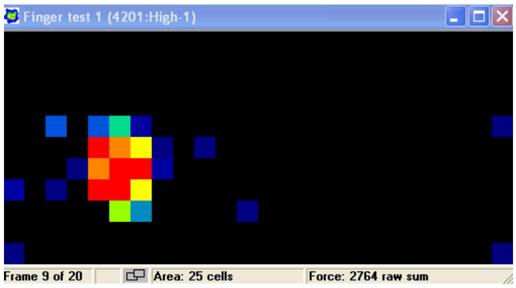
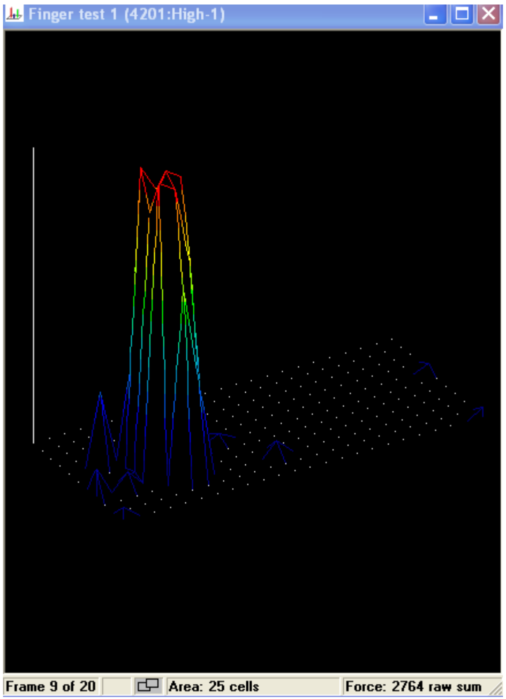


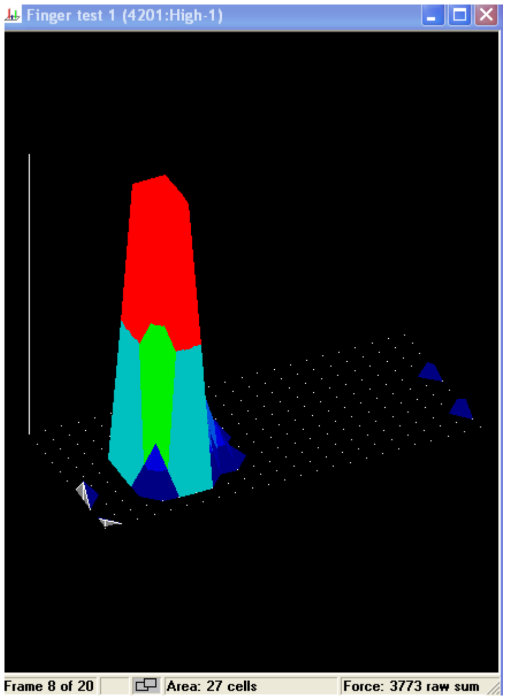
Figure 1.11 VersaTek Handle and Tekscan sensor model 4201

The I-Scan System is a tactile pressure and force measurement system consisting of a sensor sheet, a handle to hold the sensor sheet and a software package. The system allows to record and display real-time pressure data followed by data analysis and presentation. The Tekscan sensor model 4201 is an ultra-thin flexible printed circuit that measures the contact force and pressure between virtually any two contacting surfaces with a resistive-based technology. The thickness of a typical sensor sheet is 0.1 mm. The sensor acts as a variable resistor in an electrical circuit. The application of a pressure to an active sensor results in a change in the resistance of the sensing element in inverse proportion to the pressure applied. When the sensor is unloaded, its resistance is very high; when a force is applied to the sensor, the resistance decreases. This decreased resistance is converted to a digital value as a raw sum number with arbitrary unit in the range of 0 to 255. When a finger is placed onto force on the sensor sheet (Figure 1.12), for example, the raw digital value is the sum of the force perceived in the certain cells of the area where the finger touches. The heart of the I-Scan sensor sheet is the pressure sensitive layer producing its varying sensitivity. The pressure range of sensor model 4201 purchased for this study is from 0 to 5 PSI (0 - 34 kPa) with 264 individual pressure sensing cells. Each cell has a measurable force. The active sensing area of the sensor is surrounded by substrate material that contains conductive leads which connect the rows and columns of the active sensing area to the tab (terminal section) of the sensor.



A: 2-D window





B: 3-D Wireframe

C: 3-D contours

Figure 1.12 A finger force recording sample shown in two versions

Four parameters, force, contact area, contact pressure and peak force converted from the system were selected for use in this study. The following shows their ‘definition’ as taken from the instrument’s manual (Tekscan, 2011a):

Force: Total force for the object in contact with the sensor sheet. The unit of force is arbitrary unit is the total sum across all cells activated, labeled as 'raw sum'.

Contact area: Number of cells activated. The unit of contact area uses 'cells'.

Contact pressure: Result of force divided by contact area. The unit of contact pressure is labeled as 'raw'.

Peak force: The highest force recorded across cells and has unit 'raw sum'.

Tekscan I-Scan System is the leading system of tactile pressure and force measurement in the world. Its data acquisition enables researchers to analyze object's movement conveniently. Compared with the sensors of other instruments, the paper-thin sensor model 4201 of Tekscan is comparatively flexible and soft to attach the size of tongue. Therefore, the Tekscan was adopted for this study.

1.6 Summary of Introduction

Tongue movement manipulated by the innervations of nerve system on tongue muscles, is an oral behavior of human physiology (Section 1.2). It has usually been studied under the research of oral processing (Section 1.3) as the operation of tongue is tightly related to bolus formation and transportation and swallowing. Subjects in previous studies (Section 1.4) were asked to intake water (Tamine *et al.*, 2010), gummy jelly (Hori *et al.*, 2006), self-made syrup and agar (Taniguchi *et al.*, 2008), gelatine drink (Sanwa Kagaku Kenkyusho, Nagoya, Japan) (Kodaira *et al.*, 2006), and other solid foods to evaluate the oral behavior. Few samples were selected from common commercial foods and food texture studies (section 1.1) were less combined with tongue attributes. Even the development of devices (Section 1.4) to assess oral processing was mostly in the clinical context, for example the relationship between tongue functions and gender, aging or disease such as dysphagia. In summary, there is a gap in the knowledge about the movement as well as the forces or pressures exerted by the tongue during oral processing of daily foods.

1.7 Aim of the current project

The aim of this dissertation is to apply a commercially available pressure measurement system based on 0.1mm thick sensor sheets to evaluate tongue movement during oral processing of semi-solid and liquid foods. A specific objective is to quantify the pressures exerted by the tongue onto the upper palate and to test whether the in-vivo acquired data are correlated to physical measurement data of food texture by a Texture Analyzer. The key objectives are therefore to:

a) Adapt the sensor sheet to the upper palate and develop an experimental procedural for in-vivo measurement using Tekscan I-Scan System.

b) Evaluate the capacity of Tekscan I-Scan System on in-vivo measurement to Discriminate tongue parameters by consuming semi-solid and liquid products.

c) Compare Tekscan date with Texture Analysis of physical measurement on semi-solid products

2. Materials and Methods

2.1 Selection of foods

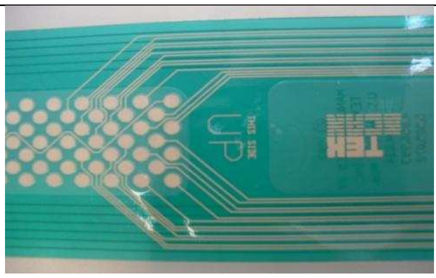
Six varieties of semi-solid foods with different texture were selected for this study: crème caramel (Sainsbury’s basics, J Sainsbury plc), crème fraîche (Sainsbury's, J Sainsbury plc), cheese spread (Dairylea, Kraft), custard (Ambrosia Devon, Premier Foods), jelly (Hartley's, Premier Foods), and stirred yogurt (Sainsbury's, J Sainsbury plc). Additionally, Yogurt drink (Actimel, Danone) is one liquid food included in the measurement for comparison. All these foods were commercial products purchased from a local supermarket (Sainsbury’s, UK). Product information is shown in Appendix I.

2.2 Tongue measurement protocol

2.2.1 Sensor sheet preparation

The Tekscan sensor model 4201 (Figure 1.8) (Tekscan, Inc. USA) was used. To prepare the sensor for in-mouth use, it was wiped with alcohol followed by wrapping in household cling film. Care was taken to not trap air bubbles. The cling film was changed after each subject. For measurement, the sensor sheet was fixed to the subject’s upper palate using denture cushions (Snug denture cushions, The Mentholatum Company, Canada) and denture cream (Poligrip denture fixative flavor free cream, GlaxoSmithKlein; United Kingdom). Both dental tools are flavor free to eliminate the flavor effect on subjects’ eating with the sensor sheet fixed in the mouth.

One piece of denture cushion cut to a suitable size was placed on the upper face of the sensor sheet and denture cream was squeezed on. The cushion was also moistened with water to enhance the adhesiveness to the upper palate. After this preparation, the sensor sheet was inserted in subject's oral cavity and attached firmly onto the upper palate. Figure 2.1 illustrates the process.

<table>
<tr><td></td><td></td></tr>
<tr><td>A: Upper side</td><td>B: Cling film covered</td></tr>
<tr><td colspan="2">
</td></tr>
<tr><td colspan="2">C: Denture Cushions</td></tr>
</table>

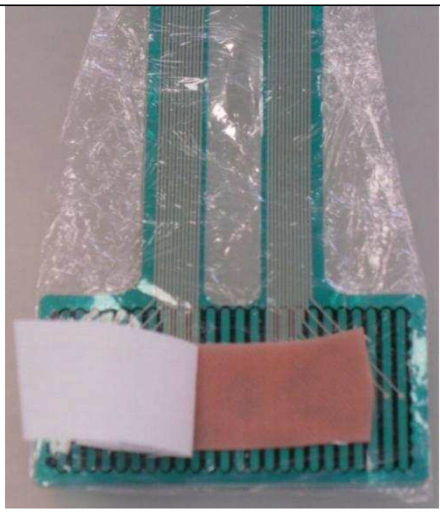
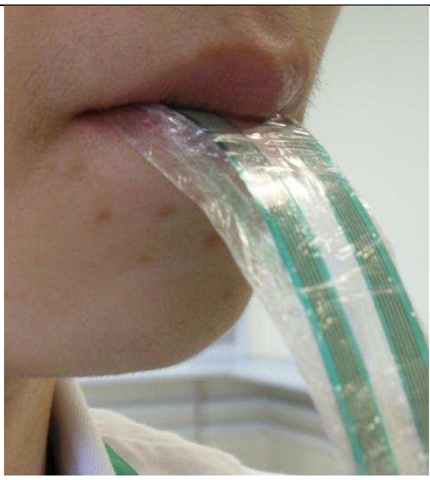
	
D: Appropriate size of Denture Cushion	E: Appropriate amount of Denture Cream
	
F: Sensor sheet inserted	G: Sensor sheet held on palate

Figure 2.1 Images of sensor sheet preparation

2.2.2 Food sample preparation

Crème fraîche, cheese spread, custard, stirred yogurt and yogurt drink were transferred from their original packaging into separate transparent plastic cups. Crème caramel and jelly were presented to subjects in their original packages as they were set products and cannot be transferred into other containers without appreciably changing product texture. All samples were prepared and then stored at 4°C before serving on a tray also holding knives, teaspoons, water and tissue paper.

Samples were presented in a randomized order as produced by the FIZZ Sensory Analysis Software (Biosystèmes, France).

2.2.3 Amount intake

The amount of sample in each measurement used was one teaspoon 5 mL which was referred to in previous tongue studies (Pouderoux and Kahrilas, 1995; Taniguchi *et al.*, 2008; Tachimura *et al.*, 2005). One study had used 1 mL to 20 mL water, 3 mL pudding and 3 mL potato for quantifying the tongue forces in different bolus volumes and the different volumes of samples did not change 'the timing of the pulsive tongue force' and 'the force produced by tongue' ($p \leq 0.05$) in Pouderoux and Kahrilas's study (1995), but 3 mL of the most viscous samples (e.g. pudding and potato) increased the tongue clearing pressure. In Taniguchi's study (2005), the volumes of semi-solid samples were 5 mL each samples for different tongue variable. Only when the amount of samples was equal in each measurement, the data could be statistically analyzed. In this study, the semi-solid food samples were viscous and hard. The time lengths of oral process, convenient operation and the subjects' acceptable capacity in one oral process were considered for the amount intake. 3 mL of sample was able to be used for the tongue pressure measurement but it was not good enough to compare the time lengths of oral process across different foods because the time of finishing 3 mL samples by subjects would not be differentiated clearly. It would give the subjects a mental pressure if the same experiment was taken five times with each subject having 10 mL each time and 50 mL in total. Therefore, 5 mL was an appropriate volume for the comparison in time lengths of oral processing across foods, easy operation and less pressure.

2.2.4 Participating subjects

The 10 subjects participating in this study were volunteers and recruited from the Division of Food Sciences at The University of Nottingham. There were 6 females and 4 males aged 22 to 30. Due to the small panel size, age and sex were not considered in the panel selection or interpretation of the results.

Each subject attended two sessions within one week. In the first session, 3 samples were served while 4 samples were served in the second session. 5 replicates of each sample were presented in one session. During measurement, the subject was seated at a table normally and naturally with samples and Tekscan instrument, facing a window of outside natural landscape.

2.2.5 Measurement process

The use of the Tekscan for in-mouth measurement was novel. The measurement process had to be developed. This was a collaborative process between the panelists and the operator. The measurement started when the sensor sheet had been firmly attached to subject’s upper palate.

Each subject was given one teaspoon amount (5 mL) of the sample. The panelists inserted the teaspoon into the mouth and then by turning it over left the sample on the tongue. Then the teaspoon was removed. The panelists then showed a thumb-up gesture to indicate readiness to start. Upon a sound prompt from the computer, the panelist started to eat the sample. During the eating process, panelists were asked to manipulate the food only using their tongue without any help from the teeth. Once the panelists had finished eating, another thumb-up gesture was shown to the operator to stop the recording. Water was used to clean the palate and there was a five-minute break before the next sample.

2.2.6 Measurement variables

All data was exported from the Tekscan I-Scan System into Microsoft Office Excel 2007 (Microsoft Corporation, USA). Force, contact area, contact pressure and peak force with their recording time were the four parameters recorded in this study. It should be noted that the I-Scan software does not attach physical units to the measurement parameters which are replaced by arbitrary units due to an unavailable calibration device. Within the Tekscan I-Scan System, the units of force and peak force are labeled as ‘raw sum’ and contact area is a number of ‘cells’ while contact pressure is ‘raw’. From the four sets of data the 16 variables shown in Table 2.1 were chosen. All the variables were quantitative and analyzed with ANOVA.

Table 2.1 Measurement variables grouped by force, area and pressure based parameters

Force (raw sum)	
Maximum Force (Max Force)	Time at Maximum Force (MFT, s)
Contact Area (cells)	
Maximum contact Area (Max Area)	Time at Maximum contact Area (MAT, s)
Contact Pressure (raw)	
Maximum contact Pressure (Max Pressure)	Total contact Pressure
Time at Maximum contact Pressure (MPT, s)	Contact pressure at 0.3 s
Number of the peaks in contact Pressure (NO. Peaks in Pressure)	End contact Pressure
Average contact Pressure	Finish Time (FT, s)
Peak Force (raw sum)	
End Peak Force	Total Peak Force
Number of the highest Peak Force	Average Peak Force

'Maximum force', 'maximum contact area' and 'maximum contact pressure' were extracted as the maximum values during the recording. The 'times' to each of the maximum variables were also selected. Parameters are recorded every 0.25 s in the I-Scan System and the 'total contact pressure' and 'total peak force' are the sum values of all records within the recording time. Total recording time is referred to as 'Finish Time' in this thesis. 'Average contact pressure' and 'average peak force' are the 'total contact pressure' and 'total peak force' divided by their corresponding recording time

(Finish time). 'Contact pressure at 0.3 s' was selected for comparison with previous studies that showed discrimination in pressure applied across other products (Kohyama and Nishi, 1997). 'End contact pressure' was the value selected at the last second of recording when there was no food left in the mouth as indicated by the subjects. 'Number of peaks' is the number of the peaks shown in the output from I-Scan System. Figure 2.2 illustrates an example of a graph with 6 peaks in one cheese sample used in this research.

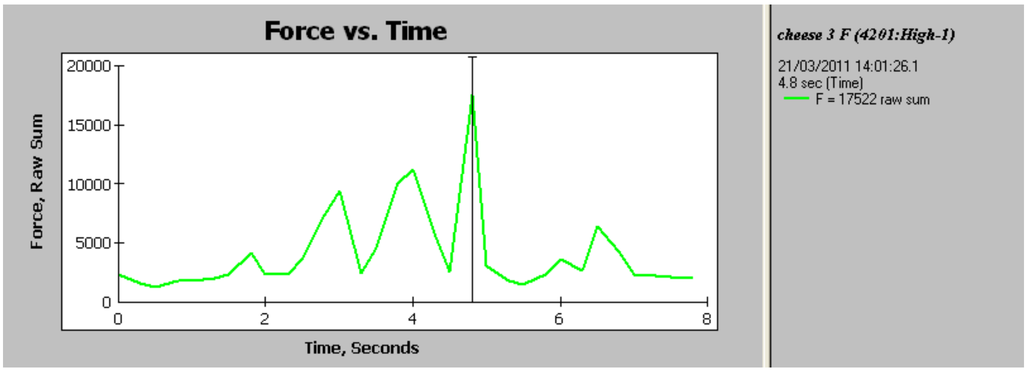


Figure 2.2 Example of a graph in I-Scan System. A record of one cheese sample consumed by subject F.

2.3 Texture analysis

Tongue movement measured by the new technique Tekscan I-Scan System presents the figures on varieties of foods with subjective variation. To assess whether the tongue measurement is able to discriminate between different food textures Texture Analysis (TA) was conducted on the foods included in this research.

The TA.XT-Plus Texture Analyzer (Stable Micro Systems Ltd., Surrey, UK) was used to measure the texture of the semi-solid foods. The back extrusion test with a cylindrical aluminum probe (diameter 38 mm, height 5 mm) was applied. It has previously been used to study the texture properties consistency, firmness, viscosity and cohesiveness of stirred yogurt (Rawson and Marshall, 1997) and dairy cream (Piazza *et al.*, 2009). The products in this study resemble these types of foods, thus choice of the back extrusion test seemed appropriate.

Crème fraîche, cheese spread, custard, stirred yogurt and yogurt drink were transferred from their original packaging into 100 mL polypropylene containers (height 72 mm, top diameter 56 mm, and base diameter 45 mm). The container was filled 50 mm high. Crème caramel and jelly were examined in their own package so it was unnecessary to disturb product texture by transferring these set products into another container. It should be noted that the polypropylene containers chosen here were of similar dimensions to the packaging of crème caramel and jelly which was deliberate.

Ten replicate samples of each product were prepared and stored at 4°C before texture measurement. The order of measurement in terms of food product was randomized to minimize the temperature effect on the measurement.

The test speed for all test intervals was 2 mm/s. The test was set up with a trigger force of 15 g following detection of which the probe moved into the sample to a depth of 25 mm. As soon as the probe reached the maximum sample depth, the direction of movement was changed and the probe moved upwards out of the sample. It was necessary to firmly hold down the sample container to prevent it from being lifted upwards by the probe.

The force data collected were analyzed for firmness, consistency, cohesiveness and index of viscosity as illustrated in Figure 2.3 using instrument's software (Texture Exponent 32 version 2.0.6.0).

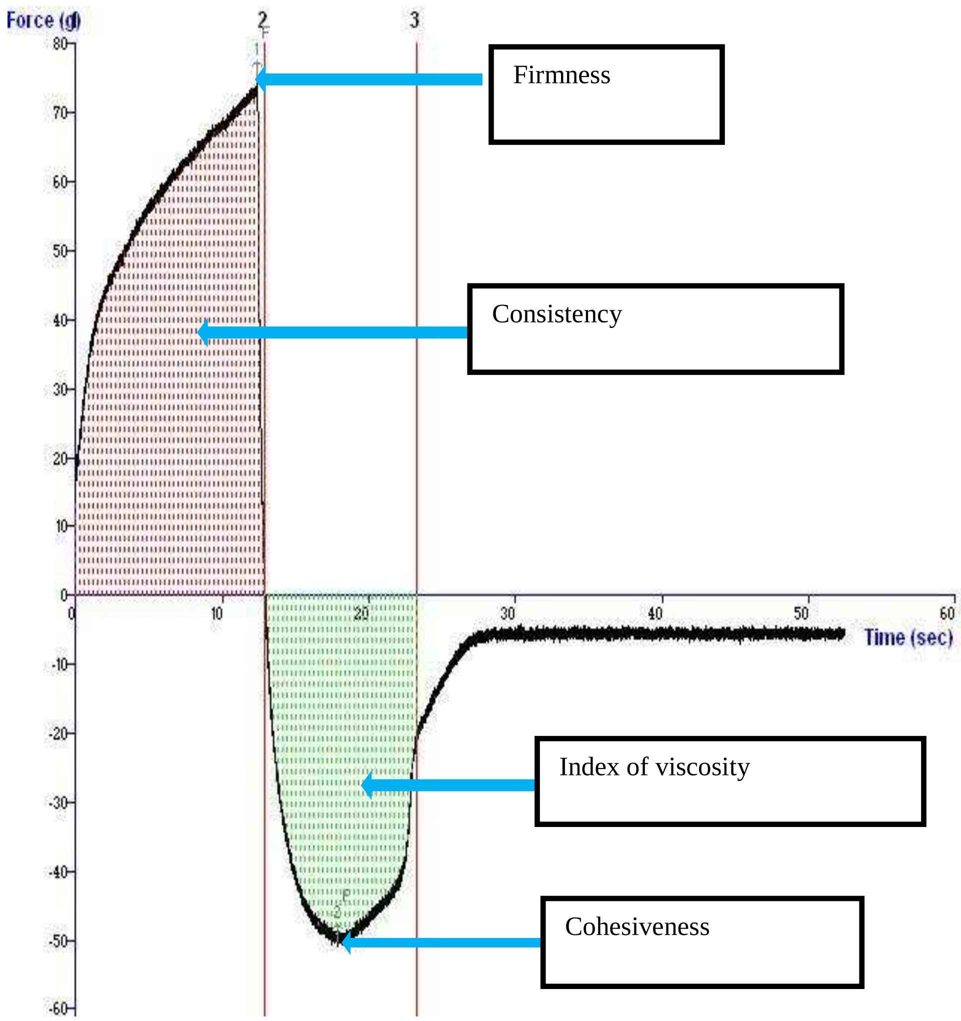


Figure 2.3 Example of a back extrusion result for custard

Firmness is defined as the maximum positive force and is usually detected when the probe reaches the chosen maximum depth (25 mm). The area underneath the positive curve up is taken as a measurement of consistency. Cohesiveness relates to the maximum negative force attained on removal of the probe out of the sample. It should be noted that all values recorded while the probe moved upwards have a negative sign. The area underneath the negative region of the curve is an indication of the index of viscosity. In Figure 2.3, the boundary of this area is along line 3 when the probe leaves the sample. The force values shown on the right of line 3 are results from the residual food stuck to the probe. The unit of the force variables, firmness and cohesiveness is grams, whereas grams*second is used for the area variables consistency and index of viscosity.

2.4 Additional instrumental developments

Further attempts to optimize experimental protocol and data analysis, and other observations worth reporting are summarized.

2.4.1 Half size sensor sheet

The width of the sensor sheet model 4201 is 51 mm which is rather large compared to the size and shape of the upper human palate. Whereas it was possible to use this sensor sheet, it would have been desirable to have a smaller sized sensor sheet. The edges of the original sensor sheet bended and touched both sides near to the gums. It might have an influence on the result when teeth touched the edge of the sensor sheet which would be recorded as a part of the pressure signal. Therefore, this size problem was attempted to be resolved by cutting the sensor sheet to a smaller size in two different cuts using a pair of scissors.

One sensor sheet was cut carefully along the middle black line (Figure 2.4 A) but its pressure distribution did not work as the circuit might have been destroyed by the cut. Another sensor sheet was cut along the both third black height lines from either side (Figure 2.4 B). A measurement with 5 subjects and 3 products (crème fraîche, custard, and stirred yogurt) was carried out using the half size sensor sheet. However, the pressure distribution was found to be extremely high during the measurement and maybe the circuit was damaged by the liquid and saliva penetration through the cut edges of sensor sheet despite tight coverage with three layers of adhesive tape. As the sensors are costly, it was decided to not risk damaging further sensory sheets and to use full sized sheets only.

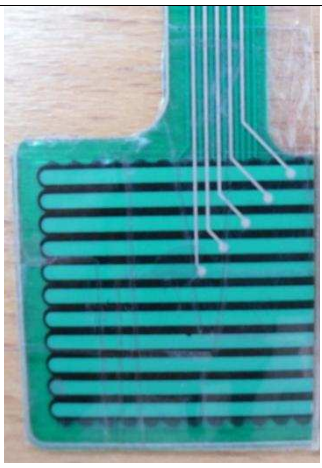
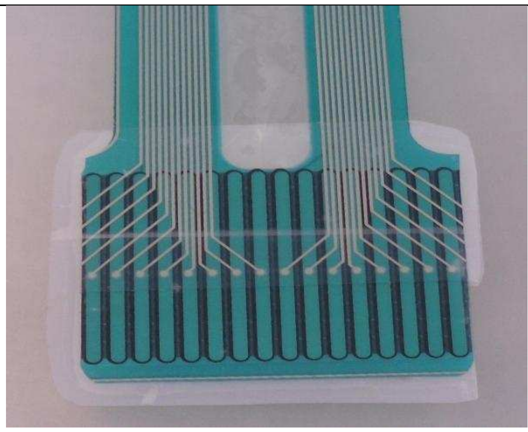
	
A: Cutting along the middle black line	B: Cutting along the third black height lines from both sides

Figure 2.4 Attempts of sensor sheet cutting

2.4.2 Calibration of Tekscan data

The Tekscan data were not calibrated as such. An instrument specific calibration device can be obtained but it was not available in this research. It is in principle possible that the performance of the sensor sheet changes from use to use. To still be able to compare data collected on different days, an extra set of measurements was performed at the beginning of each day of data collection. Five replicates of crème fraîche were measured each experimental day by the operator manipulating to examine the data variation of I-Scan system. This variability was factored in the data analysis through ANOVA.

2.5 Data analysis

In absence of a calibration device for the Tekscan I-Scan instrument, the consistency of data was considered. Therefore, before data analysis of the tongue variables, force, contact area, contact pressure and peak force, data measured on different days were averaged and then analyzed using ANOVA to determine if differences existed. If differences existed, the minimum mean value in averaged variables on some day was set as the numerator. For example, the minimum mean value in average force was on day three so that its mean value was set as the numerator in average force. Then, the mean values on day one and day two were divided by the numerator respectively, which the results were the correction factors of the data on the corresponding day. Correction factors of the four variables on days were necessary to apply to the data prior to further analysis.

The data of the 16 tongue variables (for 10 subjects, 7 products with 5 replicates each) were averaged using Microsoft Office Excel 2007 (Microsoft Corporation, USA) and the standard deviations were calculated through SPSS (SPSS Inc., Chicago). The same analysis was performed on the data of the 4 TA variables (7 products with 10 replicates each). Consistency and the index of viscosity were transferred into their absolute values for analysis to only deal with positive figures.

T tests (SPSS) were used to compare two variables while analysis of variance (ANOVA) in SPSS was applied to compare both the tongue and TA variables across different products. Multiple Comparisons under Tukey's Post-hoc Test in ANOVA were conducted where was appropriate.

Pearson correlative coefficients, a measure of the strength of linear dependence between two variables (for example, X and Y), were calculated to assess correlation between tongue and TA variables, giving a value between +1 and −1. A value of 1 means that the linear relationship between the two variables is perfectly positive, with all data points lying on a line for which Y increases as X increases. A value of −1 means that there is a perfectly negative linear relationship between X and Y, with all data points lying on a line for which Y decreases as X increases. The relationships between tongue variables and attributes from Texture Analysis were visualized using principal component analysis (XLSTAT, Version 2011) presenting the data in a two dimensional space. The range of the correlation coefficient is from -1 to 1.

3. Results and Discussion

In this research a new tool to analyze tongue movement while manipulating commercial semi-solid food was evaluated. Comparing with model samples, the advantages of commercial food samples were their convenient preparation and production stability. A range of semi-solid foods as well as one liquid food was selected and characterized through food texture analysis. The seven specific foods were selected depending on their discriminate mouth feel in firmness and viscosity of which the different samples were inferred to show a gradient magnitude data under the Texture Analysis. Then, whether and how tongue movement corresponding to certain firmness or viscosity of foods could be found through statistics analysis.

The liquid food was yogurt drink and it was included simply to test whether the new in-vivo tool could be applied to liquid foods or drinks. The results on yogurt drink were not considered in the principal component analysis because its texture values were too low to be discriminated by the Texture Analyzer and thus could not be compared with the results from the in-vivo measurements.

3.1 Tongue movement

Tongue movement variables: maximum values, time values, total values, average and end values, number values in the peaks of contact pressure, and average peak force were extracted.

3.1.1 Consistency of data in absence of a calibration device

In case of the average force and average contact area (Table 3.1 A and B), significant differences ($p \leq 0.05$) were found among their mean values acquired on the three days of measurement. In average contact pressure (Table 3.1 C), the mean values on day three was significantly different (p ≤ 0.05) from that of day one and two; however, there was no significant difference between its means on day one and day two. No significant differences were observed between the means of the three experimental days in peak force (Table 3.1 D).

Table 3.1 I-Scan Data in three experimental dates analysed through ANOVA

A: Average Force

Day	Force (mean, raw sum)	Standard Deviation	Multiple Comparisons (Mean Square Error = 91630)	Sig. (p≤0.05)	Correction factors
One	3401	129	Day 1 vs. Day 2	0.000*	0.77
			Day 1 vs. Day 3	0.004*	
Two	4444	348	Day 1 vs. Day 2	0.000*	0.59
			Day 3 vs. Day 2	0.000*	
Three	2609	369	Day 1 vs. Day 3	0.004*	1
			Day 2 vs. Day 3	0.000*	

B: Average contact Area

Day	Area (Mean cells)	Standard Deviation	Multiple Comparisons ((Mean Square Error = 26)	Sig. (p≤0.05)	Correction factors
One	83	2.0	Day 1 vs. Day 2	0.000*	0.82
			Day 1 vs. Day 3	0.002*	
Two	107	4.6	Day 1 vs. Day 2	0.000*	0.64

			Day 3 vs. Day 2 0.000*	
Three	68	7.2	Day 1 vs. Day 3 0.002*	1
			Day 2 vs. Day 3 0.000*	

C: Average contact Pressure **D: Peak Force**

Day	Mean (raw)	S.D.	Multiple Comparisons (Mean Square Error = 2.5)	Sig. (p≤0.05)	Mean (raw sum)	S.D.	Multiple Comparisons (Mean Square Error = 806)	Sig.
One	40	0.9	Day 1 vs. Day 2	0.979	380	16	Day 1 vs. Day 2	0.375
			Day 1 vs. Day 3	0.014*			Day 1 vs. Day 3	0.937
Two	41	2.1	Day 1 vs. Day 2	0.979	405	35	Day 1 vs. Day 2	0.375
			Day 3 vs. Day 2	0.010*			Day 3 vs. Day 2	0.232
Three	37	1.6	Day 1 vs. Day 3	0.014*	373	30	Day 1 vs. Day 3	0.937
			Day 2 vs. Day 3	0.010*			Day 2 vs. Day 3	0.232

While appreciating that use of the purpose build calibration device would be ideal, to overcome variation of data measured on different days in this research, correction factors were determined and applied to data acquired on the actual samples as follows.

As significant differences ($p \leq 0.05$) were observed between the means of different experimental days, data of average force and average contact area measured on respective experimental days were processed by multiplying with their corresponding correction factors before further analysis. The means of day three in average force and average contact area were selected as reference and the correction factors were obtained by dividing the mean from day three by the mean on the day one (or two). On the contrary, significant differences of the means in different experimental days for peak force were not observed to have significant differences, and the means between day one and day two in average pressure were not observed either. Therefore, no correction factors were applied to the values of contact pressure and peak force.

3.1.2 Maximum tongue variables

ANOVA results as well as means and standard deviations for the three types of maximum variables analyzed are presented in Table 3.2 and Figure 3.1 A. Maximum force is discussed first. The values in standard deviations were relatively large among the maximum tongue variables due to the large variation between each subject in oral processing. The means of the maximum force ranged from 3888 ± 2999 raw sum (arbitrary unit of force in Tekscan System) up to 7849 ± 4547 raw sum which were the results for yogurt drink and cheese, respectively. The six semi-solid products could be classified into two groups of significantly different maximum force values (Figure 3.1 A): (i) custard, stirred yogurt, crème caramel, crème fraîche and jelly, (ii) cheese crème caramel, crème fraîche and jelly. The maximum force measured for cheese was significantly higher ($p<0.05$) than for custard and stirred yogurt, and higher than but not significant to crème caramel, crème fraîche and jelly. Yogurt drink was not significantly different to custard.

Maximum contact area represents the maximum value of the contact area between tongue and palate. The mean of the maximum contact area in case of consumption of cheese spread was 110 ± 32 cells, the largest area compared with other products

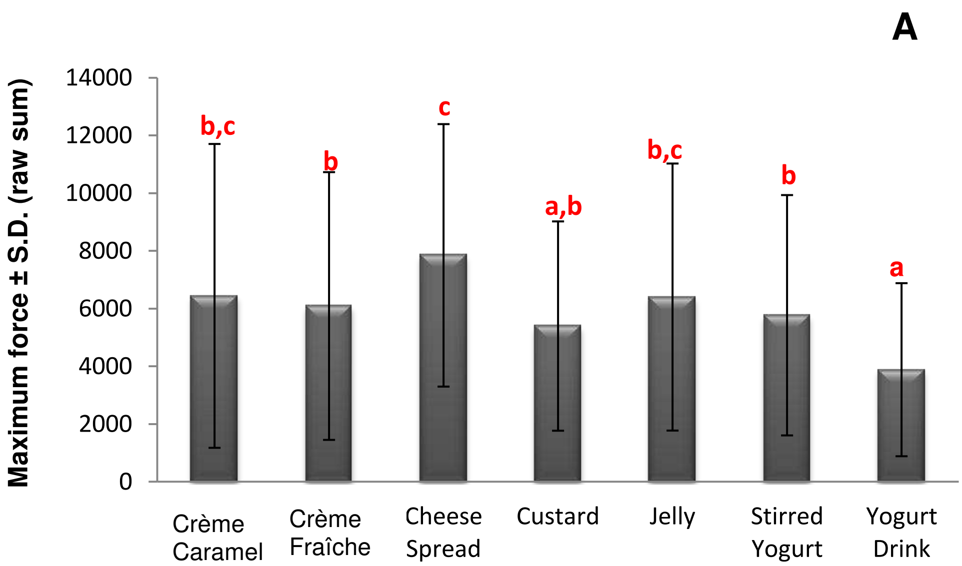
(Figure 3.1 B). The maximum area was up to 100 cells for crème caramel as well as jelly. Among the semi-solid foods, three homogeneous subsets were classified: (i) custard, crème fraîche and stirred yogurt, (ii) crème fraîche, stirred yogurt, crème caramel and jelly (iii) crème caramel, jelly and cheese spread. Cheese spread was significantly different ($p \le 0.05$) to custard, crème fraîche and stirred yogurt. Stirred yogurt only showed significantly difference ($p \le 0.05$) to cheese among the semi-solid foods. Yogurt drink was significantly different ($p \le 0.05$) to all the six semi-solid foods in maximum contact area.

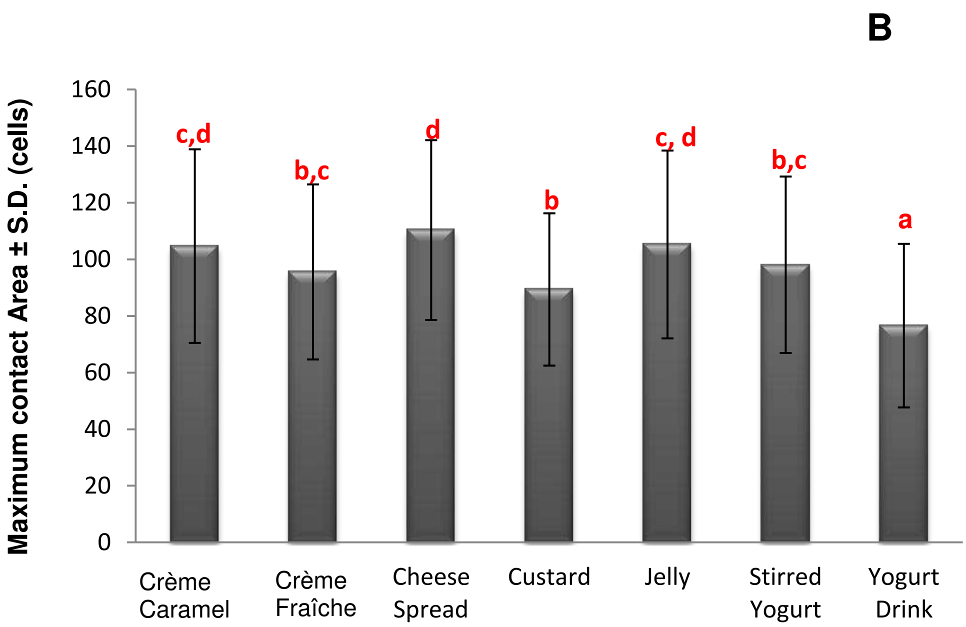
In the case of maximum contact pressure, the highest value was found for cheese spread with 78 ± 36 raw (arbitrary unit of pressure in Tekscan System) (Figure 3.1 C) and it is significantly different ($p \le 0.05$) to the values for all other products. The maximum contact pressures detected for the other five semi-solid foods were not significantly different to each other. Yogurt drink was not significantly different to stirred yogurt and custard.

For all three types of maximum tongue variables, the mean values obtained for yogurt drink were lower than those of the other semi-solid foods but it did not show significant difference to custard and stirred yogurt in maximum contact pressure. It means that the tongue cannot distinguish the differences between yogurt drink, custard and stirred yogurt. It may be their liquid-like attributes that are too soft to stimulate different pressures of the tongue.

Table 3.2 ANOVA results of maximum tongue variables based on seven selected products

Variables	F value	Sig.
Maximum force	5.634	< 0.0001
Maximum contact area	12.809	< 0.0001
Maximum contact pressure	6.222	< 0.0001





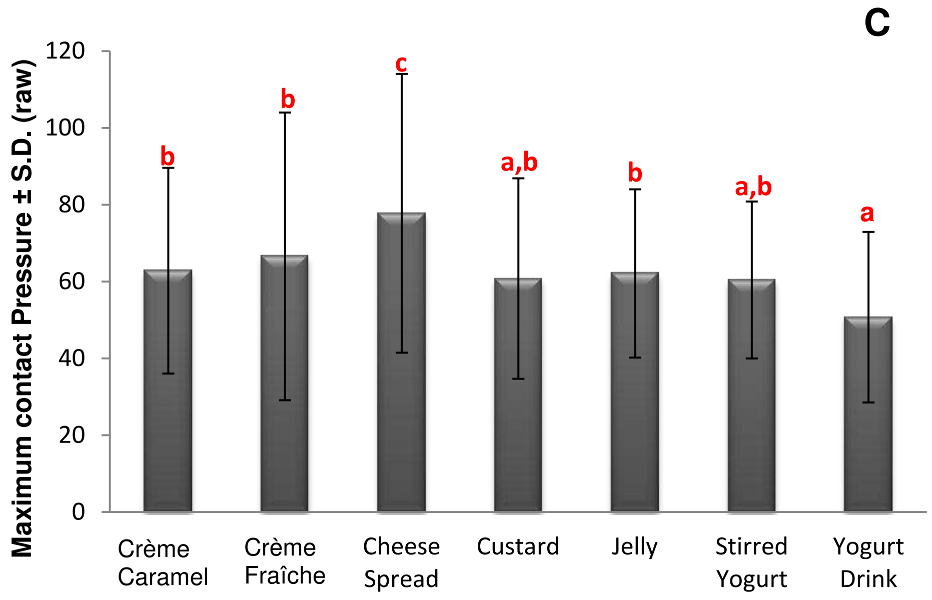
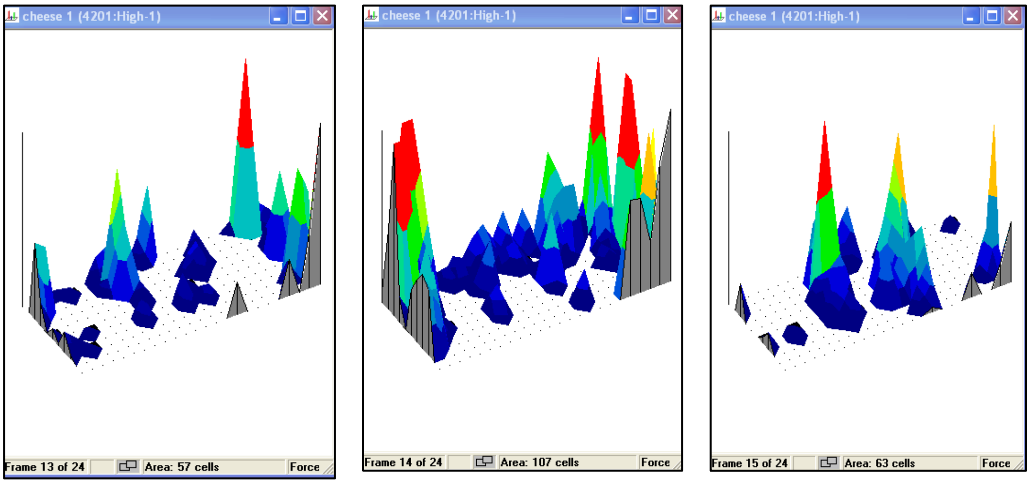


Figure 3.1 Means and ± standard deviations (S.D.) of (A) maximum force, (B) maximum contact area and (C) maximum contact pressure. Data marked with the same letter are not significantly different from each other ($p<0.05$).

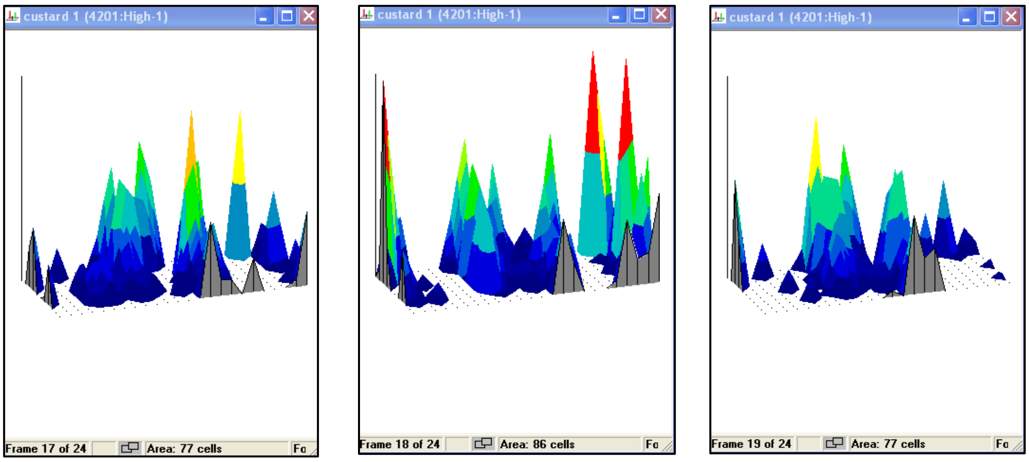
The data indicates that the tongue manipulation of cheese spread is somewhat different to that of the other products included in this study. This is illustrated in Figure 3.2 by a copy of contact pressure screenshots where the maximum pressure was recorded at the time step on either side of tongue for cheese spread and custard.

High pressure values are indicated in red and for both samples. It is evident that the highest pressures were recorded at the right and left edges of the sensor sheet in red.



A-1: Frame 13 A-2: Frame 14 A-3: Frame 15

A: Recordings from individual F eating the first sample of cheese spread. The maximum value was recorded at frame 14.



B-1: Frame 17 B-2: Frame 18 B-3: Frame 19

B: Recordings from individual F eating the first sample of custard. The maximum value is recorded at frame 18.

Figure 3.2 Two examples of recordings around the tongue maximum values.

The results show maximum pressure is produced when the tongue contacts the either side of the upper palate where it is close to molars. Actually, the right and the left edges of the sensor sheet touch some mucous membrane of molars, where the hardness is higher than the upper palate. Therefore, the pressure produced by the tongue pressing against the molars is higher than the pressure produced by the tongue pressing upper palate.

In this section, the figures of maximum tongue variables show similar magnitude orders of the values across the seven foods. The distribution of maximum contact pressure and the distribution of contact pressure recorded at other moments are compared through the screenshots of Tekscan I-Scan system. These results are clues for the other variables to be discussed in following sections.

3.1.3 Characteristic times

Several characteristic times were recorded: The time it took to consume each food sample referred to as the ‘Finish time (FT)’; the time of maximum force (MFT), maximum contact area (MAT), and maximum pressure (MPT) was recorded. MFT, MAT and MPT were the time at which maximum force, maximum contact area and maximum contact pressure recorded.

The values for FT together with statistical analysis are presented in Table 3.3 and Figure 3.3. FTs were around 10 s. Cheese spread with 14 s took the longest to consume, and the shortest in-mouth residence time of 8 s and 7 s respectively were recorded for the more liquid products stirred yogurt and crème fraîche.

ANOVA results for the times at maximum force (MFT), maximum contact area (MAT) and maximum contact pressure (MPT) are also presented in Table 3.3. Their corresponding means and standard deviations are included in Figure 3.3 (their actual values are shown in appendix 3).

The significant trends of magnitudes among the seven products in the four time variables are similar. There are no significant differences between crème caramel and crème fraîche for all the four time variables. The means of finish time for the other five products were significantly different ($p \leq 0.05$) to each other. In terms of time of maximum force and contact pressure, stirred yogurt was not significantly different to crème caramel or custard.

It should be noted that the relatively high standard deviations in the time variables are likely to be due to 'subject' variation in the natural behavior of eating.

Table 3.3 ANOVA results of time variables (A) Significant values (B) Homogeneous subsets based on seven selected products

A: Significant values

Variables	F value	Sig.
Finish time (FT)	22.603	<0.0001
Time at maximum force (MFT)	5.634	<0.0001
Time at maximum contact area (MAT)	12.809	<0.0001
Time at maximum contact pressure (MPT)	6.222	<0.0001

B: Homogeneous subset

Variables / Foods	Finish Time	Time of maximum force	Time of maximum contact area	Time of maximum contact pressure
Crème Caramel	d	c	c	c, d
Crème Fraîche	d	c	c	d
Cheese Spread	f	e	e	f
Custard	b	b	b	b
Jelly	e	d	d	e
Stirred Yogurt	c	b, c	b	b, c
Yogurt Drink	a	a	a	a

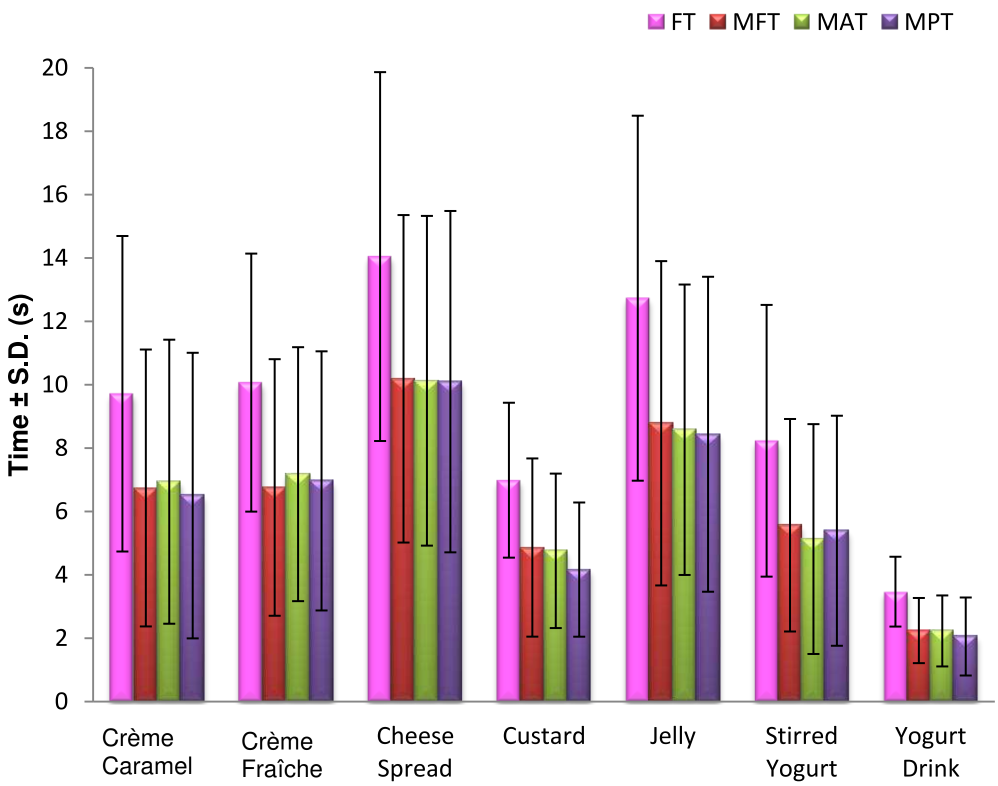


Figure 3.3 Time related parameters (seconds +/- 1 SD) for each food sample.

For each of the foods, all three types of maximum time values are statistically not different and vary across the foods from about 10 s for cheese spread to 2 s for yogurt drink. These times correspond to around 60 to 70% of the recording time (FT) as shown in Table 3.4. It highlights that maximum force, maximum contact area and maximum contact pressure occurred at the same moment near to 70 % of the whole eating duration. This observation agrees in general with the oral residence study reported by Chen and Lolivret (2011). They found that foods of, in their terms, low viscosity, such as custard and jelly, required 3 to 5 s of oral processing before they were swallowed whereas the higher viscous foods, such as set honey and smooth peanut butter, were swallowed only after up to 8 s (Chen and Lolivret, 2011) which demonstrated the link between the event of swallowing and food consistency. The maximum tongue variables were attained at the point of swallowing.

Table 3.4 Time to maximum variables as a percentage of finish time

Variables \ Food	Crème Caramel	Crème Fraîche	Cheese Spread	Custard	Jelly	Stirred Yogurt	Yogurt Drink
MFT/ FT	69%	67%	73%	70%	69%	68%	65%
MAT/ FT	71%	71%	72%	68%	67%	62%	64%
MPT/ FT	67%	70%	73%	60%	66%	66%	60%

3.1.4 Total contact pressure

All values recorded for the contact pressure were summed up for each replicate sample. Recording frequency was every 0.25 s throughout the duration of the eating process. The results are shown in Figure 3.4. The total contact pressures measured for cheese spread and jelly are not statistically different, neither are the values for crème caramel and crème fraîche which are lower. The values for crème fraîche, stirred yogurt and yogurt drink are statistically different ($p \leq 0.05$) to other foods.

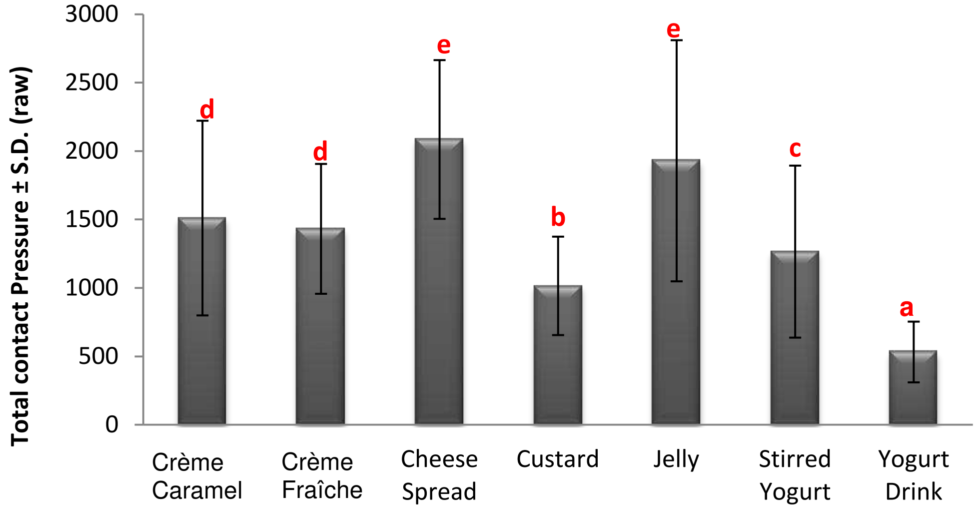


Figure 3.4 Mean and standard deviation (S.D.) of the total tongue contact pressure. F value is 24.005 and Sig. < 0.0001 through ANOVA analysis. Data marked with the same letter are not significantly different from each other (p<0.05).

The data for total contact pressure were further analyzed and a linear correlation was found between the total contact pressure and the finish time for all seven products included in this study (Figure 3.5). The correlation is positive which may not be surprising as longer eating time means extended oral processing and application of masticatory forces to the food. Nevertheless, the linearity of the correlation and the high correlation coefficient is something that was not necessarily expected. Depending on food texture, it is supposed that the sensation of human tongue is very high and the sensitive signal innervated via central nerve system to the tongue pressure. The distribution of the selected products in the figure reflects that total contact pressure associates with texture attributes of the products. Indeed, Jack and Gibbon (1995) used the technique of electropalatography (EPG) to find that semi-solid foods require three rolling tongue motions to clear the food from the mouth and jelly requires up to six rolling cycles while liquid milk requires two of these, some of which do not give full contact between the tongue and upper palate. It implies the tongue motions are associated with foods. Therefore, a further analysis between the total contact pressure and food texture attributes is illustrated in Section 3.3.2 by the means of principal component analysis.

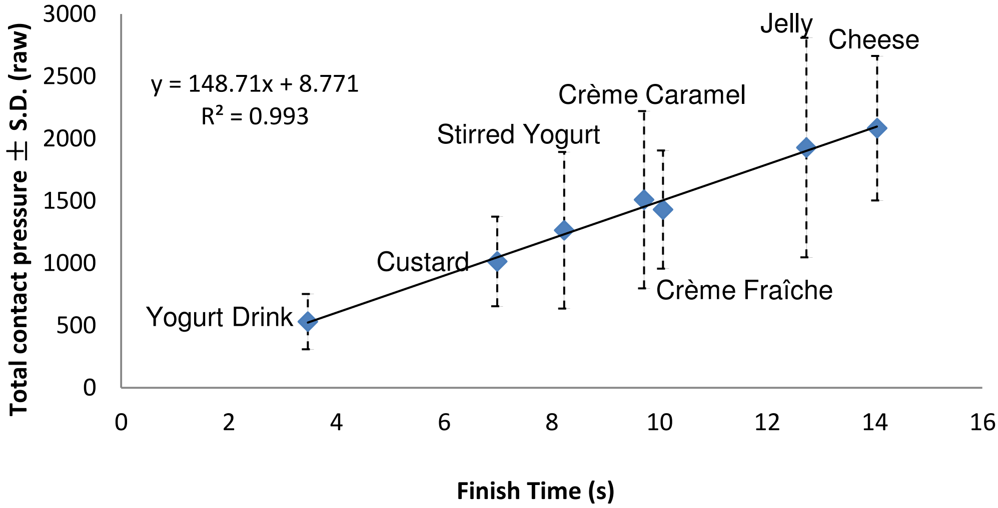


Figure 3.5 A Linear relationship between total contact pressure and finish time.

3.1.5 Evolution of contact pressure during eating

The evolution of the contact pressure during eating can be analyzed on the basis of the average contact pressure parameter. It represents the average pressure in each recording period (0.25 s) produced by the tongue contacting the upper palate during the whole eating process. Contact pressure at 0.3 seconds is the pressure produced at 0.3 seconds of the eating process where no swallow has yet occurred. End contact pressure is the pressure produced at the last second of the recording when the food had been swallowed completely and is referred to as blank contact pressure without food in the mouth. Comparison between the average tongue contact pressures during the whole eating process and the blank (end) contact pressure analyzed by t test showed no significant difference, neither between the contact pressure with food consumption at 0.3 s and the blank contact pressure. Contact pressure at 0.3 seconds was analyzed as Kohyama and Nishi (1997). However, such differences were not found for the semi-solid foods investigated in this research. Actually, contact pressures at 1.0 seconds and at 2.0 seconds (some subjects finished samples within 3 seconds) were both compared with the end contact pressure and the average contact pressure, but there were the same outcomes.

The results reflect that pressure produced by tongue movement during the whole eating process has a basic or balance level whether there is food consumed or not. This implies that tongue movement during eating is not controlled by food texture – at least in the context of semi-solid foods mostly manipulated with the tongue during eating. Controlled by the central nervous system a ‘natural’ force may be applied. However, it has been suggested that the processes of bolus transport and aggregation facilitated by tongue movement may be altered by volition (Palmer *et al.*, 2007).

3.1.6 Number of peaks in contact pressure

During the eating process, the tongue contacts the upper palate rhythmically by touch-separate-touch movements and these can be identified by peaks in contact pressure data. Examples are shown in Figure 3.6 for subject B and subject F consuming cheese spread with 8 and 6 peaks respectively.

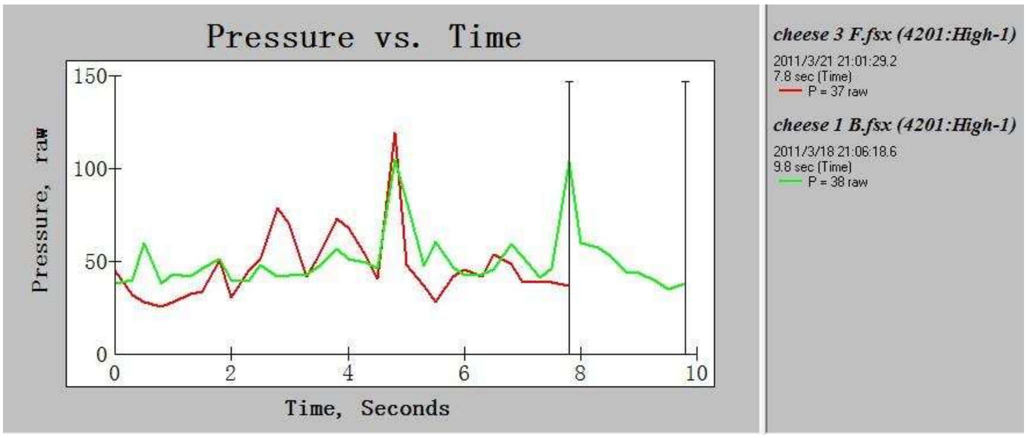


Figure 3.6 Screenshot example of the Pressure and Time graph from I-Scan system. Cheese 1 B was the first replicate of cheese spread individual B ate; Cheese 3 F was the third replicate of cheese spread individual F ate.

Different products produced different rhythms of the tongue-palate contact movement. Five groups were identified with significant difference ($p<0.05$) between each other and these were: (i) yogurt drink, (ii) custard and stirred yogurt, (iii) crème caramel and crème fraîche, (iv) jelly and (v) cheese spread. The results are shown in Figure 3.7.

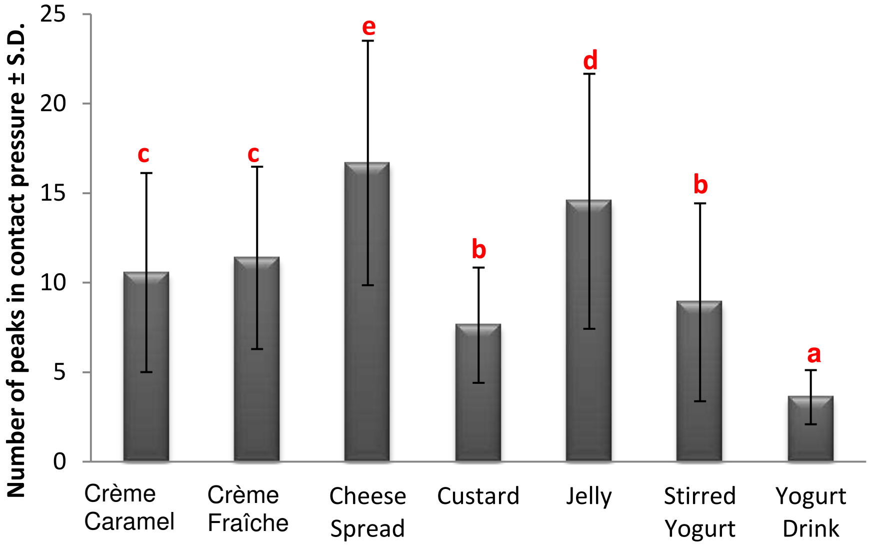


Figure 3.7 Means and ± one standard deviation of the number of peaks in contact pressure. F value is 21.342 and Sig. < 0.0001 through ANOVA analysis. Data marked with the same letter are not significantly different from each other (p<0.05).

A positive linear relation was found between the total number of peaks in contact pressure and finish time (FT) (Figure 3.8). According to the order of the increased finish time of products, Figure 3.9 illustrates the relationship between the number of peaks in contact pressure and finish time for the different foods across all subjects. These results suggest that the rhythm of tongue movement is related to food varieties but is not affected by variation in eating behavior.

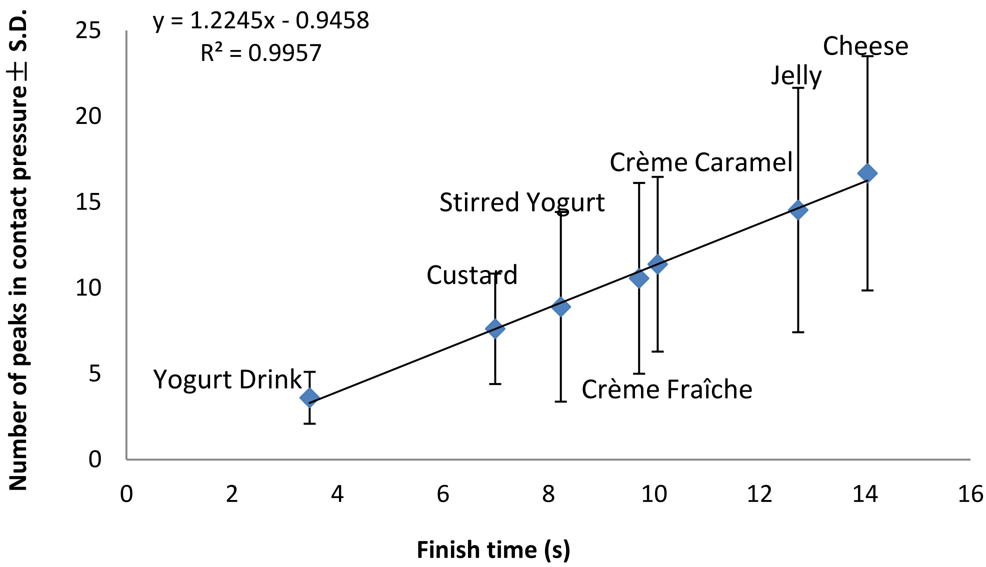


Figure 3.8 Linear relationships between numbers of peaks in contact pressure and finish time.

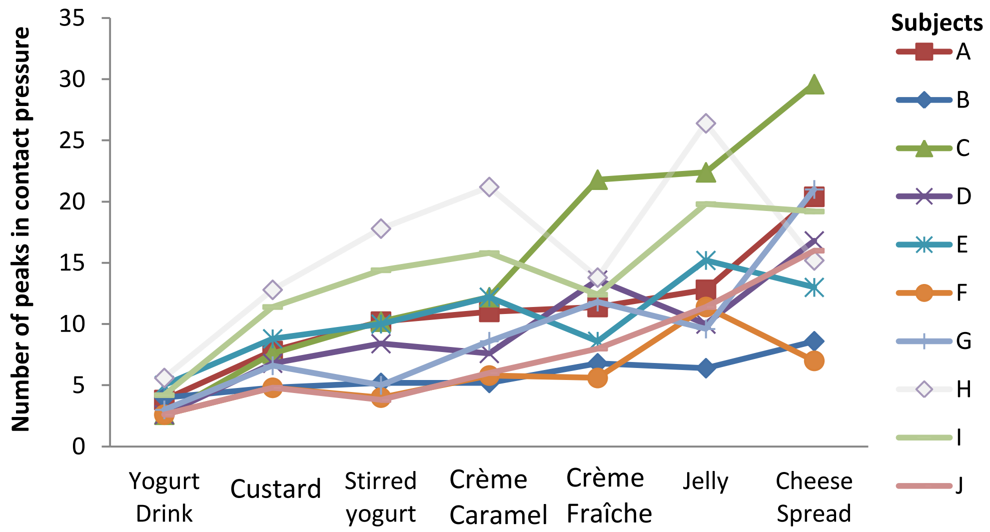


Figure 3.9 Relationships between number of peaks in contact pressure and products based on different subjects.

The values of the number of peaks in contact pressure divided by finish time are around 1.1 s across the food products investigated (Table 3.5). It means that the rhythms of tongue movement manipulating these different products are about one per second and they are not affected by food texture or subject variation. It may be the regular behavior of human beings with the unconscious control by central nerves system. Previous researchers (Jiang *et al*., 1991; Fregosi and Fuller, 1997; Ono *et al*., 1998) found considerable evidence indicating that tongue contractile properties are controlled by the activity of hypoglossal motoneurons which is modulated by a respiratory rhythm initiated by complex nerve stimulation (Sawczuk and Mosier, 2001).

Table 3.5 Result of the division by 'number of peaks in contact pressure / finish time'

Food	Crème Caramel	Crème Fraîche	Cheese Spread	Custard	Jelly	Stirred Yogurt	Yogurt Drink
Division	1.09	1.13	1.19	1.09	1.18	1.07	1.04

3.1.7 Average peak force

Peak force corresponds to the highest force reading in each recording period (0.25 s). Statistical analysis showed that there were no significant differences between the six semi-solid products. The variable of peak force is similar across the tested products. The lowest average peak force was measured for yogurt drink which was not significantly different to crème fraîche and custard.

Table 3.6 Means and ± one standard deviation of peak force (mean unit: raw). F value is 8.081 and Sig. < 0.0001 though ANOVA analysis

Food	Mean	S.D.	Homogeneous subsets
Crème Caramel	394	153	b
Crème Fraîche	356	101	a, b
Cheese Spread	382	100	b
Custard	351	105	a, b
Jelly	394	129	b
Stirred Yogurt	386	106	b
Yogurt Drink	327	111	a

End peak force was not significantly different between the seven food products. Total peak force, similar to the total contact pressure, had a linear correlation with the finish time. Number of the highest peak force was the times of the maximum recordable force of 1020 raw sum attained during the recording. It was less than once on average across the seven products. Analysis of end peak force, total peak force and number of the highest peak force data did not present significantly different results of tongue movement. Therefore, corresponding Figures and Tables are presented in the Appendix IV.

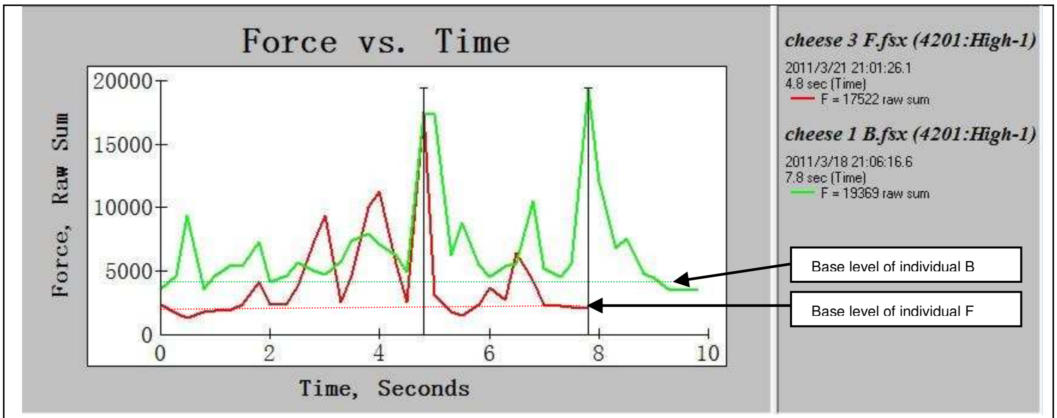
3.1.8 Changes of force, area and pressure versus time in individual experiments

The figure 3.10 presents three graphs of force, contact area and contact pressure versus time recorded by the measurements of individual B (green curve) and individual F (red curve) eating cheese, respectively.

For example, the force base level of individual B is around 4000 raw sum while the force base level of individual F is around 2500 raw sum. There are similar situations presented in the area-time graph and the pressure-time graph. It reflects that individuals have their own base level of tongue force, tongue contact area and tongue contact pressure during their own eating process.

Besides, in the process of individual B eating cheese spread, there are two obvious peaks at 4.8 s and 7.8 s in the graph of force versus time. The peak force at the latter time is higher than the previous one. However, in the graph of area-time curve, the two peaks are not the case of force-time curve, but they happen a little later. Finally, in the graph of pressure-time curve, the higher peak is attained at 4.8 s but not at the 7.8 s. In the process of individual F eating cheese, although the highest peaks in the pressure-time curve and in the force-time curve both are attained at 4.8 s, the highest peak in the area-time curve is not attained at 4.8 s. The result of tongue contact pressure is affected by tongue force and its contact area.

In Section 3.1.3, it was inferred that the time of maximum tongue variables attained were the time of swallowing, but the three graphs here cannot illustrate the relationships between the time of maximum tongue variables and swallowing because of the small quantity of examples for comparison.



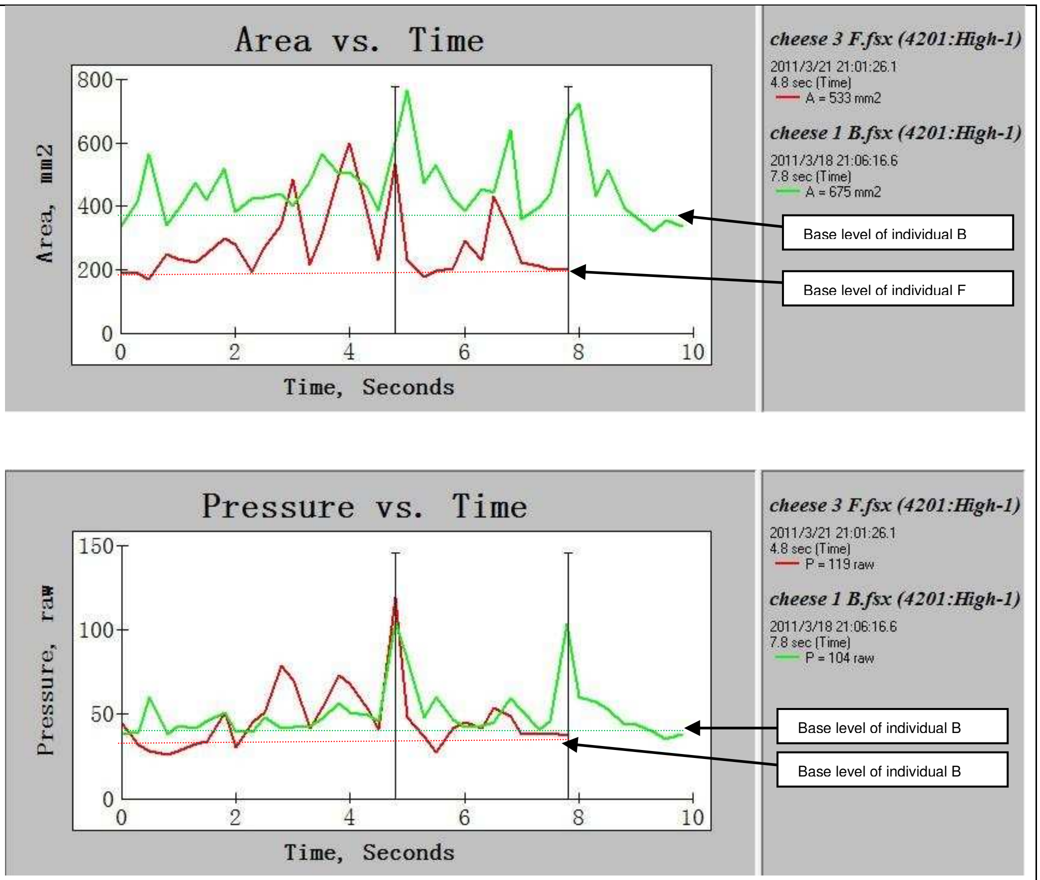


Figure 3.10 Screenshot examples of the Force, Area and Pressure versus Time graph for individual experiments from I-Scan system. Cheese 1 B was the first replicate of cheese spread individual B ate; Cheese 3 F was the third replicate of cheese spread individual F ate.

3.1.9 Concluding remarks to the in-vivo pressure sensor sheet measurements of tongue pressures during oral manipulation of semi-solid foods

Over 15 groups of analyzed data measured by Tekscan sensor sheet were illustrated and discussed in Section 3.1. The three tongue variables --- total contact pressure, number of peaks in contact pressure and finish time --- discriminated the semi-solid foods investigated in this oral manipulation research. A linear relationship between total contact pressure and finish time across the selected products indicated that the total contact pressure is associated with textural differences between the foods. Except between crème caramel and crème fraîche, significant differences in the mean of the finish time were found between the other five products, including the yogurt drink. The eating durations are affected by food texture. However, the rhythm of tongue movement showed by the number of peaks in contact pressure was found to be one per second independent of food product and subject.

On the other hand, average contact pressure, contact pressure at 0.3 s and end contact pressure are not significantly different between the foods (including the liquid product). It was shown that the pressure produced by tongue movement during the whole eating process remains constant whether there was food consumed or not. These findings indicate the tongue movement is controlled by central nerves system unconsciously which may be the neurological feature of human beings.

Although the maximum tongue variables do not discriminate the different foods, recorded images show that the tongue is contacting the palate near gums (edges of the sensor sheet) where the hardness is harder than in other regions of the palate so that the contact pressure is higher near gum than it in other parts of palate. When comparing the screenshots at the moment when maximum values were recorded and those at other periods, it would be found that the tongue movement on food consumption normally contacts the middle region of upper palate except for the moment maximum values were recorded when the contacts were near to 70% of the whole eating duration. It is questioned whether the behavior of tongue at this moment was associated with swallowing.

The Tekscan I-Scan System with the sensor sheet model 4021 is able to reflect tongue movement through the extracted variables, although the standard variation of data is large due to the subjects' variation. One of the limits of the system is that instrumental variation cannot be eliminated and absolute values for pressure and force cannot be obtained without a calibration device. However, figures obtained in this research are comparable for statistical analysis after the data were processed with suitable correction factors.

3.2 Texture analysis

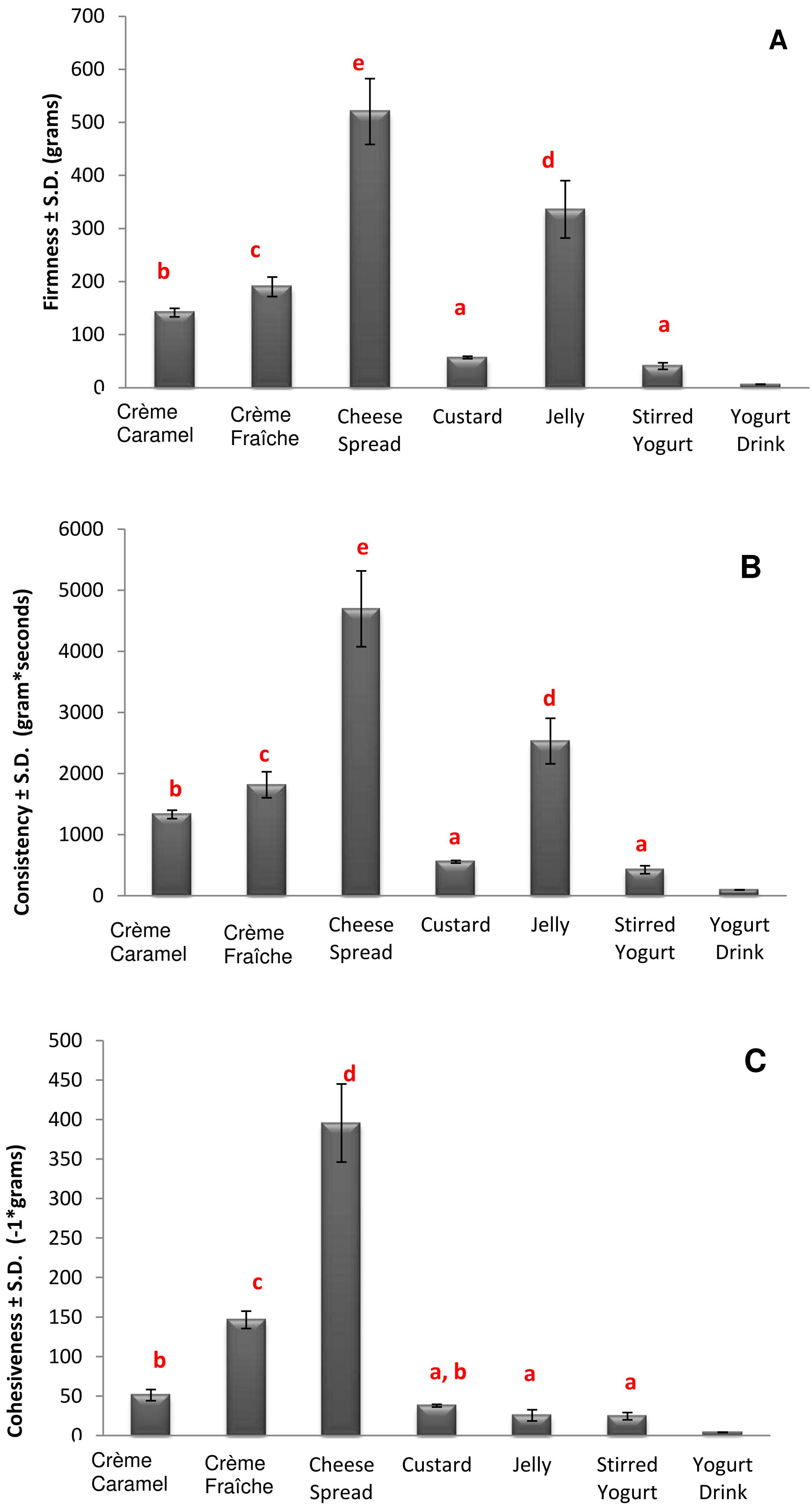
The physical properties of the seven food products included in this study were characterized by using the classical method of Texture Analysis following the method described in Section 2.3. This delivered physical measurement data to test for correlation with the tongue movement data obtained through in-vivo measurement. The data on the positive force are axis related to the insertion of the cylindrical probe into the sample and the data on the negative force axis correspond to those recorded during withdrawal of the probe from the sample. The ANOVA results are presented in Table 3.7 and the corresponding graphs are shown in Figure 3.11. The texture data for yogurt drink were not statistically analyzed because measured forces were close to the resolution of the load cell of Texture Analyzer.

The selected products show a range of firmness with cheese spread and jelly being the firmest products. Not surprisingly the lowest value for firmness is found in yogurt drink. Statistical analysis show that the firmness values in stirred yogurt and custard are not significantly different. The data for consistency (Figure 3.11 B), corresponding to the area under the positive force versus time curve (Appendix VII), show the same trend as the firmness data (Figure 3.11 A) among the food products.

The pattern changes for the cohesiveness and index of viscosity data were acquired on withdrawal of the probe from the sample. The cheese spread still shows the highest values for peak force in cohesiveness and in area under the curve in index of viscosity but the values acquired for jelly are not significantly different to the values for custard and stirred yogurt.

Table 3.7 ANOVA results of four texture attributes based on the six semi-solid foods (excluding yogurt drink)

Variables	F value	Sig.
Firmness	281.543	< 0.0001
Consistency	259.695	< 0.0001
Cohesiveness	472.823	< 0.0001
Index of viscosity	263.867	< 0.0001


A
Firmness ± S.D. (grams)
700
600
500
400
300
200
100
0
b
c
e
a
d
a
Crème Caramel
Crème Fraîche
Cheese Spread
Custard
Jelly
Stirred Yogurt
Yogurt Drink
B
Consistency ± S.D. (gram*seconds)
6000
5000
4000
3000
2000
1000
0
b
c
e
a
d
a
Crème Caramel
Crème Fraîche
Cheese Spread
Custard
Jelly
Stirred Yogurt
Yogurt Drink
C
Cohesiveness ± S.D. (-1*grams)
500
450
400
350
300
250
200
150
100
50
0
b
c
d
a, b
a
a
Crème Caramel
Crème Fraîche
Cheese Spread
Custard
Jelly
Stirred Yogurt
Yogurt Drink

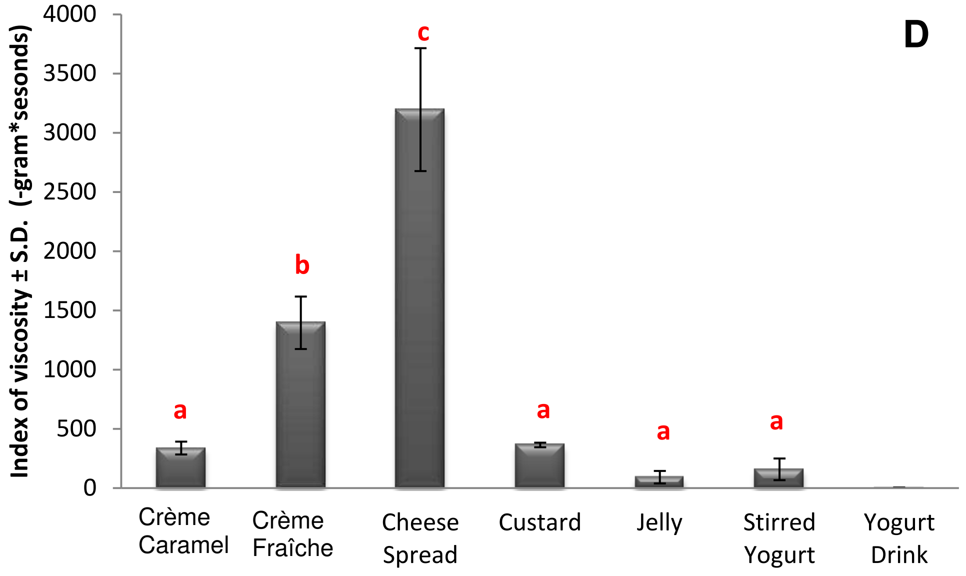


Figure 3.11 Means and ± one standard deviation of the four texture variables. A: firmness, B: consistency, C: cohesiveness, and D: index of viscosity. Data marked with the same letter are not significantly different from each other ($p<0.05$).

Food texture is essentially the result of the choice of food ingredients and production process (Brennan and Cleary, 2005; Yu *et al.*, 2007). However, as food texture measurement in this research was used as a tool to generate instrumental data for comparison with in-vivo acquired data and not to investigate food texture, the TA results are not discussed in further detail. To outline that the products chosen for this research texturally behave as expected, previous texture studies on semi-solid foods have been introduced in Section 1.1.

Relationships between the food physical properties from Texture Analysis and the tongue variables measured by Tekscan I-Scan system are the subject of the following Section 3.3

3.3 Relationship between tongue movement and variables of Texture Analysis

3.3.1 Pearson correlation coefficient

The Pearson correlation coefficient reflects the strength of linear correlation between two variables (Rodgers and Nicewander, 1988). A value highly closes to 1 implies a highly positive relationship between two variables, while a value highly close to -1 implies that a highly negative relationship between two variables. Based on the correlation coefficient, Pearson invented Principal Component Analysis in 1901 (Pearson, 1901).

Before further interpreting the figures of Principal Component Analysis, the correlation coefficient matrix presented in Table 3.8 reflecting the relationship between the variables of texture properties and tongue movement will be discussed first. All texture variables are correlated with each other but consistency is more highly correlated with firmness than cohesiveness and index of viscosity. Similarly, cohesiveness is more highly correlated with index of viscosity than consistency and firmness. The reason can be found from the calculated way of texture measurement in which the value of consistency includes the value of firmness and the value of index of viscosity includes the value of cohesiveness. 10 out of 13 the tongue variables are positively correlated with the four texture variables. In fact, the values of the 10 tongue variables in Section 3.1 have shown their differences across foods. End contact pressure, average contact pressure and contact pressure at 0.3s show negatively correlation with the texture variables and other tongue variables. The values of these three tongue variables have shown their no significant differences across foods. Although they are not strong correlations, average peak force has a positive low correlation with firmness and consistency but negative correlation with cohesiveness and index of viscosity. Contrary to other tongue variables, maximum contact pressure (Max Pressure) is correlated higher with cohesiveness and index of viscosity than firmness and consistency. One possible reason is that the maximum contact pressure was used to move bolus from palate the movement of which was associated with the cohesiveness and the viscosity of foods. It has been found that the bolus transit is dependent on its viscosity of food (Taniguchi *et al.*, 2008).

Table 3.8 Correlation coefficient matrix between the variables of texture properties and tongue movement

Variables	Firmness	Consistency	Cohesiveness	Index of viscosity
Firmness	1	0.991	0.797	0.760
Consistency	0.991	1	0.867	0.836
Cohesiveness	0.797	0.867	1	0.996
Index of Viscosity	0.760	0.836	0.996	1
FT	0.966	0.941	0.673	0.629
MFT	0.981	0.961	0.715	0.669
MAT	0.975	0.964	0.734	0.697
MPT	0.966	0.955	0.735	0.696
Max Force	0.921	0.947	0.858	0.815
Max Area	0.795	0.780	0.539	0.470
Max Pressure	0.847	0.909	0.994	0.985

No. Peaks in Pressure	0.980	0.959	0.711	0.670
Total contact Pressure	0.942	0.911	0.620	0.568
End contact pressure	-0.536	-0.542	-0.516	-0.445
Average contact pressure	-0.205	-0.237	-0.430	-0.483
Contact pressure at 0.3s	-0.258	-0.287	-0.451	-0.510
Average peak force	0.319	0.265	-0.043	-0.126

3.3.2 Principal component analysis (PCA)

Principal component analysis (PCA) was used to analyze the relationships between the variables obtained from in-vivo pressure sensor sheet measurement while orally processing the semi-solid foods chosen for this research (excluding yogurt drink as explained in the first paragraph in Section 3). It is a graphical projection of data in a two dimensional space. The two-dimension map with the first and second factorial axes is shown in Figure 3.12. It describes 99.92% of the variability of the data which is exceptionally close to the maximum possible of 100%.

On the PCA map (Figure 3.12), plots of the four food texture variables, firmness, consistency, cohesiveness and index of viscosity, locate on the circle line close to the F1 axis which also represents the principal component 1 (PC1). Firmness and consistency have a close correlation with each other while a close correlation is also between cohesiveness and index of viscosity, confirming their correlation coefficients. The variables from tongue measurement include FT, MFT, MAT, MPT, Total Pressure, Max Force, Max Area and NO. Peaks in Pressure are distributed close to the texture variables firmness and consistency in the plots of PCA while only Max Pressure is close to cohesiveness and index of viscosity. It is said the four texture variables and the tongue variables mentioned above concentrate on PC1, highlighting the close relationship among these variables. Also, significant differences were present between food products in these variables in reviewed previous ANOVA results in Section 3.1 and 3.2. It reflects the Tekscan I-Scan System has the capacity to discriminate the food physical properties measured by Texture Analyzer through these variables.

Contrarily, significant differences were not shown between products in average contact pressure, end contact pressure and contact pressure at 0.3s. The three variables were not closely correlated with PC1 or PC2. Although average peak force distributes on PC2 (close to F2), its ANOVA results show no significantly different between the semi-solid products. These four variables cannot discriminate the physical properties of food texture.

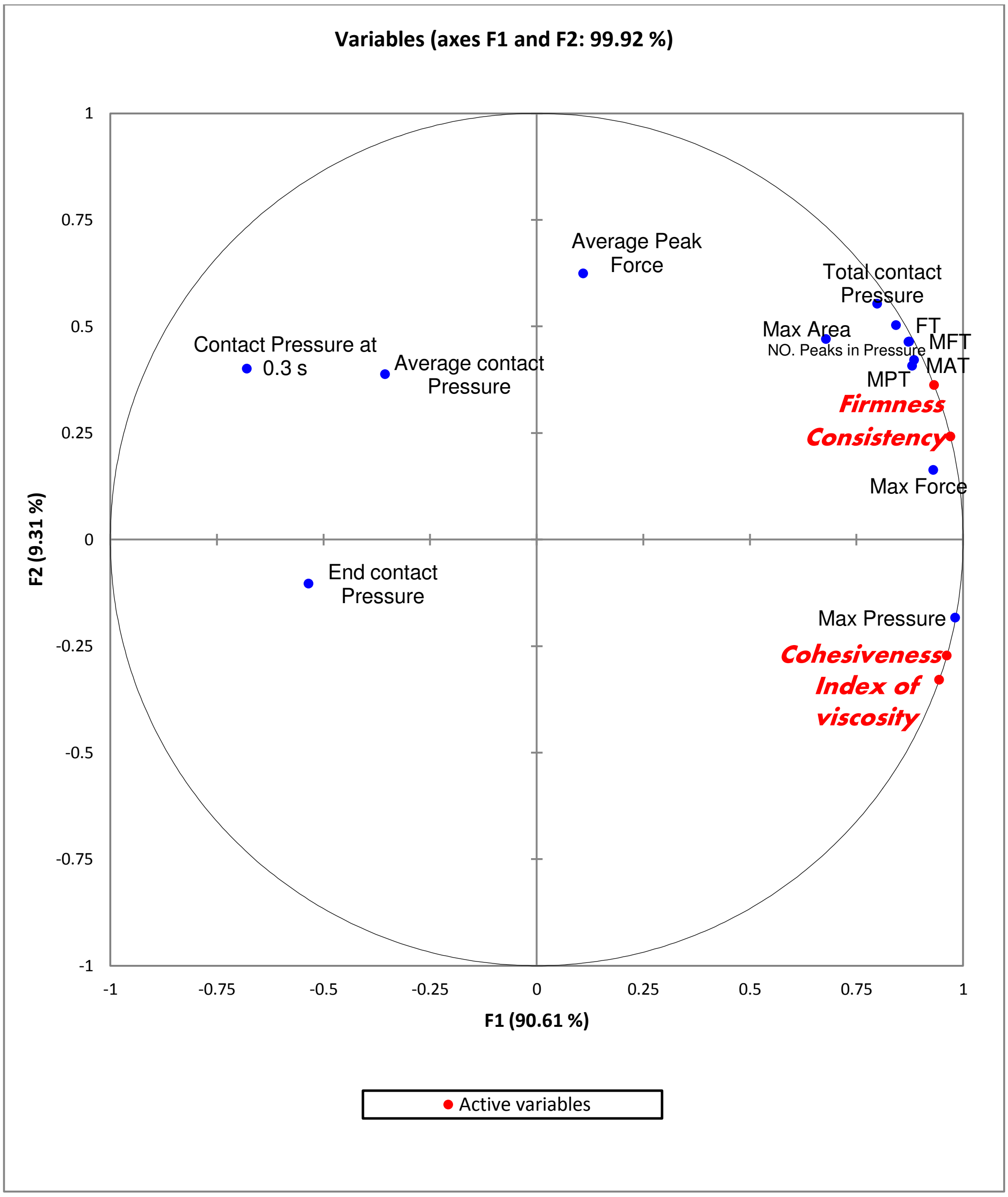


Figure 3.12 Plots of PCA performed on the variables combined from tongue movement with food texture.

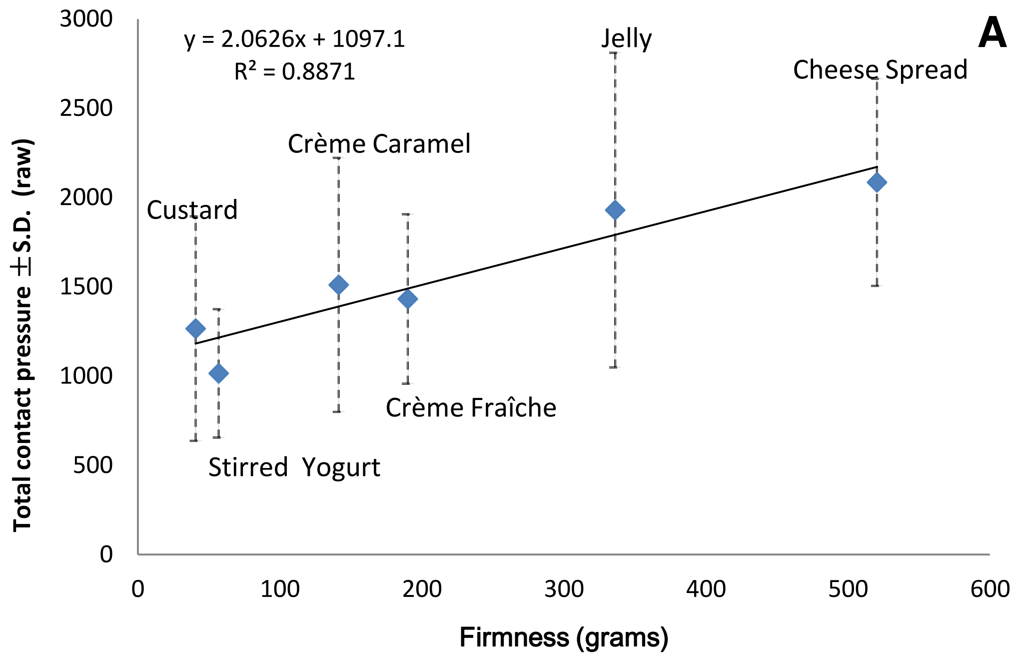
Based on the variables above, Figure 3.13 presents a biplot with an additional projection of the six semi-solid foods. Stirred yogurt and custard plots are close to each other at the far negative end of PC1. Values for most of the tongue variables (expect total contact pressure) and the four texture variables were not significant differences between these two products. It is said the texture properties between stirred yogurt and custard are similar to each other. Cheese spread and crème caramel score on the middle of PC1 while jelly and crème fraîche are separate across on PC2. The ANOVA results indicated that cheese spread attained the highest significant values in all of the texture variables and most of tongue variables. Its texture properties are quite different to other products. A similar situation is seen for jelly which attained the second highest significant values of tongue variables as well as firmness and consistency compared with other products. Although the values of tongue variables in crème caramel were not significantly different from those in crème fraîche, but the values of texture variables in crème fraîche were significant higher than those in crème caramel. In daily experiences, the texture perception of crème caramel by human beings would agree with its pudding mouth feel of ‘gel’ that is more like the texture of jelly than crème fraîche. However, due to time constraints, sensory perception was not included in our study to determine how the texture sensation of the products perceived by human beings related to the Texture Analysis. This is an area for future work.

Figure 3.13 Distribution of PCA performed on semi solid products with evaluated variables.

3.3.3 Relationships between instrumental variables

According to the PCA results, further statistic relationships are observed between two food texture variables (firmness and consistency) and two tongue variables (total contact pressure and number of peaks in contact pressure). Their linear relationships are shown in Figure 3.14 and Figure 3.15.

Indeed, it has been found that total contact pressure is linear-correlated with finish time (Figure 3.5). When the figure of finish time (Figure 3.3) and the figure of firmness (Figure 3.11 A) or consistency (Figure 3.11 B) are compared, the magnitude orders of foods can be observed that are the same in finish time and in firmness or consistency, correspondingly. Also, finish time has a close correlation with firmness present on the PCA map (Figure 3.12). Therefore, a linear relationship between total contact pressure and firmness or consistency is in a result without any doubt. The inference of the linear correlation between number of peaks in contact pressure and firmness or consistency is the same as the inference of the linear correlation between total contact pressure and texture variables.



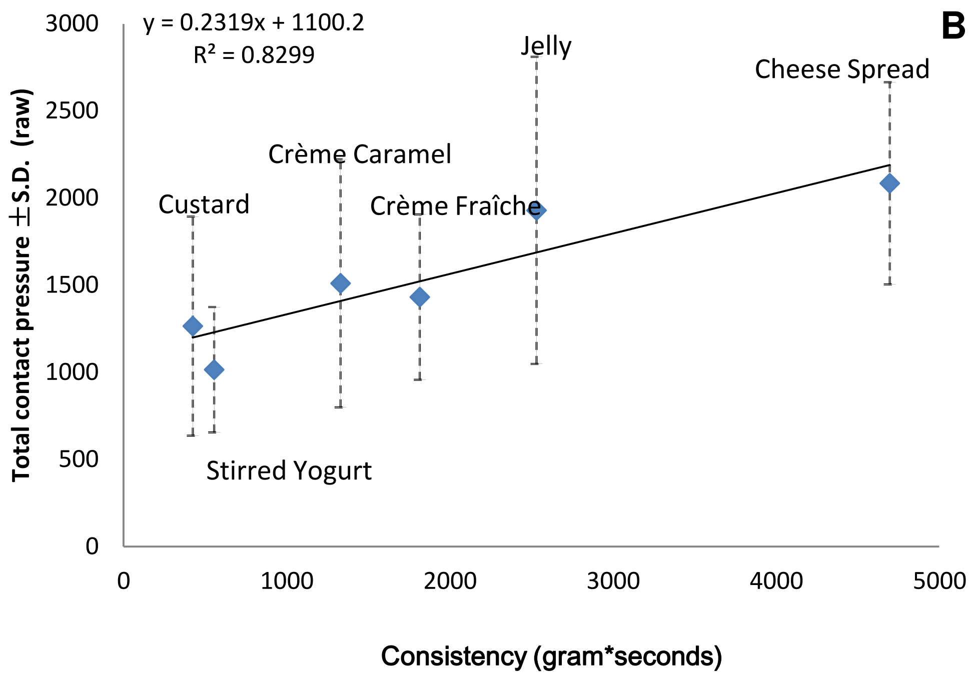
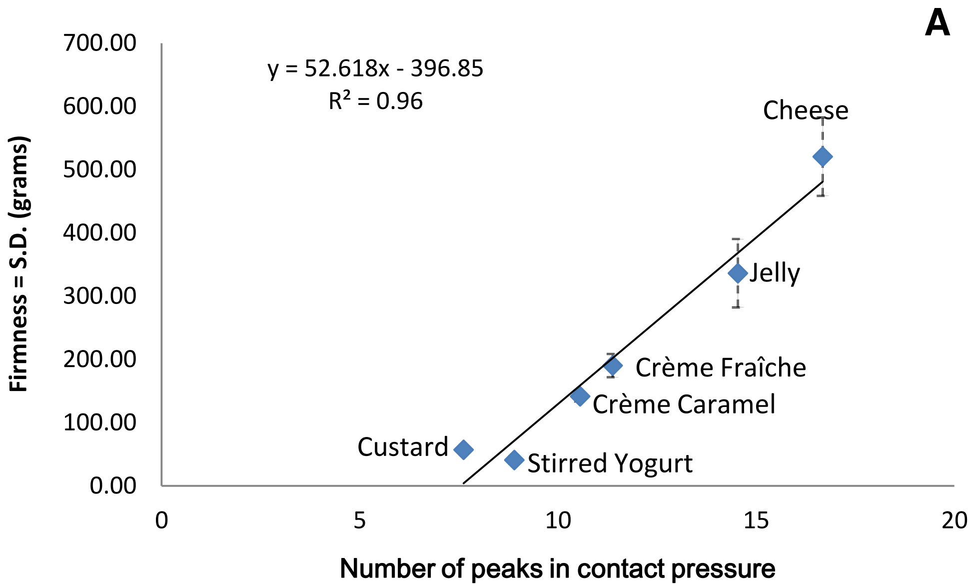


Figure 3.14 Linear relationships between total contact pressure and food texture. A: Total contact pressure and firmness; B: Total contact pressure and consistency



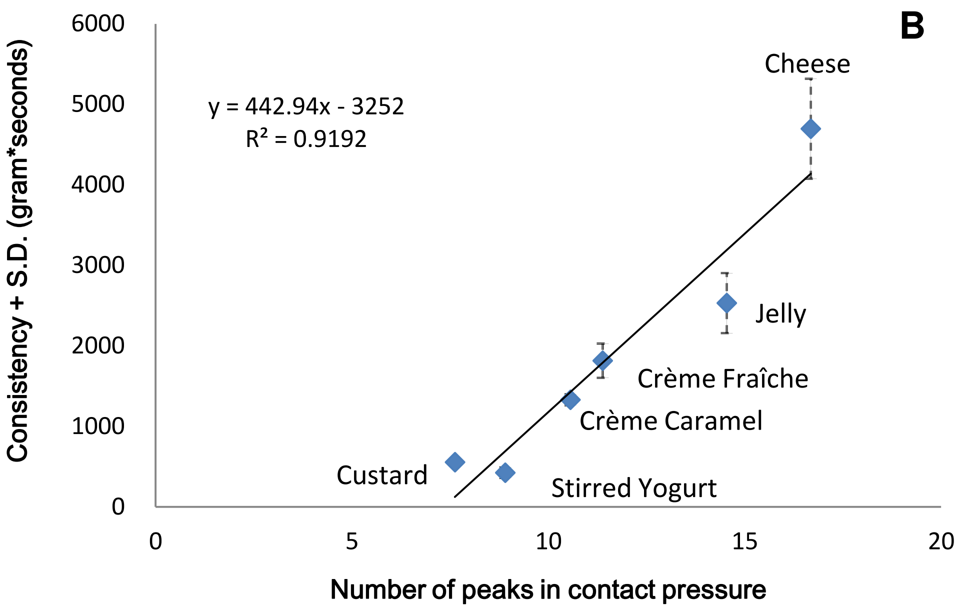
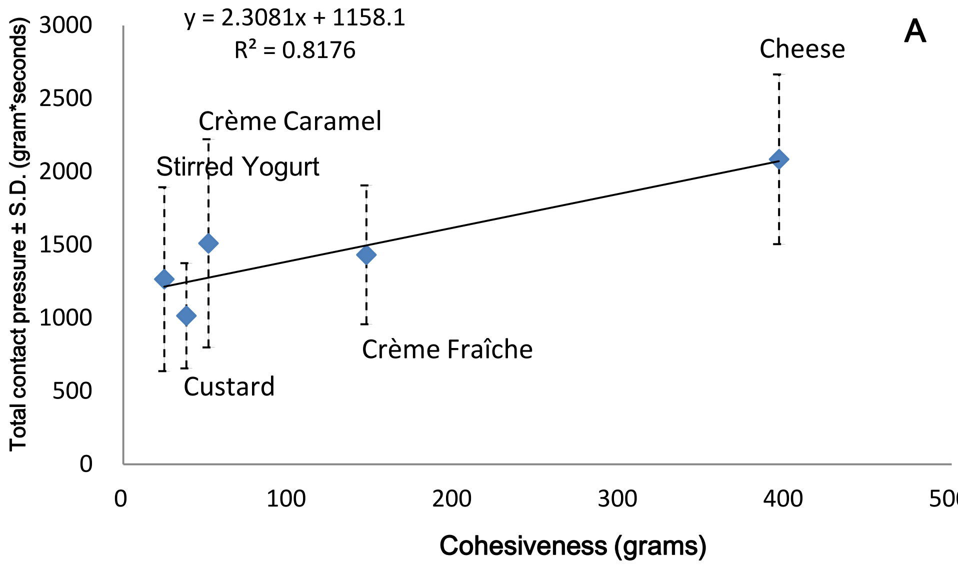


Figure 3.15 Linear relationships between Number of peaks in contact pressure and food texture. A: Number of peaks in contact pressure and firmness; B: Number of peaks in contact pressure and consistency

The same magnitude orders of semi-solid foods in these two figures again confirm the relationships between tongue movement and food texture observed during the whole eating process. This result could be compared with the outcomes in Tsukada *et al.*'s study (2009) which also observed the relationship between tongue movement and food texture but used other techniques. It found that increasing firmness of food leads to an increased duration of tongue and suprahyoid muscle activity. Taniguchi *et al.* (2008) also indicated that food consistency had a strong effect on tongue pressure that activated the actions of the tongue on palate. Further, when associating with the composition of food ingredients (listed in Appendix I), the food with a close proportion among protein, carbohydrate and fat presents a higher value in texture variables, which is observed between cheese spread and crème fraîche. The proportion of protein, carbohydrate and fat is 11 : 5.9 : 19.5 per 100 g cheese spread while the proportion in crème fraîche is 2.7 : 2.8 : 31.1, respectively. Even if the fat proportion of crème fraîche is much higher than it in cheese spread, the values of texture variables in cheese spread is conversely higher than the values of crème fraîche. However, it is not the case between other products. The food texture / structure formed is resulted by many reasons including other unlisted ingredients and biochemical reactions during cooking. The main content of jelly is gelling agent which can create high firmness and consistency, but its comparatively low viscosity and cohesiveness that may be because of its low protein and little fat contents. If the data of jelly were removed, linear relationships would be obtained between total contact pressure / number of peaks in contact pressure and cohesiveness / index of viscosity. The confirmed figures were present in Figure 3.16 & 3.17.



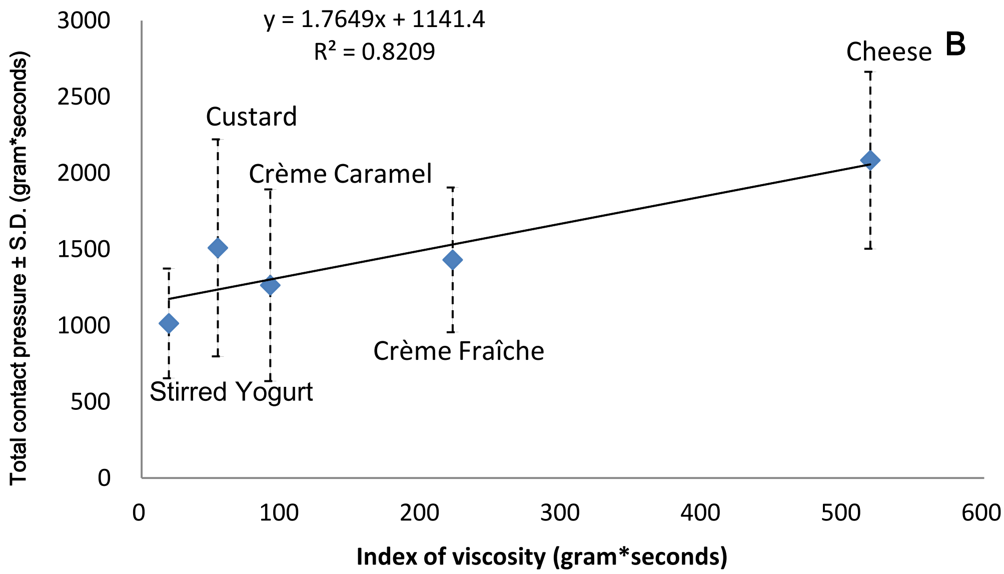


Figure 3.16 Linear relationships between total contact pressure and food texture (without the data of jelly). A: Total contact pressure and cohesiveness; B: Total contact pressure and index of viscosity

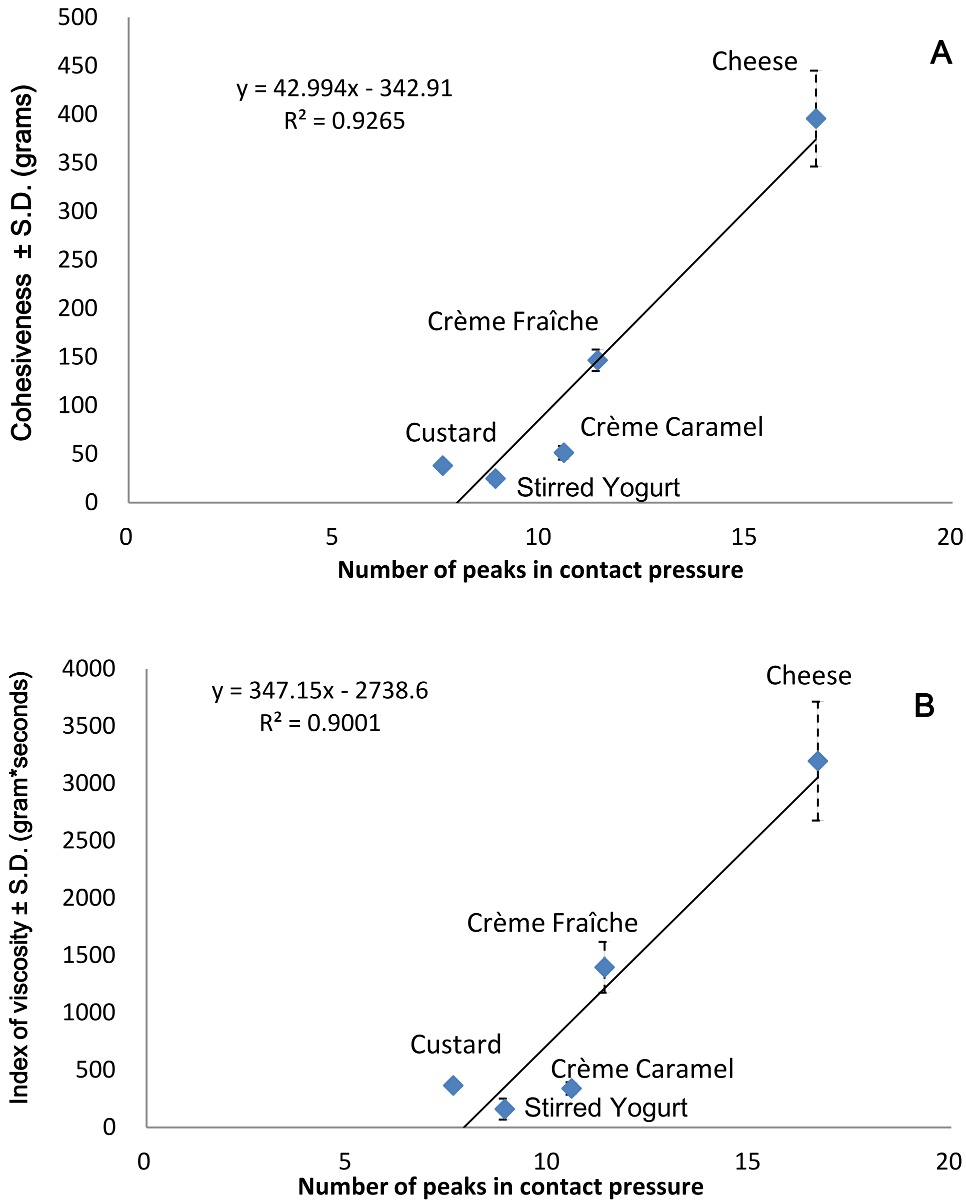


Figure 3.17 Linear relationships between Number of peaks in contact pressure and food texture (without the data of jelly). A: Number of peaks in contact pressure and cohesiveness; B: Number of peaks in contact pressure and index of viscosity.

The relationships or trends between tongue variables and texture variables indicate the capacity of Tekscan I-Scan System to discriminate the differences of physical properties across semi-solid foods. It also reflects that Tekscan I-Scan System is as distinguishable as Texture Analysis through selected tongue variables, such as total tongue contact pressure and number of peaks in contact pressure, at certain extent. However, the large range of food products in the physical properties is a limit in our study, especially the viscosity of dairy products between crème fraîche and cheese spread. Jelly may be not a good sample to observe the relationship between tongue parameters and texture viscosity or cohesiveness, due to its ingredients comparatively different from dairy foods. Therefore, other suitable products should be considered to fill the gaps of foods in the range of physical properties between cheese spread and crème fraîche in the future study.

4 Overall Discussion

The Tekscan I-Scan System with the sensor sheet model 4201 has been successfully applied to study the tongue movement during oral processing of semi-solid foods through appropriate design of the measurement procedure and selection of tongue variables.

Tongue pressure distribution during the eating process was recorded with the Tekscan I-Scan System. Through comparing each measurement time frame acquired at time intervals of 0.3, differences in tongue–palate contact area in different periods of eating were observed. At the time of maximum contact pressure, it was discovered that the tongue was contacting the palate near the gums while the highest pressure produced in other periods was through the tongue contacting the middle region of palate. The behavior of the tongue contacting the palate near the gums was conjectured to be an effect of swallow on tongue movement. It was inferred by the time when maximum tongue variables were attained, which occurred close to the 70% of the whole eating duration when the swallow was likely to be happening. Ishida *et al.* (2002) indicated that the swallowing process is related to the forward movement of the tongue meaning that a large contact area between the tongue and upper palate including the gums of the molars at this point of time. The Tekscan I-Scan System has picked this up. Swallowing is the final stage of eating, and typically several swallows take place before the oral cavity has finally been cleared from the food ingested. Assuming that the maximum contact pressure measured by the Tekscan I-Scan System corresponds to the point in time when swallowing was occurring, the close correlation between maximum contact pressure and index of viscosity (Figure 3.12) would be in agreement with de Wijk *et al.*'s study (2006) reporting that the tongue movement during swallowing is primarily affected by the viscosity of food. The more viscous the food, the higher tongue pressure was required during swallowing.

Also, the rhythm of tongue movement was clearly identifiable from the data obtained with the Tekscan I-Scan System. A linear relationship between the number of peaks in contact pressure and finish time of eating (Figure 3.8) was found. Although the number of peaks for each food varied across subjects, the trend in number of peaks across the different food products remained fairly constant (Figure 3.9). It indicates that different subjects have their own range of tongue moving rhythm for different foods although relative differences between the foods evaluated in this study remain similar. In addition, it was found that the frequency of tongue-moving rhythm was one per second (Table 3.5) which indicated that the rhythm of tongue movement was not affected by foods and subjects. Nakamura and Katakura (1995) said rhythm of tongue movement during the eating processing is a neural base activity with the rhythm generated by the central pattern generator and the rhythmical tongue movement is accompanied by rhythmical jaw movement and secretion of saliva. Maybe, the rhythm of tongue movement has evolved as a regular behavior of human beings and is unconsciously controlled by the central nervous system.

Other than that, significant differences between average contact pressure and end contact pressure were not discovered. Although pressure detection of differences during the first 0.3 s of biting measured by an I-SCAN 50 system has been reported (Kohyama and Nishi, 1997), the tongue-palate contact pressure measured at 0.3 s or other moment (except for the time of maximum contact pressure) in this study did not show statistically significant differences between all semi-solid foods investigated including yogurt drink. The bite pressure was produced by certain incisors or molars contacting solid foods and its magnitude depended on the hardness of foods. This was not the case for the tongue as it is soft and flexible to contact upper palate and has even pressure distribution on it during eating process. Even average tongue contact pressures were not only observed for the different foods during the whole eating process but also during measurements on the empty mouth.

Although finish time is not the main variable to show the capacity of Tekscan I-Scan System, it plays an important role in the study of tongue movement and food texture properties. Significant differences were found in finish time (Table 3.3) between the selected food products. Both total contact pressure and number of peaks in contact pressure were associated with finish time (Figure 3.5 and Figure 3.8). It can be inferred that food texture has an effect on oral processing time. This agrees with Taniguchi *et al.'s* (2008) study. They found the durations of tongue pressure activities tended to be prolonged with increasing firmness of food. These three tongue variables have high correlation coefficients with the food physical properties in firmness and consistency

(Table 3.8). What's more, linear relationships were found between both total contact pressure and number of peaks in contact pressure and both firmness and consistency (Figure 3.15). Except for jelly which little protein and fat contents contributes low viscosity and cohesiveness of jelly, linear relationships between both cohesiveness and index of viscosity and both total contact pressure and number of peaks in contact pressure are observed among the dairy semi-solid foods (Figure 3.16 & 3.17). Close proportion of protein, carbohydrate and fat may result in higher texture attributes, but this is only confirmed in cheese spread and crème fraîche. Different types of food structure are formed by many factors (ingredients, cooking methods, etc.) that affect tongue manipulation indirectly.

Most of the tongue variables selected in this study show close correlations with the food texture variables. In other words, food texture affects tongue behavior, especially tongue pressure during the whole eating process, the rhythm of tongue movement and tongue movement during swallowing. Contrarily, some tongue variables, like average contact pressure, end contact pressure and contact pressure at 0.3 s, indicate that tongue movement is controlled by the central nervous system. When subjects start eating the food, texture informaiton of the food is felt via tongue contact and the sensory signals are transmited to the central nervous system. The tongue pressure is then produced by the control of the extrinsic muscles assisted with the intrinsic muscles (Utanohara *et al.*, 2008). Palmer *et al.* (2007) found that the processes of bolus transport and aggregation by tongue movement as well as swallow initiation may be altered by volition.

The Tekscan I-Scan System is a useful tool to measure the pressure distribution during tongue movement. Its movie and graphic functions provide dynamic images to analyze and understand tongue movement. However, two limitations of the Tekscan I-Scan System as applied in this research have become obvious: the large size of the sensor sheet and the variation in data acquired on different days impeding its effective application. As a measurement technique, these two limitations may create errors in the results. The contact between teeth and the edge of large-size sensor sheet cannot be avoided totally. Then, the recorded data are not all from the tongue pressure but also included the teeth pressure. Also, the circuit of sensor sheet cannot be guaranteed that is not destroyed after multiple measurements, which affects the recorded data. Problems with data variation can and should be overcome by using a specific calibration device or by developing other calibration procedures. One potential calibration experiment is to give a series of even an known forces covering the full size of sensor sheet by a force device, which the corresponding forces recorded by Tekscan can be developed as a standard curve. However, the force device has not been found before this study finished. Although the sensor sheet can be cut to smaller size and this has been tried, it is not trivial to come up with solutions to seal the sensor and prove to be unsuccessful here.

Besides, the four physical properties measured via back extrusion by the Texture Analyzer represent a somewhat limited set of texture data. How the four food textures measured in this study represent their sensory evaluation of food is not clear. Also, the wider range of food texture cannot show a good picture in the range of food texture differences associated with tongue variables, especially the viscosity of dairy products between crème fraîche and cheese spread. Neither are the contents of food well considered when they are selected. It is reflected on the cohesiveness and viscosity of jelly in which the values do not show good relationships with total contact pressure and number of peaks in contact pressure. The reason may be the different way of food structures being broken down between jelly and dairy foods.

Based on the results, recommendations for further research to finalize evaluation of the system are concluded in Section 5.2.

5 Conclusions and Future Work

5.1 Conclusions

This study is the first application of Tekscan I-Scan System with sensor sheet Model 4201 to investigate the tongue movement during oral processing. Through an appropriate method protocol design of the novel tongue measuring instrument attached onto subjects' upper palate, combined with texture analysis on a range of seven selected semi-solid commercial products, the potential capacity of Tekscan I-Scan System for tongue study has been developed. The novel technique – Tekscan I-Scan System enables the presentation of the tongue movement with its pressure distribution during whole eating process through the movie recording and the rhythm of tongue movement through its graphic function. The tongue behaviors of subjects are comparatively stable during eating process, except for when swallowing happens, whereby the maximum contact pressure and area were produced between tongue and upper palate. The textures of the selected products were not all differentiated obviously but the close correlative PCA results and linear relationships between texture data and tongue variables reveal the high interaction between food texture and tongue manipulation.

However, there were some limitations on the technique application and method design that should be improved and developed in further study on tongue movement, described in the Section 5.2.

5.2 Future Work

Tekscan I-Scan System with model 4201 sensor sheet is the first application on tongue measurement. The large size of sensor sheet is the first disadvantage for the adaptation to the shape of palate in mouth. Although two attempts of the cut on sensor sheet did not succeed, a suitable size and shape of sensor sheet for palate should be manufactured with good protection in the future that will enable us to measure the pressure distribution of the whole shape of tongue. Also, the data of the pressure distribution in Tekscan I-Scan System can only be exported one row or one column area each time so that a quantity of data processing would not be done if the whole area distribution in statistical analysis is required. Another limitation of Tekscan I-Scan System is its data variation without a calibration device. The figures in our study are arbitrary units. Some attempts can be made to calibrate the instrument without the calibration device. For example, a known pressure can be exerted consistently on the sensor sheet while recording the force through the function --- dynamic calibration of the System. Overcoming these hurdles should form an important part of future work with the Tekscan I-Scan System.

Besides, Back Extrusion is the protocol adopted on the Texture Analyzer to measure the food texture of semi-solid foods. Firmness is high correlated with consistency while cohesiveness is high correlated with viscosity. To what extent these four texture properties represent the sensory perception has not been studied. It will be good to develop a sensory – instrumental profile for reference. Texture attributes, such as firmness, viscosity, smoothness and stickiness should be included. In addition, the texture diversity and unity should be considered when selecting the food objects. If different food objects with a range magnitude of viscosity, for example, were studied, it would be better to concentrate on the texture of viscosity for analysis and discussion. The texture study also can be connected with food molecular structure and their components.

At last, during the measurement of oral process, swallow observation is suggested to be included, which may affect the tongue movement, so that it can be judged whether the maximum contact pressure happens at the point of swallowing. It would be better to measure the tongue movement with Tekscan System combined with video fluorography that is able to reflect the fluoroscopy images of whole oral processing. It would be interesting to test out the relationship among the tongue movement, swallowing and respiratory rhythm.

References

Agrawal, K. R., Lucas, P. W., Prinz, J. F. & Bruce, I. C. 1997. Mechanical Mechanical properties of foods responsible for resisting food breakdown in the human mouth. *Archives of Oral Biology,* 42**,** 1-9. 1-9.

Akgul, Y. S., Kambhamettu, C. & Stone, M. 1999. Automatic extraction and tracking of the tongue contours. *IEEE Transactions on Medical Imaging,* 18**,** 1035-1045.

Alves, P. 2010. Imaging the hypoglossal nerve. *European Journal of Radiology,* 74**,** 368-377.

Armstrong, E. 1998. Articulation: Tongue. *Journey of the Voice*.

Barigou, M., Fairhurst, P. G., Fryer, P. J. & Pain, J. P. 2003. Concentric flow regime of solid-liquid food suspensions: theory and experiment. *Chemical Engineering Science,* 58**,** 1671-1686.

Beal, C., Skokanova, J., Latrille, E., Martin, N. & Corrieu, G. 1999. Combined effects of culture conditions and storage time on acidification and viscosity of stirred yogurt. *Journal of Dairy Science,* 82**,** 673-681.

Blissett, A., Hort, J. & Taylor, A. J. 2006. Influence of chewing and swallowing behavior on volatile release in two confectionery systems. *Journal of Texture Studies,* 37**,** 476-496.

Bourne, M. (ed.) 2001. *Food texture and viscosity - concept and measurement*.

Brennan, C. S. & Cleary, L. J. 2005. The potential use of cereal (1 -> 3,1 -> 4)-beta-D-glucans as functional food ingredients. *Journal of Cereal Science,* 42**,** 1-13.

Brennan, J. G. 1989. Texture perception and measurement. *In Sensory Analysis of Foods, (J.R. Piggott, ed.), Elsevier, London.***,** 69-101.

Brighenti, M., Govindasamy-Lucey, S., Lim, K., Nelson, K. & Lucey, J. A. 2008. Characterization of the Rheological, Textural, and Sensory Properties of Samples of Commercial US Cream Cheese with Different Fat Contents. *Journal of Dairy Science,* 91**,** 4501-4517.

Buchheim, W. & Welsch, U. 1973. Evidence for submicellar composition of casein micelles on basis of electron microscopical studies. *Netherlands Milk and Dairy Journal,* 27**,** 163-180.

Buschang, P. H., Throckmorton, G. S. & Travers, K. H. 1997. The effects of bolus size and chewing rate on masticatory performance with artificial test foods. *Journal of Oral Rehabilitation,* 24**,** 522-526.

Cardarelli, H. R., Aragon-Alegro, L. C., Alegro, J. H. A., De Castro, I. A. & & Saad, S. M. I. 2008. Effect of inulin and Lactobacillus paracasei on sensory and instrumental texture properties of functional chocolate mousse. *Journal of the Science of Food and Agriculture, Agriculture,* 88**,** 1318-1324.

Cayot, N. 2007. Sensory quality of traditional foods. *Food Chemistry,* 101**,** 101**,** 154-162.

Cerning, J. 1995. Production of exopolysaccharides by lactic acid bacteria and dairy propionibacteria. *Lait,* 75**,** 463-472.

Chen, J. S. 2009. Food oral processing - A review. *Food Hydrocolloids,* 23**,** 1-25.

Chen, J. S. & Lolivret, L. 2011. The determining role of bolus rheology in triggering a swallowing. *Food Hydrocolloids,* 25**,** 325-332.

Chiba, Y., Motoyoshi, M. & Namura, S. 2003. Tongue pressure on loop of of transpalatal arch during deglutition. *American Journal of Orthodontics and Dentofacial Orthopedics,* 123**,** 29-34.

Christensen, C. M. & Casper, L. M. 1987. Oral and Nonoral Perception of of Solution Viscosity. *Journal of Food Science,* 52**,** 445-447.

Clark, H. M., Henson, P. A., Barber, W. D., Stierwalt, J. a. G. & Sherrill, M. M. 2003. Relationships among subjective and objective measures of tongue strength and oral phase swallowing impairments. *American Journal of Speech-Language Pathology,* 12**,** 40-50.

Coggins, P. C., Rowe, D. E., Wilson, J. C. & Kumari, S. 2010. Storage and temperature effects on appearance and textural characterisitics of conventional milk yogurt *Journal of Sensory Studies,* 25**,** 549-576.

Corradini, M. G. & Peleg, M. 2000. Lubricated squeezing flow viscometry for dulce de leche (milk sweet). *Food Science and Technology International,* 6**,** 339-344.

Cunha, C. R. & Viotto, W. H. 2010. Casein Peptization, Functional Properties, and Sensory Acceptance of Processed Cheese Spreads Made with Different Emulsifying Salts. *Journal of Food Science,* 75**,** C113-C120.

Cunningham D. P. & Basmajian J. V. 1969. Electromyography of genioglossus and geniohyoid muscles during deglutition. *The Anatomical Record,* 165 (3)**,** 401-409.

Dan, H. & Kohyama, K. 2007. Interactive relationship between the mechanical properties of food and the human response during the first bite. *Archives of Oral Biology,* 52**,** 455-464.

De Wijk, R. A., Janssen, A. M. & Prinz, J. F. 2011. Oral movements and the perception of semi-solid foods. *Physiology & Behavior,* 104**,** 423-8.

De Wijk, R. A., Rasing, F. & Wilkinson, C. L. 2003. Texture of semi-solids: Sensory flavor-texture interactions for custard desserts. *Journal of Texture Studies,* 34**,** 131-146.

De Wijk, R. A., Wulfert, F. & Prinz, J. F. 2006. Oral processing assessed by M-mode ultrasound imaging varies with food attribute. *Physiology & Behavior,* 89**,** 15-21.

Dodds, W. J., Taylor, A. J., Stewart, E. T., Kern, M. K., Logemann, J. A. & Cook, I. J. 1989. Tipper and dipper types of oral swallows. *American Journal of Roentgenology,* 153**,** 1197-1199.

Doty, R., Cummins, D., Shibanova, A., Sanders, I. & Mu, L. 2009. Lingual distribution of the human glossopharyngeal nerve. *Acta Oto-Laryngologica,* 129**,** 52-56.

Drake, M. A. 2007. Invited review: Sensory analysis of dairy foods. *Journal of Dairy Science,* 90**,** 4925-4937.

Dubrul, E. L. 1988. Oral anatomy. Chapter 6.

Duizer, L. 2001. A review of acoustic research for studying the sensory perception of crisp, crunchy and crackly textures. *Trends in Food Science & Technology,* 12**,** 17-24.

Elenbogen G. D. & Baron M. 1964. Imitation cream cheese spread containing polyunsaturated fat. *United States Parent Office,* 3397994.

Foegeding, E. A. & Drake, M. A. 2007. Invited review: Sensory and mechanical properties of cheese texture. *Journal of Dairy Science,* 90**,** 1611-1624.

Foster, K. D., Woda, A. & Peyron, M. A. 2006. Effect of texture of plastic and elastic model foods on the parameters of mastication. *Journal of Neurophysiology,* 95**,** 3469-3479.

Fregosi, R. F. & Fuller, D. D. 1997. Respiratory-related control of extrinsic tongue muscle activity. *Respiration Physiology,* 110**,** 295-306.

Guinard, J. X. & Mazzucchelli, R. 1996. The sensory perception of texture and mouthfeel. *Trends in Food Science & Technology,* 7**,** 213-219.

Haque, A., Richardson, R. K. & Morris, E. R. 2001. Effect of fermentation temperature on the rheology of set and stirred yogurt. *Food Hydrocolloids,* 15**,** 593-602.

Hiiemae, K., Heath, M. R., Heath, G., Kazazoglu, E., Murray, J., Sapper, D. & Hamblett, K. 1996. Natural bites, food consistency and feeding behaviour in man. *Archives of Oral Biology,* 41**,** 175-189.

Hiiemae, K. M., Hayenga, S. M. & Reese, A. 1995. Patterns of tongue and jaw movement in a cinefluorographic study of feeding in the macaque. *Archives of Oral Biology,* 40**,** 229-246.

Hiiemae, K. M. & Palmer, J. B. 1999. Food transport and bolus formation during complete feeding sequences on foods of different initial consistency. *Dysphagia,* 14**,** 31-42.

Hiiemae, K. M. & Palmer, J. B. 2003. Tongue movements in feeding and speech. *Critical Reviews in Oral Biology & Medicine,* 14**,** 413-429.

Hoebler, C., Devaux, M. F., Karinthi, A., Belleville, C. & Barry, J. L. 2000. Particle size of solid food after human mastication and in vitro simulation of oral breakdown. *International Journal of Food Sciences and Nutrition,* 51**,** 353-366.

Horne, D. S. 1999. Formation and structure of acidified milk gels. *International Dairy Journal,* 9**,** 261-268.

Huang, R. J., Zhi, Q. X., Izpisua-Belmonte, J. C., Christ, B. & Patel, K. 1999. Origin and development of the avian tongue muscles. *Anatomy and Embryology,* 200**,** 137-152.

Imai, A., Tanaka, M., Tatsuya, M. & Kawazoe, T. 1995. Ultrasonic images of tongue movement during mastication. *J Osaka Dent University,* 29**,** 61-69.

Inagaki, D., Miyaoka, Y., Ashida, I. & Yamada, Y. 2009. Activity pattern of swallowing-related muscles, food properties and body position in normal humans. *Journal of Oral Rehabilitation,* 36**,** 703-709.

Ishida, R., Palmer, J. B. & Hiiemae, K. M. 2002. Hyoid motion during swallowing: Factors affecting forward and upward displacement. *Dysphagia,* 17**,** 262-272.

Jack, F. R. & Gibbon, F. 1995. Electropalatography in the study of tongue movement during eating and swallowing (a novel procedure for measuring texture-related behaviour). *Int. J. Food Sci. Technol.,* 30**,** 415-423.

Janssen, A. M., Terpstra, M. E. J., De Wijk, R. A. & Prinz, J. F. 2007. Relations between rheological properties, saliva-induced structure breakdown and sensory texture attributes of custards. *Journal of Texture Studies,* 38**,** 42-69.

Jiang, C., Mitchell, G. S. & Lipski, J. 1991. Prolonged augmentation of respiratory discharge in hypoglossal motoneurons following surerior laryngeal nerve - stimulation. *Brain Research,* 538**,** 215-225.

Kealy, T. 2006. Application of liquid and solid rheological technologies to the textural characterisation of semi-solid foods. *Food Research International,* 39**,** 265-276.

Kerrod, R. 1997. MacMillan's Encyclopedia of Science. Macmillan Publishing Company, Inc.

Kohyama, K. & Nishi, M. 1997. Direct measurement of biting pressures for crackers using a multiple-point sheet sensor. *Journal of Texture Studies,* 28**,** 605-617.

Lawless, H. T. & Heymann, H. H. 1998. Sensory Evaluation of Food: Principles and Practices, Chapman and Hall, New York, NY.

Lin, H. C. & Barkhaus, P. E. 2009. Cranial Nerve XII: The Hypoglossal Nerve. *Seminars in Neurology,* 29**,** 45-52.

Lucas, P. W. & Luke, D. A. 1984. Optimum mouthful for food comminution in human mastication. *Archives of Oral Biology,* 29**,** 205-210.

Lucas, P. W., Prinz, J. F., Agrawal, K. R. & Bruce, I. C. 2002. Food physics and oral physiology. *Food Quality and Preference,* 13**,** 203-213.

Malone, M. E., Appelqvist, I. A. M. & Norton, I. T. 2003. Oral behaviour of food hydrocolloids and emulsions. Part 1. Lubrication and deposition considerations. *Food Hydrocolloids,* 17**,** 763-773.

Martin, R. E., Macintosh, B. J., Smith, R. C., Barr, A. M., Stevens, T. K., Gati, J. S. & Menon, R. S. 2004. Cerebral areas processing swallowing and tongue movement are overlapping but distinct: A functional magnetic resonance imaging study. *Journal of Neurophysiology,* 92**,** 2428-2443.

McCarthy, K. L. & Seymour, J. D. 1993. A fundamental approache for the relationship between Bostwick measurement and Newtonian fluid viscosity. *Texture Stud.,* 24**,** 1-10.

Mioche, L. & Peyron, M. A. 1995. Bite force displayed during assessment of hardness in various texture contexts. *Archives of Oral Biology,* 40**,** 415-423.

Mishellany, A., Woda, A., Labas, R. & Peyron, M. A. 2006. The challenge of mastication: Preparing a bolus suitable for deglutition. *Dysphagia,* 21**,** 87-94.

Moritaka, H., Naito, S., Nishinari, K., Ishihara, M. & Fukuba, H. 1999. Effects of gellan gum, citric acid and sweetener on the texture of lemon jelly. *Journal of Texture Studies,* 30**,** 29-41.

Mu, L. C. & Sanders, I. 2010. Human Tongue Neuroanatomy: Nerve Supply and Motor Endplates. *Clinical Anatomy,* 23**,** 777-791.

Nakamura, Y. & Katakura, N. 1995. Generation of masticatory rhythm in the brain-stem *Neuroscience Research,* 23**,** 1-19.

Okada, A., Honma, A., Nomura, S. & Yamada, Y. 2007. Oral behavior from food intake until terminal swallow. *Physiology & Behavior,* 90**,** 172-179.

Ono, T., Ishiwata, Y., Inaba, N., Kuroda, T. & Nakamura, Y. 1998. Modulation of the inspiratory-related activity of hypoglossal premotor neurons during ingestion and rejection in the decerebrate cat. *Journal of Neurophysiology,* 80**,** 48-58.

Palmer, J. B., Hiiemae, K. M., Matsuo, K. & Haishima, H. 2007. Volitional control of food transport and bolus formation during feeding. *Physiology & Behavior,* 91**,** 66-70.

Pedersen, A. M., Bardow, A., Jensen, S. B. & Nauntofte, B. 2002. Saliva and gastrointestinal functions of taste, mastication, swallowing and digestion. *Oral Diseases,* 8**,** 117-129.

Peyron, M. A., Mishellany, A. & Woda, A. 2004. Particle size distribution of food boluses after mastication of six natural foods. *Journal of Dental Research,* 83**,** 578-582.

Piancino, M. G., Bracco, P., Vallelonga, T., Merlo, A. & Farina, D. 2008. Effect of bolus hardness on the chewing pattern and activation of masticatory muscles in subjects with normal dental occlusion. *Journal of Electromyography and Kinesiology,* 18**,** 931-937.

Piazza, L., Gigli, J., Rojas, C., Ballabio, D., Todeschini, R. & Tripaldi, P. 2009. Dairy cream response in instrumental texture evaluation processed by multivariate analysis. *Chemometrics and Intelligent Laboratory Systems,* 96**,** 258-263.

Pouderoux, P. & Kahrilas, P. J. 1995. Deglutive tongue force modulation by volition, volume, and viscosity in humans. *Gastroenterology,* 108**,** 1418-1426.

Prinz, J. F. & Lucas, P. W. 1997. An optimization model for mastication and swallowing in mammals. *Proceedings of the Royal Society of London Series B-Biological Sciences,* 264**,** 1715-1721.

Proffit, W. R., Kydd, W. L., Taylor, D. T. & Wilskie, G. H. 1964. Intraonal pressures in young adult group. *Journal of Dental Research,* 43**,** 555-&.

Prow, L. A. & Metzger, L. E. 2005. Melt analysis of process cheese spread or product using a rapid visco Analyzer. *Journal of Dairy Science,* 88**,** 1277-1287.

Raffo, A., Sinesio, F., Moneta, E., Nardo, N., Peparaio, M. & Paoletti, F. 2006. Internal quality of fresh and cold stored celery petioles described by sensory profile, chemical and instrumental measurements. *European Food Research and Technology,* 222**,** 590-599.

Rawson, H. L. & Marshall, V. M. 1997. Effect of 'ropy' strains of Lactobacillus delbrueckii ssp bulgaricus and Streptococcus thermophilus on rheology of stirred yogurt. *International Journal of Food Science and Technology,* 32**,** 213-220.

Robin, D. A. & Luschei, E. S. 1991. *Reference manual for the Iowa Oral Performance Instrument*, Oakdale, IA: Breakthrough.

Robin, D. A., Somodi, L. B. & Luschei, E. S. 1991. Measurement of tongue strength and endurance in normal and articulation disordered subjects. *Dysarthria and apraxia of speech: Perspectives on management***,** 173-184.

Rodgers, J. L. & Nicewander, W. A. 1988. Thirteen ways to look at the correlation coefficient. *The American Statistician,* 42.

Rohm, J. 2003. The rheology and textural properties of yogurt. *In:* MCKENNA, B. M. (ed.) *Texture in Food, Volume 1 : Semi-solid Foods.* Cambridge, GBR: Woodhead Publishing, Limited.

Saigusa, H., Tanuma, K., Yamashita, K., Saigusa, M. & Niimi, S. 2006. Nerve fiber analysis for the lingual nerve of the human adult subjects. *Surgical and Radiologic Anatomy,* 28**,** 59-65.

Sainani, M. R., Vyas, H. K. & Tong, P. S. 2004. Characterization of particles in cream cheese. *Journal of Dairy Science,* 87**,** 2854-2863.

Sanguineti, V., Laboissiere, R. & Payan, Y. 1997. A control model of human tongue movements in speech. *Biological Cybernetics,* 77**,** 11-22.

Sawczuk, A. & Mosier, K. M. 2001. Neural control of tongue movement with respect to respiration and swallowing. *Critical Reviews in Oral Biology & Medicine,* 12**,** 18-37.

Schmitt, C., Sanchez, C., Desobry-Banon, S. & Hardy, J. 1998. Structure and technofunctional properties of protein-polysaccharide complexes: A review. *Critical Reviews in Food Science and Nutrition,* 38**,** 689-753.

Schwedoff, T. 1889. Recherches experimentales sur la cohesion des liquides. *J. Phys.Theor. Appl.,* 8**,** 341-359.

Sloot, J. 2010. *Widest tongue* [Online]. Available at: < http://www.guinnessworldrecords.com/records/size/widest-tongue > Accessed 23/11/11. [Accessed].

Smith, S. E. 2011. What is a Hypoglossal Nerve? *Conjecture Corporation*.

Snoeren, T., Daman, A. & Klok, H. 1982. The viscosity of skim-milk concentrates. *Netherlands milk and dairy Journal* 36**,** 305-316.

Stierwalt, J. a. G. & Youmans, S. R. 2007. Tongue measures in individuals with normal and impaired swallowing. *American Journal of Speech-Language Pathology,* 16**,** 148-156.

Stone, M. & Shawker, T. 1986. An ultrasound examination of tongue movement during swallowing. *Dysphagia,* 1**,** 78-83.

Stone, M. & Vatikiotis-Bateson, E. 1995. Trade-offs in tongue, jaw and palate contributions to speech production. *J Phonet* 23**,** 81-100.

Sorensen L.B., Moller P., Flint A., Martens M. & Raben, A. 2003. Effect of sensory perception of foods on appetite and food intake: a review of studies on humans. *International Journal of Obesity,* 27**,** 15.

Tachimura, T., Ojima, M., Nohara, K. & Wada, T. 2005. Change in palatoglossus muscle activity in relation to swallowing volume during the transition from the oral phase to the pharyngeal phase. *Dysphagia,* 20**,** 32-39.

Takahashi, T., Nitou, T., Tayama, N., Kawano, A. & Ogoshi, H. 2002. Effects of physical properties and oral perception on transit speed and passing time of semiliquid foods from the mid-pharynx to the hypopharynx. *Journal of Texture Studies,* 33**,** 585-598.

Tamine, K., Ono, T., Hori, K., Kondoh, J., Hamanaka, S. & Maeda, Y. 2010. Age-related Changes in Tongue Pressure during Swallowing. *Journal of Dental Research,* 89**,** 1097-1101.

Taniguchi, H., Tsukada, T., Ootaki, S., Yamada, Y. & Inoue, M. 2008. Correspondence between food consistency and suprahyoid muscle activity, tongue pressure, and bolus transit times during the oropharyngeal phase of swallowing. *Journal of Applied Physiology,* 105**,** 791-799.

Tarr, L. W. 1926. *Fruit Jellies III.Jelly strength measurements*. NO.142.

Taylor, S. 2009. Longest tongue. *Guinness World Records.* Available at: <http://www.guinnessworldrecords.com/records/size/longest-tongue> Accessed 23/11/11.

Tekscan, I. 2011a. Changing Graph Display Options. *I-Scan Pressure Measurement System help file Version 6.0x*.

Tekscan, I. 2011b. *Pressure and Force Measurement Applications* [Online]. Available at: < http://www.tekscan.com/applications > Accessed 23/11/11. [Accessed].

Templeton, H. L. & Sommer, H. H. 1932. Cheese Spreads. *Journal of Dairy Science,* 15, 155-162.

The Mcgraw-Hill Companies, I. 2012. Muscles of Tongue. *Rutgers, the State University of New Jersey,* Available at: http://www.rci.rutgers.edu/~uzwiak/AnatPhys/APFallLect14.html, Accessed 23/11/11.

Tomita, H., Ikeda, M. & Okuda, Y. 1986. Basis and practice of clinical taste examinations. *Auris, nasus, larynx,* 13 Suppl 1, S1-15.

Tsukada, T., Taniguchi, H., Ootaki, S., Yamada, Y. & Inoue, M. 2009. Effects of food texture and head posture on oropharyngeal swallowing. *Journal of Applied Physiology,* 106, 1848-1857.

Utanohara, Y., Hayashi, R., Yoshikawa, M., Yoshida, M., Tsuga, K. & Akagawa, Y. 2008. Standard values of maximum tongue pressure taken using newly developed disposable tongue pressure measurement device. *Dysphagia,* 23, 286-290.

Walstra, P., Geurts, T. J., Noomen, A., Jellema, A. & van Boekel, M.A.J.S. 1999. *Dairy Technology,* New York, Marcel Dekker.

Yoleri, L. & Mavioglu, H. 2000. Total tongue reconstruction with free functional gracilis muscle transplantation: A technical note and review of the literature. *Annals of Plastic Surgery,* 45, 181-186.

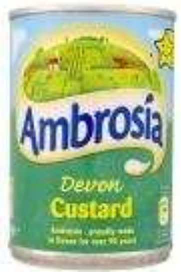
Yu, J., Ahmedna, M. & Goktepe, I. 2007. Peanut protein concentrate: Production and functional properties as affected by processing. *Food Chemistry,* 103**,** 121-129.

Zheng, C. X., Sun, D. W. & Zheng, L. Y. 2006. Recent applications of image texture for evaluation of food qualities - a review. *Trends in Food Science & Technology,* 17**,** 113-128.

Appendix

I - A Products information-Brands and Ingredients

Products	Ingredients	Image
Sainsbury's Basics Crème Caramel (Crème Caramel)	Skimmed Milk (70%)*, Sugar, Water, Caramel (6%) (Sugar, Glucose, Water, Modified Potato Starch, Thickeners: Pectin, Xanthan Gum), Cream (2%)*, Modified Potato Starch, Gelling Agent (Carrageenan), Lactose*, Flavouring, Colour (Annatto, Curcumin), *from Cows' Milk.	
Sainsbury's British Crème Fraîche (Crème Fraîche)	Cows' milk	

Dairylea Cheese Spread (Cheese)	Concentrated Skimmed Milk, Butter, Cheese (17%), Milk Proteins, Emulsifying Salts ((e452, E341, E339)), Salt, Lactic Acid	
Ambrosia Devon Custard (Custard)	Skimmed Milk, Buttermilk, Sugar, Modified Starch, Vegetable Oil, Whey, Flavouring, Colour (Curcumin, Annatto). Total Milk Content 73%.	
Sainsbury's 2% Fat Natural Yogurt (Stirred yogurt)	Sainsbury's probiotic bacteria, Cows' milk	

Hartley's Low Calorie Cranberry & Raspberry Jelly (Jelly)	Water, Cranberry Juice from Concentrate (1%), Raspberry Juice from the Concentrate (1%), Gelling Agents (Potassium Citrate, Xanthan Gum, Locust Bean Gum, Gellan Gum), Citric Acid, Preservative (Potassium Sorbate), Flavorings, Sweeteners (Aspartame, Acesulphame K), Color (Carmoisine)	
Actimel Strawberry Yogurt Drink (Yogurt drink)	Yogurt, Skimmed Milk, Liquid Sugar (Sucrose (11.3%)), Strawberry (2.1%), Dextrose, Stabiliser (Modified Tapioca Starch), Flavourings, L.casei Imunitass Cultures, Acidity Regulator (Sodium Citrate).	

I - B Products information – Components

Name	Components (g / 100g)					
	Protein(g)	Carbohydrate (g)	Fat(g)	Fibre (g)	Salt/sodium (g)	Others
Sainsbury's Basics Crème Caramel	2.4	21.6	0.9	<0.1	N/A	75
Sainsbury's British Crème Fraîche (L)	2.7	2.8	31.1	Nil	Trace/0.03	63.37
Dairylea Cheese Spread	11.0	5.9	19.5	Nil	2.0/0.8	60.8
Ambrosia Devon Custard	2.9	16	2.9	Nil	0.3/Trace	77.9
Sainsbury's 2% Fat Natural Yogurt	5.6	8.0	1.3	Nil	0.2/Trace	84.9
Hartley's Low Calorie Cranberry & Raspberry Jelly	0.0	1.0	Nil	0.4	N/A	98.6
Actimel Strawberry Yogurt Drink	3.0	12.0	1.6	Nil	Nil	83.4

II Means and standard deviations of FT (finish time), MFT (time of maximum force), MAT (time of maximum contact area) and MPT (time of maximum contact pressure).

Variables \ Foods		Crème Caramel	Crème Fraîche	Cheese Spread	Custard	Jelly	Stirred Yogurt	Yogurt Drink
FT	Mean	9.716	10.068	14.046	6.988	12.732	8.232	3.47
	S.D.	4.979	4.072	5.822	2.445	5.760	4.288	1.102
MFT	Mean	6.742	6.758	10.188	4.862	8.784	5.566	2.242
	S.D.	4.37	4.049	5.168	2.813	5.118	3.354	1.028
MAT	Mean	6.94	7.178	10.126	4.758	8.58	5.13	3.631
	S.D.	4.483	4.008	5.203	2.438	4.583	3.627	1.231
MPT	Mean	6.502	6.966	10.098	4.166	8.438	5.392	2.054
	S.D.	4.507	4.900	5.387	2.118	4.970	3.631	1.231

III Texture comparison between Crème Caramel with juice and without juice

Texture attributes	Firmness	Consistency	Cohesiveness	Viscosity
F value	1.422	2.497	4.279	7.934
Sig. [a]	0.267	0.153	0.072	0.023
t value	-0.580	-0.924	-2.327	-1.813
Sig. [b]	0.578	0.383	0.048	0.129

SB: N, 5; df (t-Test), 8; [a], Levene's Test of Equality of Error Variances for F test, α = 0.05； [b], two-tail t Test, α = 0.05;

The t test between crème caramel with juice and without juice does not show a statistical difference in the four texture variables. Therefore, the juice on the surface of crème caramel won't affect the data of texture analysis.

IV T- test comparisons between the values of pressure. (N, 10; df, 18; a, Levene's Test of Equality of Error Variances for F test, $\alpha = 0.05$; b, two-tail t Test, $\alpha = 0.05$)

A: Comparison between average contact pressure and end contact pressure

Food	Crème Caramel	Crème Fraîche	Cheese Spread	Custard	Jelly	Stirred Yogurt	Yogurt Drink
F value	0.791	1.630	0.093	0.943	0.000	0.318	0.525
Sig. [a]	0.386	0.218	0.763	0.344	0.992	0.580	0.478
t value	-0.561	0.719	-0.376	0.740	0.061	-0.068	0.571
Sig. [b]	0.582	0.481	0.711	0.469	0.952	0.947	0.575

B: Comparison between contact pressure at 1.0 s and end contact pressure

Food	Crème Caramel	Crème Fraîche	Cheese Spread	Custard	Jelly	Stirred Yogurt	Yogurt Drink
F value	2.565	2.692	2.333	1.403	0.028	0.948	1.228
Sig. [a]	0.127	0.118	0.144	0.252	0.869	0.343	0.282
t value	0.212	1.608	1.582	1.458	0.945	1.460	1.040
Sig. [b]	0.834	0.125	0.131	0.162	0.357	0.162	0.312

Significant differences are not shown the contact pressure at 1.0 s, 3.0 s and 5.0 s across the food products. Therefore, it can be inferred that the contact pressures were even at each recording point except the point of maximum contact pressure during the whole eating process.

V Mean and ± one standard deviation of (A) end peak force, (B) number of highest peak force and (C) total peak force through ANOVA analysis

A: End peak force

Food	Crème Caramel	Crème Fraîche	Cheese Spread	Custard	Jelly	Stirred Yogurt	Yogurt Drink
Mean	406.8	356.1	361.3	379.0	406.8	391.2	371.1
S.D.	178.8	190.0	190.6	185.3	168.7	172.34	200.4

Source	Sum of squares	df	Mean squares	F	Sig.
Corrected Model	4.596E6	69	66614.532	2.611	0.000
Error	7144883.200	280	25517.440		
Corrected Total	1.174E7	349			

B: number of highest peak force

Source	Sum of squares	df	Mean squares	F	Sig.
Corrected Model	239.314	69	3.468	2.526	0.000
Error	384.400	280	1.373		
Corrected Total	623.714	349			

Food	Mean	S.D.	Homogeneous subsets
Crème Caramel	0.94	2.94	b
Crème Fraîche	0.3	0.81	a, b
Cheese Spread	0.46	1.05	a, b

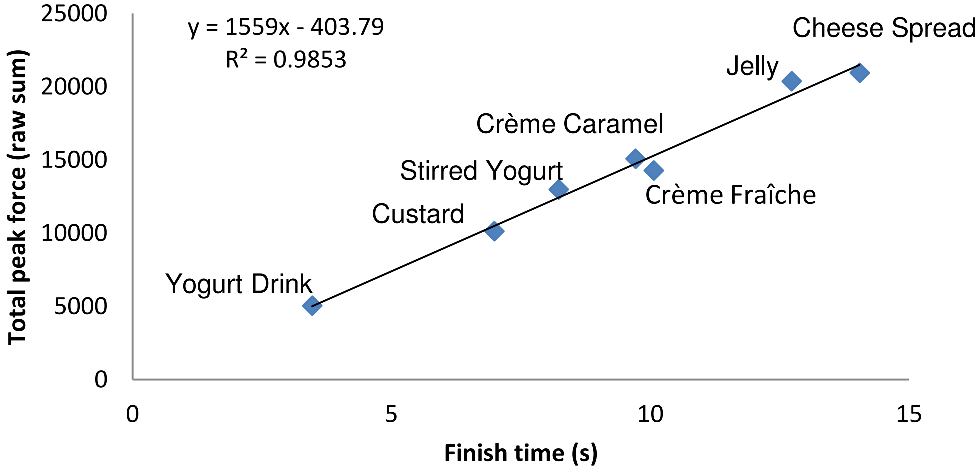
Custard	0.16	0.37	a
Jelly	0.34	0.85	a, b
Stirred Yogurt	0.32	0.87	a, b
Yogurt Drink	0.08	0.44	a

C: Total peak force

Source	Sum of squares	df	Mean squares	F	Sig.
Corrected Model	2.173E10	69	3.149E8	19.679	0.000
Error	4.480E9	280	1.600E7		
Corrected Total	2.621E10	349			

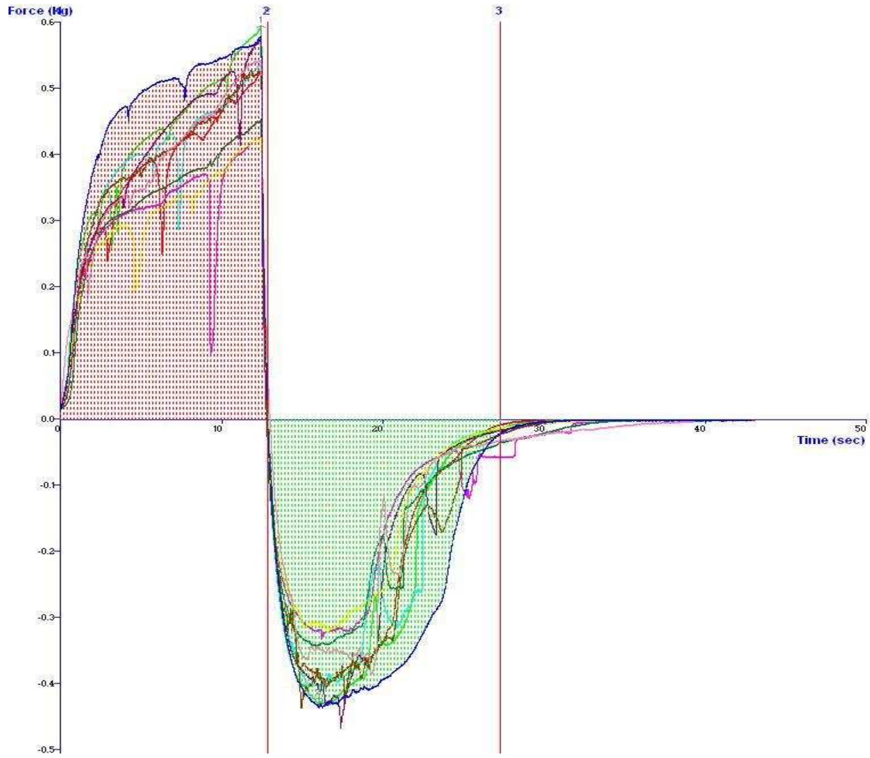
Food	Mean	S.D.	Homogeneous subsets
Crème Caramel	15087.98	7541.198	c
Crème Fraîche	14286.58	6181.345	c
Cheese	20958.38	6109.529	d
Custard	10140.92	5451.462	b
Jelly	20385.86	11297.298	d
Stirred Yogurt	12990.18	6886.932	c
Yogurt Drink	5051.66	2745.981	a

VI Linear correlation between total peak force and finish time.

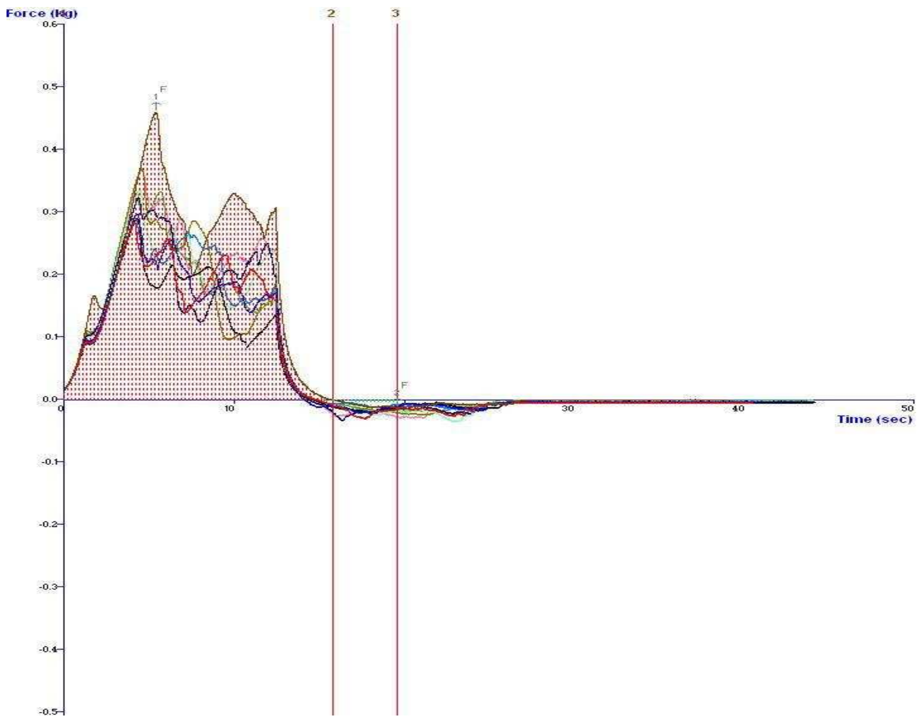


VII Texture recordings of the seven varieties of foods

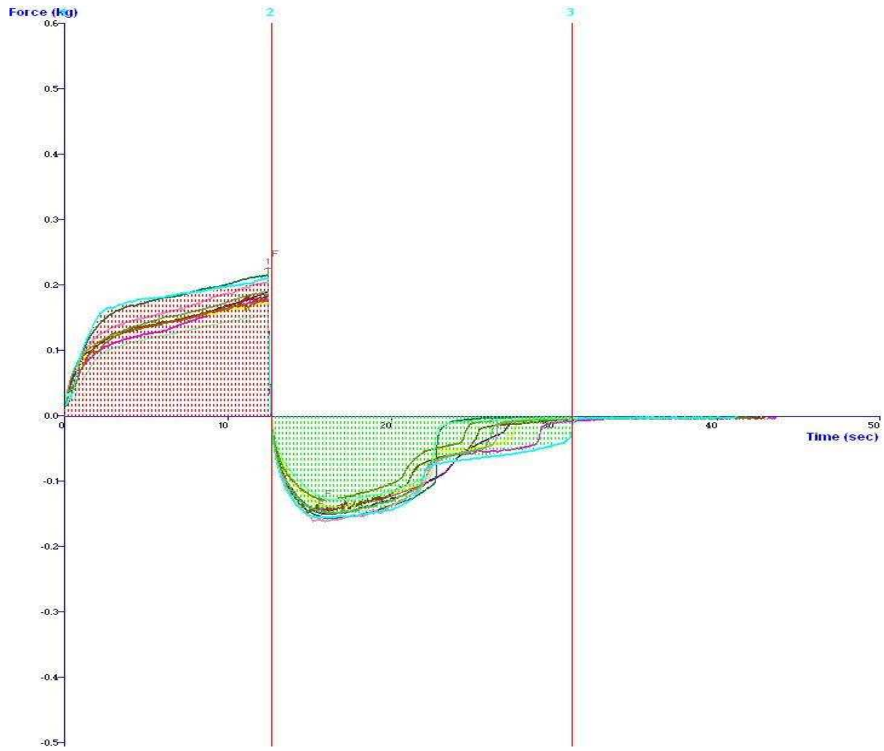
A Cheese spread



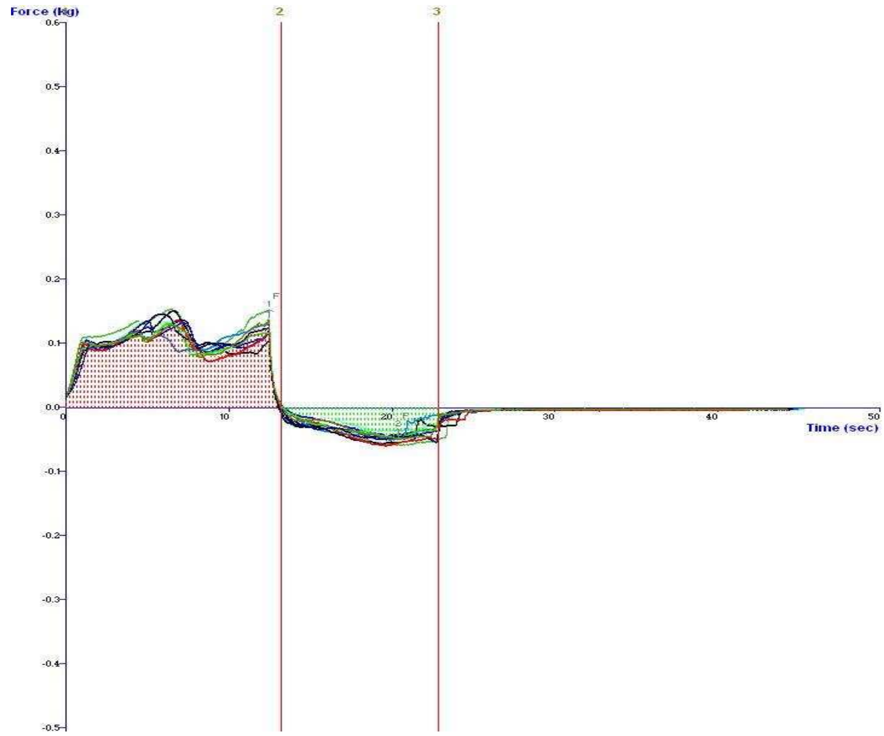
B Jelly



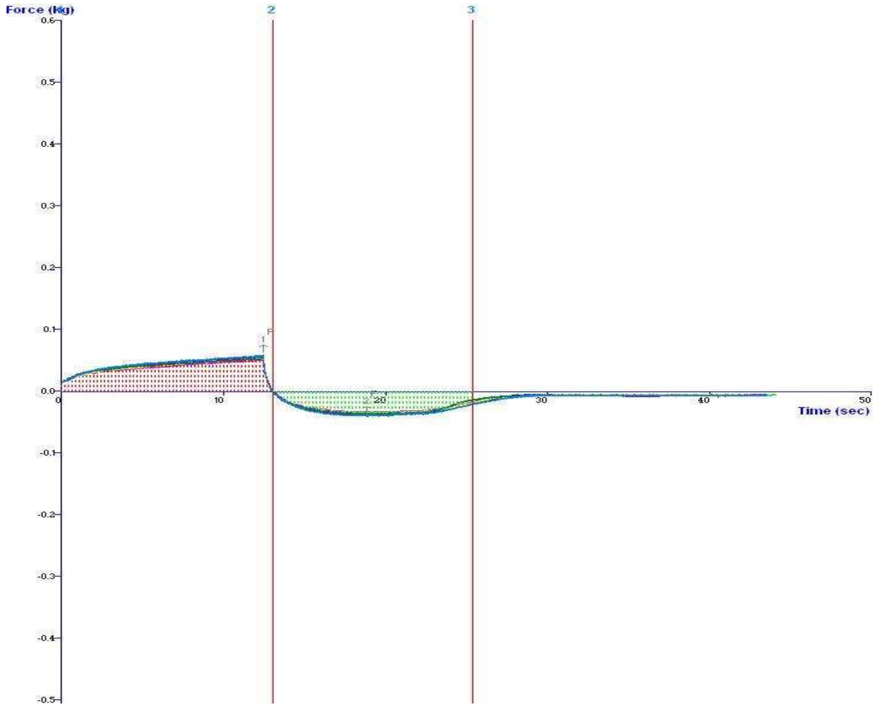
C Crème fraîche



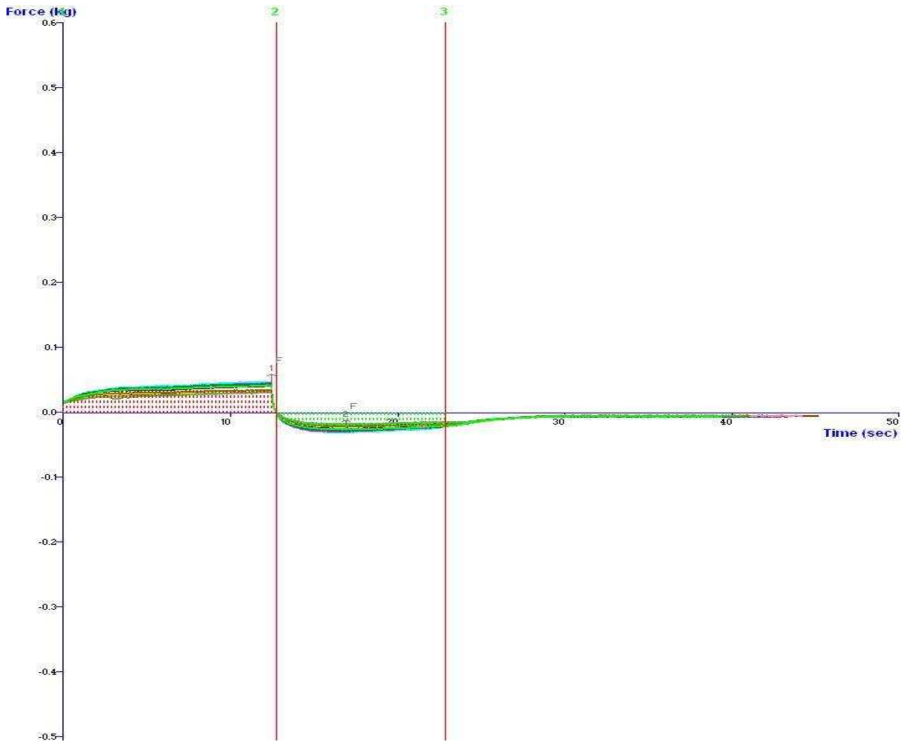
D Crème caramel



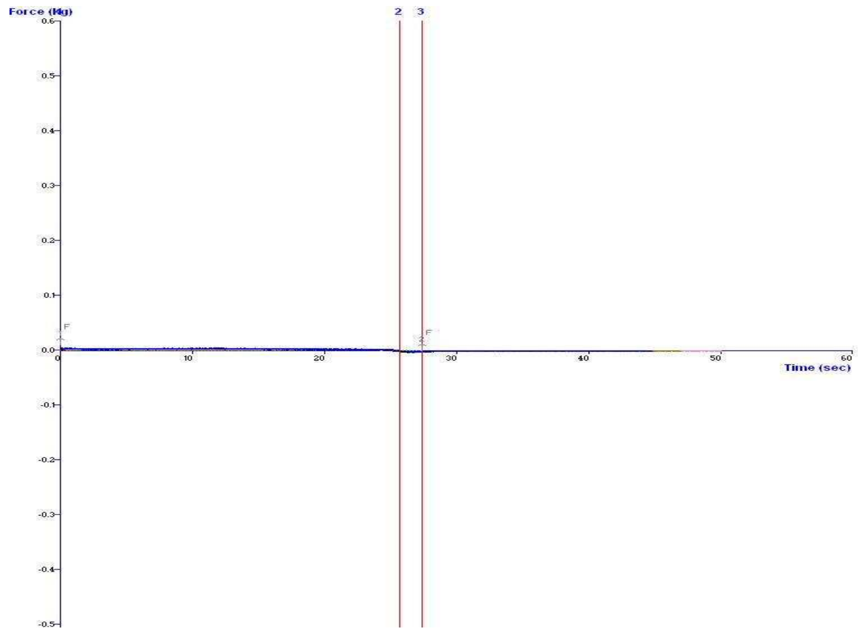
E Custard



F Stirred yogurt



G-1 Yogurt drink



G -2 Yogurt drink in larger zoom