Tongue Pressure - A Key Limiting Aspect in Bolus Swallowing

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The candidate confirms that the work submitted is her own work, except the work which has formed part of jointly-authored publications. Publications have been included. The contribution of the candidate and the other authors to this work has been explicitly indicated below. The candidate confirms that appropriate credit has been given within the thesis where reference has been made to the work of others. Details of the jointly-authored publications are outlined on the next page.

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Further details of the work from jointly-authored publications and the contributions of the candidate and the other authors to the work are included below:

Chapter 3

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Details of authorship contributions:

Alsanei: conducted the experimental designs, data analysis, method validation, laboratory work and sensory evaluation tests, data interpretation, contributed to answer the reviewer's comments and primary authorship.

Chen: guidance, supervision, data interpretation, contributed to answer the reviewer's comments and manuscript editor.

Chapter 4

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Chen (Co-author[1]): guidance, supervision, data interpretation and manuscript editor.

Ding (Co-author[2]): contributed to Task 2 "assessment of individuals' capability for tongue-only food breaking" in this paper as his research master project under Alsanei, W. and Chen, J. supervision

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Alsanei, W. A. and Chen, J. The Determining Roles of Food Rheology in Triggering a Swallow (2012) in the 6th Saudi Scientific International Conference, London, UK.

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Alsanei, W. A. and Chen, J. The Tongue Muscle Strength Determines the Capability of Oral Food Breaking (2014) in the 3rd International Conference of Food Oral Processing - Physics, Physiology, and Psychology of Eating, Wageningen, Netherlands.

Alsanei, W. A. and Chen, J. Why Food Can Be Difficult to Swallow? (2014) in the 5th Annual University of Leeds Postgraduate Research Conference, Leeds, UK.

Alsanei, W. A., Chen, J. and Ding, R. Correlations between tongue strength and mechanical properties of handling and manipulating food bolus (2014) in the 7th Saudi Scientific International Conference, Edinburgh, UK.

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Abstract

Food oral processing is very basic activity of human life, providing individuals with pleasure, enjoyment and serving their needs for social interaction. Dysphagia describes a disorder affecting the safety and/or efficiency of swallowing. To manage this reduced ability, dysphagic individuals are often prescribed a diet having specific ranges of mechanical properties. As a result, a number of sectors such as food, pharmaceutical and health care industries are eagerly searching for fundamental knowledge in order to design food for vulnerable population. This thesis addresses this gap and aims to investigate the relationship between the mechanical properties of bolus swallowing (e.g. rheology, bolus manipulations, perceived ease / difficult of initiation swallowing and perceived bolus flow behaviour) along with oral pressures (i.e. generated by the tongue) recorded in healthy subjects. This area of oral processing is researched mostly from a clinical point of view and thus knowledge in oral processing from sensory view point is currently limited as shown in the literature review. In this study, some of existing clinical researches were extended using relevant techniques (such as maximum isometric tongue pressure, oral volume and oral residence time). Findings from this thesis demonstrated a strong correlation between sensory perception of bolus (e.g. ease / difficult of swallowing, ease of break-swallow, bolus flow) and subjective measurement of tongue pressure in context of ready-to-swallow food bolus with different rheological properties. Further experiments were conducted to mechanically characterise a range of viscoelastic and pastry food systems and measure the intra-oral pressures applied when breaking these foods. Data analysis showed that a positive correlation existed between tongue strength and oral food handling. From our results, we can conclude that individual's capacity in tongue pressure generation needs to exceed a certain limit in order to perceive ease in swallowing bolus and also to perceive a bolus flow behaviour. However, such correlation was not seen for individuals with reduced capability in generating MITP. These results support the aim that both the oral physiological conditions (MITP) and the rheological properties of the food (bolus) are important factors that influence the bolus manipulations and comfortable oral handling as well as perceived ease of initiating bolus flow.

Contents

List of Figures

List of Tables

List of Equations

$$\sigma = F / A \qquad\qquad \textbf{(2.1)}$$

$$\dot{\gamma} = \Delta V / h \qquad\qquad \textbf{(2.2)}$$

$$\eta = \sigma / \dot{\gamma} \qquad\qquad \textbf{(2.3)}$$

Abbreviations and Symbols

Abbreviations

Iowa Oral Performance Instrument	IOPI
Maximum isometric tongue pressure	MITP
Maximum Oral Volume	MOV
Videofluoroscopy Swallowing Study	VFSS
Surface Electromyography	sEMG
Cervical auscultation	CA
Fibreoptic Endoscopic Evaluation of Swallowing	FEES
Temporomandibular joint	TMJ
cone-plate geometry with 2° angle cone and 60 mm diameter	CP2/60
Statistical package for the social sciences	SPSS
Male	M
Female	F
Older population, elderly people and old group	≥ 65 years
Adults	< 65 years
Made from vegetable sources	Vege-gel
Sample codes of gels	G_n
Sample codes of mashed potatoes	P_n
Maximum force	F_1
Sample size	N
Mashed potato	MP
Modified starch	MS
Golden syrup	GS
Mixture of concentrated orange juice xanthan gum	COJXG
Super concentrated orange juice	SCOJ
Ratio between mashed potato to xanthan gum	MP:XG
Texture Analyser	TA
Texture Profile Analysis	TPA
National Dysphagia Diet taskforce	NDD
Linear Viscoelastic Region	LVER
United Kingdom	UK
United States of America	USA

Symbols

Pa	Pascal
Pa.s	Pascal second
mPa.s	Millipascal seconds
kPa	Kilopascal
g	Gram
ml	Millilitre
%	Concentration
min	Minute
°C	Degree Centigrade or degree Celsius
°	Degree
s	Second
s^{-1}	Reciprocal seconds
% w/w	Percentage by weight
p-value	Calculated probability
r	Linear correlation coefficient
r^2	R-squared value
SD	Standard deviations
mm	Millimetres
η	Viscosity
$η_{app}$	Apparent viscosity
σ	Shear stress
$\dot{\gamma}$	Shear rate
δ	Phase angle
ω	Frequency
G′	Elastic-like or Storage Modulus
G″	Viscous-like or Loss Modulus
Hz	Hertz
f	Force
A	Area
π	Pi
$N\ m^{-2}s$	Newton-second per square meter
$N\ m^{-2}$	Newton per square meter
V	Velocity
h	Height

Chapter 1 Aim, Objectives and Dysphagia

1.1 Aim and Objectives of the Project

Food oral processing is very basic activities of human life, providing individuals with pleasure, enjoyment and serving their needs for social interaction. However, dysphagia describes a disorder affecting the safety and/or efficiency of swallowing. To manage this reduced ability, dysphagic individuals are often prescribed a diet having specific ranges of mechanical properties. As a result, a number of sectors such as food, pharmaceutical and health care industries have shown considerable interest in such area. These industries are eagerly searching for food related knowledge in order to design food for vulnerable population which is not only tasty and nutritious, but is also safe to consume. This research project is motivated by the idea that bolus flow depends on two sets of conditions which are the oral physiological conditions (e.g. MITP) and the mechanical properties of the bolus (e.g. flow, rheology, and perceived ease of initiating swallowing). As a minimal requirement for comfortable swallowing, the coordination of these two sets of conditions has to be properly matched. Resulting in that the tongue pressure required initiation of different boluses to flow through oropharyngeal track has to be at least matched by the oral tongue pressure produced by the swallower.

The main challenge is to investigate the relationship between the mechanical property aspects of bolus swallowing (e.g. rheology, bolus manipulations, perceived ease of initiation swallowing and perceived bolus flow behaviour) along with oral pressures (i.e. generated by the tongue) recorded in healthy subjects. It is critically important that the tongue has a key role in food oral processing, including taste and texture sensation, food oral breaking, handling and manipulation and transportation, as well as swallowing. Consequently, tongue strength (MITP) will be measured as a basic of each swallowing task in this project. To achieve this generic aim, the following investigations will be carried out:

- With the current status of growing elderly population, dysphagia is becoming an increasingly common medical condition. A brief background on dysphagia is presented in this chapter. As a number of sectors such as food, pharmaceutical and health care industries are eagerly searching for food related knowledge in order to design food for vulnerable population (Chapter 1).

- General understanding of the basic mechanisms involved in normal and abnormal swallowing in relation to physical and mechanical properties of food bolus flow in order to formulate safe, comfortable and easily flowable boluses (Chapter 2).

- Food oral processing is researched mostly from a clinical point of view and thus knowledge in oral processing from sensory view point is currently limited. Therefore, the literature review included a detailed evaluation of some existing clinical researches which were then extended using relevant techniques (such as MITP, oral volume, oral residence time) (Chapter 2).

- In the laboratory, the primary goal is to constitute ready-to-swallow food bolus with different rheological properties and matched apparent viscosities at shear rates of 10 and 50 s^{-1} to eliminate other oral processing parameters such as salivary flow, influence of mastication (Chapter 3, 4 and 5).

- Commercial hydrocolloid-based starch (Resource ThickenUp) and xanthan gum thickening agents will be used to thicken food samples.

- Subject study:

The following are criteria for the inclusion and exclusion of participation in this study.

Inclusion criteria:

1. Subject should be able to read the information sheet given before participating, and ask questions about anything they do not understand, before deciding whether or not to participate.

2. Subject provided written informed consent before participating.

3. Subjects were male and female between the age of 17 and above in order to investigate:
    - the relationship between individuals' oral physiological capabilities (MITP and oral volume) and gender and age.

4. Subject did not have any obvious oral disabilities and were to be able to use IOPI in order to:
    - record individuals' MITP.
    - investigate the relationship between MITP and the perceived ease of initiating bolus flow.
    - investigate sensory perception of bolus manipulations (ease of food oral breaking).

5. Subject were able to do swallowing test based on ready-to-swallow bolus where teeth-induced mastication was excluded.

6. Subjects were capable of self-assessing and independent living.

7. Subjects were from any sociocultural backgrounds were included as this project is for public subjects.

Exclusion criteria:

1. Subjects with influenza-related illness like cold, sore throat and flu. Such illness can affect swallowing.

2. Unhealthy subject who suffers from stroke, Alzheimer's or Parkinson's.

3. Subject suffering from any dysphagic symptoms (xerostomia, tooth loss, tongue weakness/incoordination) which can cause pain when swallowing.

4. Subjects who were either smokers or alcohol addicted which can cause muscle weakness and deterioration.

- Studying the rheological properties of food bolus with different rheological properties instrumentally using Kinexus rheometer in order to establish possible correlations between oral physiological capability (tongue pressure, oral volume and optimal bolus size) and the perceived

ease of swallowing of thicker consistencies in healthy individuals across various age groups (Chapter 3).

• Additional investigation will be to subjectively assess and to establish correlations between the types of bolus flow perceived when individual's swallowing a range of boluses with different rheological properties and these will be compared with their MITP (Chapter 5).

• Further experiments will be conducted to mechanically characterise a range of viscoelastic and pastry food systems and measure the intra-oral pressures applied when breaking these foods (Chapter 4).

• A number of instruments will be involved in this project:

1. Kinexus rheometer (Malvern Instruments Ltd, Gloucestershire, UK)

   a. Cone-plate geometry (CP2/60) was used to match the apparent viscosity of the food samples as a function of concentrations, shear rates, time and different temperatures (as presented in Chapters 3 and 5).

   b. Parallel plate geometry (CP1/60) was used to determine the viscoelasticity of concentrated orange juice and mashed potato xanthan gum mixture (as presented in Chapter 5).

2. Texture analyser (Stable Micro Systems Ltd., Surrey, UK) will be used to perform a compression test using a flat-ended, 40mm diameter, cylindrical aluminium probe at a speed of 2.0 mm/s in order to characterise the mechanical/textural properties of a series of gels (fracturability and elasticity) and mashed potatoes (deformability) ranging from soft to hard with increasing consistency (as presented in Chapter 4).

3. Iowa Oral Performance Instrument (IOPI) (IOPI Model 2.2, Medical LLC, IOPI Medical, Carnation, WA) will be used as a basis instrument for each test:

   • To evaluate and quantify tongue muscle strength applied against the hard palate in healthy subjects.

   • To study the impact of age and gender on tongue pressure performance.

- *In vivo* measurement of tongue–palate pressure generation for oral food breaking by incorporating the IOPI bulb into food samples (gels and mashed potatoes)

During this project, only healthy individuals of different age participated. It should be mentioned that elderly people will not participate in swallowing tasks of this project, but will only participate in MITP measurements and maximum oral volume. However, individuals from disadvantaged populations who are suffering from clinical dysphagia are excluded due to several reasons:

1. To test the design of the full-scale experiments using IOPI which then might be adjusted in order to establish a correlation between orofacial muscles, tongue pressure capabilities, the types of consistency and bolus flow that will be provided.
2. It is a test model to generate preliminary results that can be used for dysphagia patients in future studies.

This thesis involves seven main chapters as following:

Chapter 1 presents the aim, objectives and a brief background on dysphagia (swallowing impairment), causes, consequences and the prevalence of dysphagia.

Chapter 2 presents an introduction and literature review of the basic physiology of the bolus swallowing mechanism, oral force capability, oral physiological and biomechanical sensing assessments of swallowing, approaches for swallowing and bolus studies, hydrocolloids for dysphagia managements and brief of rheological measurements.

Chapter 3 offers a number of studies on oral physiological capabilities in relation to bolus manipulations and the perceived ease of initiating bolus flow.

Chapter 4 characterises mechanically a range of viscoelastic and pastry food materials and measure the intra-oral pressures applied when

breaking these and then determines the relationships between food oral breaking and the individual's tongue muscle strength.

Chapter 5 provides a study on perceived bolus flow behaviour during normal swallowing in relation to bolus rheological measurements and individual's MITP.

Chapter 6 provides conclusions based on all studies presented in the aforementioned chapters and prospect for future works.

1.2 Dysphagia

1.2.1 Definition

Dysphagia or swallowing disorder is a common medical term derived from the Greek word, *dys* which means 'disordered' and *phago* meaning 'eat'. It is typically characterised as a serious health problem in ageing populations and also in individuals who have suffered neurological injuries (strokes, cerebral palsy, Parkinson's and acquired brain injury). Additionally, individuals with neurodegenerative diseases or head and neck cancer and its treatment, iatrogenic conditions or trauma, Alzheimer's disease and other diseases have been known to suffer from dysphagia. Dysphagia may affect one or more of the various stages of swallowing which are the oral, pharyngeal or oesophageal phases in patients of all ages (Gillespie et al. 2005, Gottlieb et al. 1996, Halper et al. 1999, Logemann 1988, Logemann 1998, Rogers et al. 1994).

1.2.2 Consequences

Disadvantaged populations such as infant and children with infantile cerebral, the elderly, patients with myasthenia gravis, head and neck cancers as well as those who have suffered strokes are incapable of proper eating, swallowing thin liquids, semisolids and solids. These difficulties in food oral processing can compromise dysphagic patients'

quality of life and wellbeing. Other short-term symptoms of dysfunctions in oral motor control frequently include inadequate hydration and nutrition in the diet of dysphagia patients. This is also caused by an impaired clearance of swallowed material into the digestive system, failure of the immune system, psycho-social degradation, coughing or choking before, during, or after swallowing, pain when swallowing and also food coating on pharyngeal walls or chest, as well as regurgitating (Braun et al. 2001, Curran and Groher 1990, Ekberg et al. 2002, Hotaling 1992, Riensche and Lang 1992, Smithard et al. 1996, Tayback et al. 1990). Major consequences of long-term symptoms include, weight loss and aspiration (the entry of food and liquids into the airway below the true vocal folds and into the respiratory system) which leads to airway obstruction, developing repeated and frequent chest infections (pneumonia) and consequently an increased risk of mortality (Cassens et al. 1996, Ding and Logemann 2000, Marik 2001).

1.2.3 Symptoms and Prevalence

One of the signs and symptoms of dysphagia include the subjective sensation of difficulty or interference in the efficient transmission of food/liquid (bolus) from the mouth, to the stomach. With the growth of the elderly population in the late 20th century, an increasing number of people are experiencing eating difficulties, worldwide due to the effects of age-related changes in swallowing physiology and age-related diseases such as cerebrovascular accidents and sensory motor disorders associated with neurologic diseases (strokes, cerebral palsy, Parkinson's, Alzheimer's and acquired brain injury) (Barer 1989, Calis et al. 2008, Coates and Bakheit 1997, Gordon et al. 1987, Mann et al. 1999, Marik and Kaplan 2003, Wilkins et al. 2007).

It is estimated that dysphagia affects between 68 % of elderly nursing home residents and 64 % of patients who have suffered a stroke (Mann et al. 1999, Smithard et al. 1996, Steele et al. 1997). Additionally,

approximately 30% of elderly patients admitted to hospital (Lee et al. 1999) and between 13 % and 38 % of elderly people who live independently also suffer from dysphagia (Kawashima et al. 2004, Roy et al. 2007, Serra-Prat et al. 2011). Stroke and dementia are recognised as the two most prevalent diseases associated with ageing. In 2005, the prevalence rate of 2.6 % among U.S. young adults was estimated over 5 million people who had previously experienced a stroke. However, it was reported that the frequency of stroke and dementia increased with age up to 8.1 % and between 6.0 % and 14 % of people older than 65 years, respectively. For the former, an increase between 30 % and 37 % was beyond 85 and 90 years of age, respectively (Hendrie 1998, MMWR 2007, Plassman et al. 2007). Dysphagia can have devastating consequences and is often linked to increased mortality and morbidity rates (Groher and Crary 2010).

Based on this knowledge, food oral processing is a newly developing science involving oral forces, muscle coordination and the structural and textural changes of food during eating. It is researched mostly from a clinical point of view in normal and abnormal swallowing and thus knowledge in oral processing from sensory view point is currently limited. Therefore, the following chapter aimed to evaluate in detail some existing clinical researches which were then extended using relevant techniques (such as MITP, oral volume, oral residence time) and also to fill the gap in this research area by seeking insight into the limits of techniques. Additionally, the beginning of Chapter 2 provides also comprehensive coverage of the basic physiology of the bolus swallowing mechanism and the factors that influence swallowing capability such as oral forces in order to increase our understanding of swallowing and bolus flow in healthy subjects. This part followed by the coordination of these elements which facilitate the effective and efficient bolus flow of a particular consistency along the oral-pharyngeal-oesophageal track for a single swallow.

Chapter 2 Literature Review and Research Gaps

2.1 Anatomy of Swallowing (Deglutition)

In order to evaluate the process of swallowing, the actual anatomy of swallowing must be explored. Through such exploration, the basic movements of the anatomical components involved during swallowing can be visualised. These components include the oral cavity, lips, cheeks, tongue, pharynx, larynx and oesophagus.

2.2 Basic Physiology of the Bolus Swallowing Mechanism

Deglutition (the biological term used for swallowing) is a complicated mechanism, principally as a result of the pharynx that sub-serves respiration and swallowing. Swallowing is a well-defined action, controlled by very complicated and highly coordinated muscular contractions and propulsive pressure (tongue pressure). Swallowing also requires a series of voluntary and involuntary actions found within the mouth, head and neck (Robbins et al. 1992). These actions are mandatory in order to transport a bolus (with required nutrients) from the oral cavity (mouth) into the stomach for eventual digestion and absorption (Dellow 1976, Kahrilas et al. 1993). The resulting bolus that has been established within the oral cavity can be defined as:

A mass of chewed and moistened food which is manipulated by the tongue and teeth and is subsequently formed into the desired final combination of solid, semisolid and/or liquid food form.

It is believed that a single swallow involves at least 26 pairs of muscles and five cranial nerves. It acts in a highly coordinated manner in order to propel a bolus into the oropharynx to the oesophagus of (Chen 2012, Hiiemae and Palmer 2003).

2.2.1 Stages of Swallowing

Significant amounts of written material regarding oral physiology, clinical studies and the biomechanics of food processing have been devoted to the physiology of normal swallowing. Consequently, normal swallowing has been categorised into three or four swallowing stages, including oral preparatory, oral stage (Ardran and Kemp 1951, Bosma 1973, Robbins et al. 1992), pharynx (Ardran and Kemp 1967, Atkinson et al. 1957, Bosma 1957, Kahrilas et al. 1992b, Logemann et al. 1992) and oesophagus (Jacob et al. 1989, Kahrilas et al. 1988) (Figure 2.1).
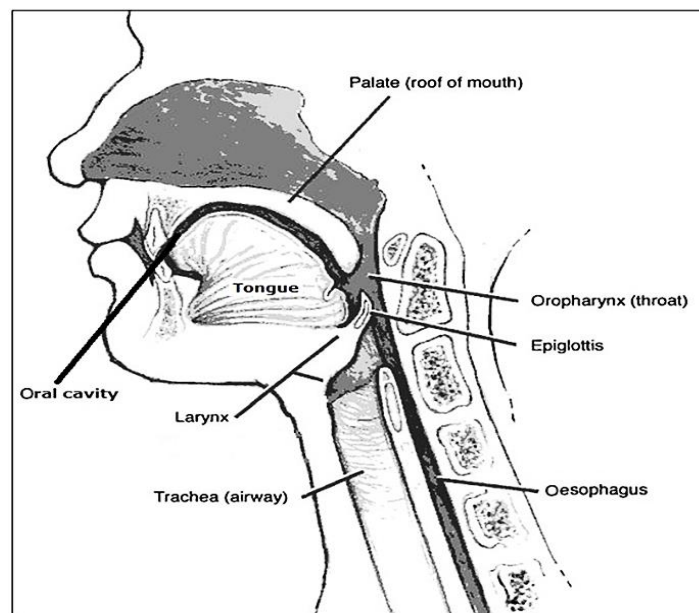
Figure 2.1 The anatomy of swallowing mechanisms, modified from Thomas and Keith (2005)

2.2.1.1 Oral Preparatory Stage

The oral preparatory stage (bolus formation) is a voluntary process involving the preparation of the bolus. The bolus is manipulated into a cohesive unit with the aid of saliva, proper sealing off of the lips, jaw and tongue movements, and mastication. The bolus will finally rest on the dorsum (middle) of the tongue, prior to the commencement of the remaining stages of the swallowing process (Logemann 1998).

2.2.1.2 Oral Stage

During the oral stage, the tongue elevates and rolls back, periodically contacting the hard and soft palate to generate tongue-palate pressure with a front-to-back squeezing action as illustrated in Figure 2.2A. The oral stage is essential and voluntary. This stage primarily involves tongue elevation. Such elevation allows for a safe and comfortable swallowing action before stripping the bolus from the hard palate and propelling it posteriorly during the oral stage to the second stage. This stage is also known as the oral propulsion or transit stage. In healthy individuals, the oral stage of swallowing is generally completed in approximately 1 second (Robbins et al. 1992).
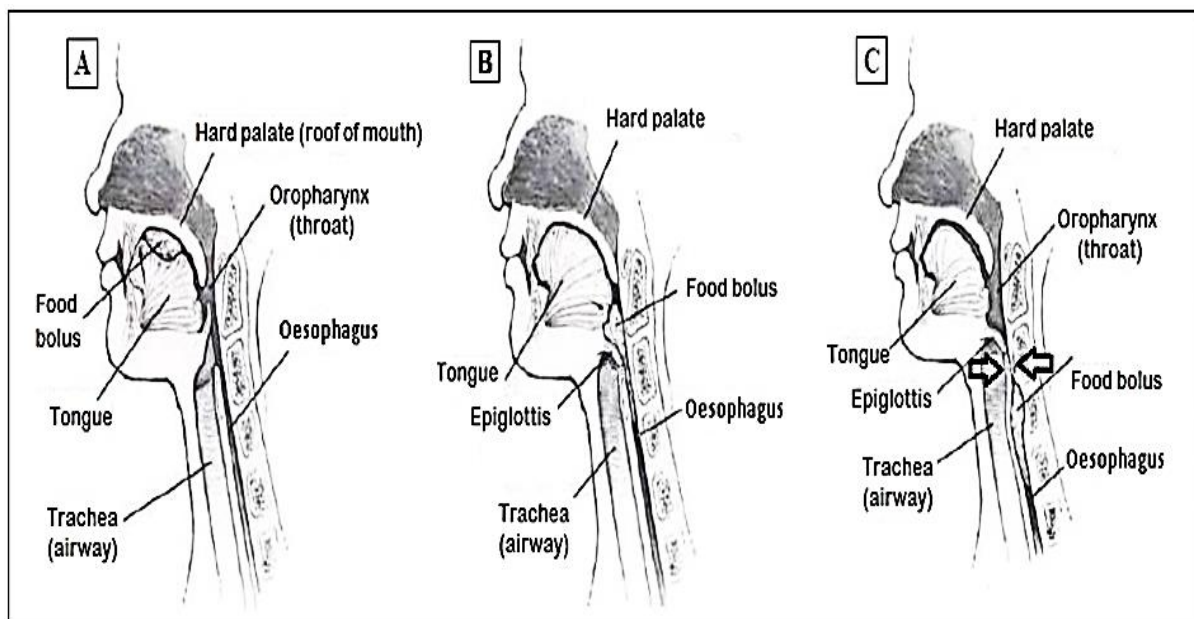
Figure 2.2 Illustration of the food bolus passing through the three major stages of normal swallowing: (A) oral stage (B) pharyngeal stage (C) oesophageal stage, modified from Thomas and Keith (2005)

2.2.1.3 Pharyngeal Stage

In response to the delivery of the bolus at the pharyngeal stage, the bolus triggers an involuntary swallowing reflex (epiglottis) which involves several sequences. When the pharyngeal pathway and the soft palate are elevated, the upper oesophageal sphincter, which is located at the lower

end of pharynx and guards the entrance into the oesophagus, is reduced and the nasopharynx is sealed off by the soft palate closing against the posterior pharyngeal wall. This stage also involves the lower oesophageal sphincter relaxing, which is a bundle of muscles at the low end of the oesophagus, and opening at the top of the oesophagus (Figure 2.2B). This contraction causes a continuous series of peristaltic (wave-like) contractions that are produced by localised reflexes in response to the distention of pharyngeal wall caused by the food bolus. As a result, the bolus is propelled into the oesophagus (Butler et al. 2004, Robbins et al. 1992). The pharyngeal stage is the most critical stage of the normal swallowing process; the involuntary closure of the larynx and suspension of respiration occur concurrently, preventing the bolus from entering the respiratory system (Ardran and Kemp 1956). Clinically, the pharyngeal stage of swallowing process is clearly the most complex in its anatomy and physiology, beginning with the actual triggering of the pharyngeal stage. However, functional disturbances in the pharyngeal phase usually manifest as abnormalities in clearance of swallowed bolus from the oropharynx. These could be a result of propulsive failure, outflow obstruction or failure to maintain the closure of luminal in entrance and exit points to the pharynx (Massey 2006).

2.2.1.4 Oesophageal Stage

In response to the delivery of the bolus at the oesophageal stage, sequential contractions of the involuntary peristalsis wave carries through the laryngopharynx (a collapsible 18–26cm long and 1.5–2.5cm wide muscular tube that stretches from the upper sphincter to the lower sphincter - Figure 2.2C) (Butler et al. 2004). Whereby, the bolus is eventually forced down through the oesophagus into the stomach whilst the hyoid bone, soft palate and tongue return to their original positions (Logemann 1998, Thexton and Crompton 1998). Table 2.1 summarises the three main stages of normal swallowing.

Table 2.1 Summarises the three stages of normal swallowing, the anatomical structures and some of their functions

Stage	Oral	Pharynx	Oesophagus
Relevant Anatomy	• Lips • Teeth • Floor of mouth • Tongue • Cheeks • Hard palate • Mandible and maxilla • Facial arches • Salivary glands	• Pharyngeal muscles • Soft palate • Base of tongue • Epiglottis • Valleculae • Hyoid bone • Larynx • Pharynx	• Cricopharyngeal muscles • Oesophagus • Upper oesophageal sphincter • Lower oesophageal sphincter
	Voluntary stage	**Involuntary stage**	
Functions	• Tongue moves a bolus to back of the mouth by propelling against hard palate • Triggering the pharyngeal swallow when the bolus passes the facial arches	• Soft palate elevates • Pharyngeal constrictor muscles push bolus through the pharynx • Larynx moves forward, elevates and closes to protect the airway	• Larynx lowers • Oesophageal peristalsis moves bolus from oesophagus to lower oesophageal sphincter • Cricopharyngeal muscle contracts to prevent swallowing reflux • Peristalsis continues to pass bolus to the stomach

2.3 Factors that Influence Swallowing Capability

The structure of the oral cavity comprises many different types of tissue which are joined together. Examples of which are, the tongue, orofacial muscles (i.e. lips and cheeks); buccal mucosa (lining of the cheeks); teeth, alveolar bone (termed residual bone if there are no teeth); maxilla and mandible (upper and lower jaws, respectively), gingivae (gums); hard and soft palates (roof of the mouth); mucous membranes; temporomandibular joint (TMJ); salivary glands; and muscles of mastication (Tortora and Derrickson 2008). Each tissue structure is designed for a specific purpose and function. The critical association of the tongue and orofacial muscles will be discussed in relation to swallowing, food ingestion, bolus breakage, bolus formation during normal swallowing.

2.3.1 Tongue Force Capability

2.3.1.1 Tongue

Tongue (lingual) is one of the major components of the oral cavity. It plays an extensive role in mastication and deglutition due to its great ability to deform and move in all directions (front to back, from the sides to the middle and from top to bottom). The clinical effort to understand how the tongue supports swallowing has led to the development of significant clinical literature and related studies documenting the tongue structure and strength in dysphagic and non-dysphagic subjects. The tongue is essentially a mass of three-dimensional muscle fibres that occupy not only the oral cavity but also the oropharynx. Logemann (2014) reported that the tongue structure during swallowing can be divided into two parts: the oral tongue located in the oral cavity (tip, blade, front, centre and back) and the base of the tongue located in the pharyngeal cavity (root and epiglottis) (Figure 2.3).
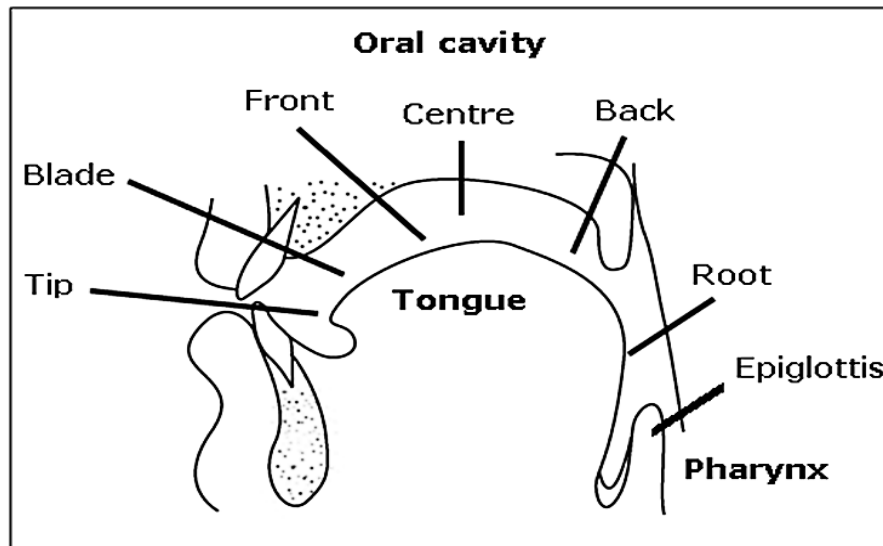
Figure 2.3 Lateral illustration of the tongue within the oral cavity and pharynx, modified Figure from (Logemann 2010)

2.3.1.1.1 Function

The tongue is a multifunctional organ that performs several critical functions such as aiding oral breaking and swallowing by masticating mouthfuls of food into swallowable consistencies. In addition, the tongue is vital in a humans ability to taste, eat, drink, suck (particularly for babies when breastfeeding), speak and also contribute to oral cleaning in healthy individuals (Kahrilas et al. 1993, Kahrilas et al. 1992b). For an efficient and safe swallow, both the oral tongue and the base of tongue are utilised as the main source for generating a pushing force forcing the bolus to flow through the oropharynx and into the oesophagus (Logemann 2014).

2.3.1.1.2 Pressure

The dense network of nerves, muscle mass in the tongue and tongue-palate interaction (strength) during food oral processing enable the tongue to be the dominant source of energy (force/pressure) when manipulating and initiating bolus flow during swallowing (Fei et al. 2013, Robbins et al. 1995, Tamine et al. 2010a). During tongue motion and

propulsion, the tongue progressively abuts the hard palate to completely obliterate the oral cavity behind the bolus. This cohesion of food-food particle interaction that exposures to saliva generates a pressure. This pressure squeezes the ready-to-swallow bolus from the oral cavity with a progressive upward and posterior movement of the tongue blade. The bolus travels posteriorly into the pharynx where continuous rhythmical muscle contractions push the bolus further down into oesophagus.

Scientists from various research disciplines (e.g. oral physiology, clinical studies, food science, etc.) have made the tongue the subject of intense attention. The influence of tongue justifies the extensive study of this muscular organ because of its role in creating a pressure gradient to facilitate the bolus flow in healthy individuals (Alsanei and Chen 2014, Kieser et al. 2011, Laguna and Chen 2015, Stierwalt and Youmans 2007, Yoshida et al. 2006). In order to diagnose tongue weakness, it is important to study the tongue movement to generate pressure and bolus flow behaviour during swallowing. The most common signs of tongue weakness in clinical literature are malpositioning or fragmenting of the bolus, multiple tongue blade movements to propel the bolus posteriorly, tremor or myoclonus, undulations of the tongue blade, failure to obliterate the oral cavity, atrophy of the tongue and low hyoid position (Jones 2003).

2.3.1.1.3 Biomechanical Sensing Assessment of Tongue Pressure

Various approaches to assess oromotor abilities and how to measure tongue-palate compression during swallowing have been recently reported. These approaches have mainly focused on modern sensing methods including, manofluorography, handy sensing probe (a small balloon-type sensor), a linked three transducer array, multiple-point pressure sensor sheet installed in the palatal plates, the Iowa Oral Performance Instrument (IOPI) and ultrasound imaging of tongue

movement. This research project is focused on the IOPI method which has been widely used as an approach to determine the effect of tongue-pressure compression on normal swallowing and dysphagia and also to evaluate an individual's tongue pressure.

2.3.1.1.3.1 The Iowa Oral Performance Instrument (IOPI)

2.3.1.1.3.1.1 Measuring system

The Iowa Oral Performance Instrument (IOPI) (IOPI Model 2.2, Medical LLC, IOPI Medical, Carnation, Washington) is a medical device used for measuring tongue strength and tongue pressure production during swallowing. Measurement involves compressing a single, air-filled bulb between the tongue and the hard palate, as shown in Figure 2.4. The disposable tongue bulb is made of polyvinyl chloride as shown in Figure 2.4A and has the following dimensions: 3.25 cm in length, 1 cm in height and 2 cm in width with a volume of around 2.7 ml. The bulb is inserted inside the oral cavity and is linked to a pressure transducer, Figure 2.4B via a small tube 11.5 cm in length Figure 2.4C. This small tube then connects to a longer tube inside the device (56 cm total length with a 5 mm end diameter and 1.5 mm middle diameter - Figure 2.4D). The pressure transducer records the tongue–palate pressure in kilopascals (kPa), and the highest peak of the tongue pressure is shown on a numeric liquid crystal display (LCD). For accurate measurement, the calibration of the IOPI should be checked monthly as recommended by the manufacturer.
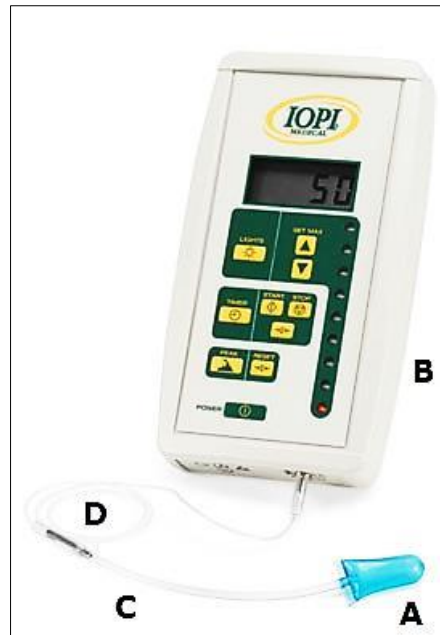
Figure 2.4 The Iowa Oral Performance Instrument (IOPI) used for measuring the tongue pressure against the hard palate during maximum tongue pressure and swallowing pressure; (A) the bulb that is placed inside the mouth - between the tongue and hard palate; (B) the IOPI electronic device with pressure in, data out ports and connected bulb; (C and D) the connecting tubes (Obtained from IOPI Medical)

2.3.1.1.3.1.2 Contributions

In the early 1990s, a number of new tools were discovered and developed to measure the pressure generated by tongue-palate compression. Such tool offered an objective means of assessing tongue strength and evaluating swallowing pressure that initiate bolus flow in healthy individuals as well as those with medical conditions (i.e. dysphagia, primarily Parkinson's disorder, head and neck cancer). IOPI is one of the tools that was originally developed to determine the differences and relationships between tongue muscle weakness (strength) and problems of speech motor control. Subsequently, the IOPI's role had been extended to also include evaluating swallowing. As a result, more informed interpretations, the ability to detect weakening tongue muscles as well as other oral/facial muscles in persons with dysphagia have been possible. A series of studies have also been documented using IOPI as

biofeedback for tongue-strength training with the goal of improving the swallowing function, increased isometric tongue strength, improved tongue pressure generation accuracy, improved bolus control on videofluoroscopy, and improved functional dietary intake by mouth (Robbins et al. 2005, Robbins et al. 2007, Yeates et al. 2008). In this project the ability to generate maximum isometric tongue pressure (MITP) has emerged as a measure tool to investigate the relationship between the mechanical property aspects of bolus swallowing (e.g. rheology, bolus manipulations, perceived ease of initiation swallowing and perceived bolus flow behaviour).

2.3.2 Orofacial Muscle Capability

2.3.2.1 Function

Beside tongue pressure and its role during bolus propulsion are critical to safe swallow, swallowing requires a synergistic and associated enlistment of the tongue muscle and surrounding oral muscles. Orofacial muscles are recognised as swallowing-related muscles contained in the oral cavity (i.e. cheek, lips). Orofacial muscles provide a counter force to the tongue in order to engulf the bolus and then to facilitate proper bolus control. However, alterations in orofacial muscle strength capability may cause major swallowing problems including impaired mastication, taking longer to chew and more chewing cycles than normal; reduction in the buccinators muscles in the cheekbone area for controlling cheek tightening or stretching (expansion) and weakness of the orbicularis oris muscle around the lips causing drooling; delayed pharyngeal swallow trigger; choking and aspiration (Ertekin et al. 2001, Peñarrocha et al. 1990, Saito et al. 1995, St. Guily et al. 1994). Therapeutic procedures for these impaired muscles are generally designed to strengthen their capabilities, to improve voluntary control over time, to increase oropharyngeal sensory input prior to the swallow, and/or to coordinate

the oropharyngeal movements and the movement of the bolus posteriorly during swallowing (Logemann 1983).

2.3.2.2 Biomechanical Assessment of Swallowing-Related Muscles

The majority of studies concerning tongue strength (elevation) focus on the pressures generated when stripping the bolus from the hard palate and when the bolus is propelled posteriorly during the oral transit stage. Subsequently the relationship between orofacial strength and the swallowing function on normal orofacial strength can be examined. (Clark et al. 2003, Lazarus et al. 2000, Robbins et al. 2005, Robbins et al. 2007, Robbins et al. 1995, Youmans and Stierwalt 2006, Youmans et al. 2009). Clark et al. (2003) and Reddy et al. (1990) reported that the measurement of tongue strength during elevation and its movement is a better prediction of the initiation of swallowing impairment than measures obtained during elevation only. Logemann et al. (1997) also indicated that the outcomes of strengthening the orofacial muscles (range of motion exercises) improve the oral and/or pharyngeal and laryngeal structures associated with the efficiency of swallow in oral cancer patients. However, this in part reflects the relative lack of methods available for measuring orofacial strength apart from tongue elevation. An ability evaluation of the orofacial muscles such as lips and cheek may contribute to the literature on normal individuals, allowing for more informed interpretations of orofacial weakness in persons with dysphagia.

2.3.2.2.1 Lip Muscle Strength

The lip muscle strength is a complex and well-organised process that is performed by the orbicularis oris muscle and additional facial muscles that have muscle fibres in various directions of the mouth. During the masticatory movement of the jaw, lip contraction occurs during the mouth opening phase whilst lip relaxation takes place in the mouth closing phase

(Standring 2005). The utilised lip closure strength (pressure) is highly important with regards to ingestion of food into the oral cavity, mastication and safe swallowing. It is well known that lip closure strength can affect the ability to obtain and/or maintain intra-oral pressure during swallowing. Inadequate pressure generated by the tongue as a result of lip muscle weakness prevents the bolus from being easily swallowed.
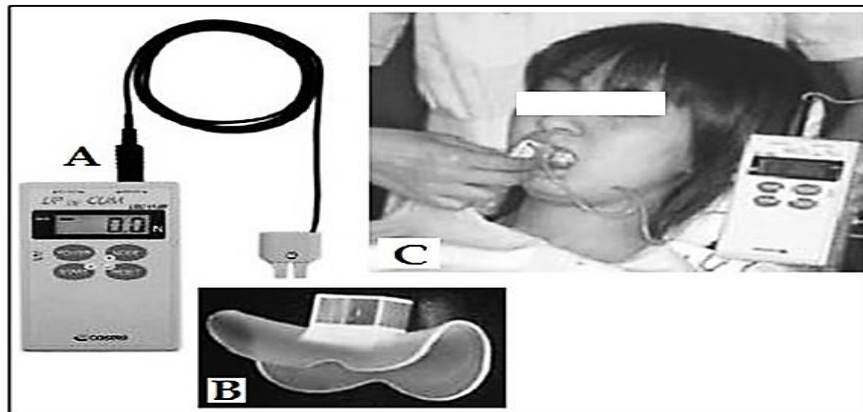
Figure 2.5 Commercially available Lip Closure Strength (force) Indicator (Lip De Cum®) (A), with a Lip holder (Ducklings®) (B); lip closure strength (force) data collection (C)

Three simple orometers are currently available to assess lip muscle strength. Such strength is determined by recording the maximal and minimal voluntary lip closing forces in the vertical direction. As presumed, these orometers aim to strengthen the lip muscles and therefore, influence the functional closing force. The first of the three devices, the Lip De Cum® (from Cosmo Instruments, Hachiouji, Tokyo, Japan) as shown in Figure 2.5. Ueki et al. (2014) reported that the maximum and minimum lip closing forces increased time-dependently in both genders after orthognathic surgery for skeletal Class III patients. However, males exhibited significant changes in the maximum lip closing force. Beauty Health Checker® (from Patakara Inc., Musashino, Tokyo, Japan) is another instrument that has an influence on the closing ability of the lips (Figure 2.6).

Figure 2.6 Lip-closing force meter, "Beauty Health Checker" with a lip holder (green part)

Finally, a study by Reddy et al. (1990) used the IOPI (discussed previously in Chapter 2, section 2.3.1.1.3.1) to measure the maximal pressure exerted by the lips against the IOPI bulb. The obtained results revealed that dysphagic participants exhibited lower lip closure strength as compared to normal participants. Dysphagic patients may consequently suffer from drooling/dribbling as an indication of the lip weakness. It is also reported that ageing alters lip muscle strength (Ono et al. 2003).

2.3.2.2.2 Cheek Muscle Strength

Increased cheek muscle activation and strength play an important role in bolus swallowing and moving the bolus to the back of the mouth by tightening the cheek muscles and pressing the tongue against the roof of the mouth. In a recent study by Clark et al. (2009), the cheek compression strength was measured during a 9-week training period by squeezing the IOPI bulb toward the tongue facing the buccal surface of the cheek with maximum effort. It was reported that the cheek muscle strengthening of thirty-nine healthy adults had slightly improved. Such a result is not surprising because the rehabilitation of these macules typically takes long periods for exercise-based training. Such training will

be conducted by patients as part of a home program with unsupervised exercise (Lucas et al. 2002, Robbins et al. 2005, Robbins et al. 2007).

2.3.2.2.3 Oral Volume Capability

Oral phase swallowing disorder has been defined as the inability to manipulate food and liquids in and through the oral cavity as a result of chewing difficulties, weaknesses and dis-coordination of tongue, and/or reduction in labial and buccal muscle tension. The cheeks contain the buccinator muscle and buccal glands, which resemble the lips in structure. Therefore, reduction in the buccal tension can cause pocketing of the bolus in the buccal cavity when the oral phase of the swallow is initiated. Some of the clinical features of this oral problem are presence of residues of food and liquids in the affected side and also spillage of food and drooling of liquids out of the mouth in the affected side (Barnes 2003, Bruce 2003, Casas et al. 2003, O'Sullivan et al. 1990). Currently, only three studies have been conducted to investigate the influences of age and gender on cheek strength using different methodologies. Study by Clark and Solomon (2012) investigated the cheek compression strength of 171 participants (aging between 18 and 89 years old) by squeezing the cheek muscles against IOPI bulb with maximum effort. Results revealed that cheek compression did not change significantly with age and also men exhibited cheek strength greater than those of women. Authors also claimed that gender differences in facial strength would follow the same pattern as that predicted for tongue strength. However, such results on cheek strength as assessed in this study would be influenced by oral containment and manipulation effectiveness.

Another simple way to measure orofacial muscle strength (i.e. cheek) was conducted by Alsanei and Chen (2014) in order to investigate the positive correlation between reduced physiological capability of the buccal muscular strength of the cheek and oral cavity size across age (aging between 22 and 94 years) and genders. An experimental procedure was

illustrated by measuring the maximum oral volume capacity of 106 participants (by filling his/her cheek with 150 ml of water). Results showed weakened orofacial muscle capability with ageing and similar result on the influence of the genders. Additionally, dripping water from the mouth was observed from some elderly people during the test indicating poor lip closure. Therefore, experimental results on age-related changes support the theory that oral physiological conditions can negatively influence an individual's swallowing capability. Whereas Nascimento et al. (2012) evaluated oral volume capacity for both genders by sucking water through a straw up to the maximum tolerated oral volume. Results showed gender effect while age between 19 and 53 years, BMI, height, and number of teeth had no influence on the intraoral tolerated volume. These current studies expand the data set describing age- and gender related differences in strength measures obtained not only from tongue strength but also from the orofacial muscles by using a variety of tasks and instructions in a relatively large group of non-dysphagic men and women. Findings from these studies may be used as a stepping stone to further studies to explore how these measures relate to specific aspects of bolus swallowing.

2.3.2.2.4 Bolus Size

Optimising the bolus size (modified and non-modified boluses) is recognised as an approach to identify and interpret the natural swallowing capability of an individual. In terms of a single swallowed bolus capacity, there are two different scenarios, a bolus of liquid drink and a bolus from chewed, solid or semisolid food. For the former, the comfortable size (volume) of a liquid bolus can be conveniently determined by monitoring the amount of water sipped during a single swallow. Macrae et al. (2011) reported that frequently sipped water volumes can reach roughly between 10 to 12 ml during natural drinking conditions. Whilst a study by Alsanei and Chen (2014) found that the average amount of water for one

comfortable swallow was on average 14 ml. Other studies suggested that the size of a normal thin liquid bolus (e.g. water) can reach up to 25 ml during cup drinking. Based on literature, there are two potential interpretations that lead to a better understanding of the variability in liquid bolus size. One interpretation is that the water-sipping volume increases when the cup size increases (Lawless et al. 2003). Another explanation might be that bolus size is dependent on the tongue muscle formation within the oral cavity. Therefore, accommodating a large bolus volume size reflects a deeper carve that formed within the tongue muscle shape (Hiiemae and Palmer 2003, Kahrilas et al. 1993). As part of the swallowing capability, the bolus size is another evidence to study the variations between an individuals' physiological capability of swallowing and the implications for bolus swallowing.

In addition, it has been shown that a custard bolus volume of a five-grams (1.5 Pa s) allowed for the most comfortable and natural swallow in healthy individuals (Alsanei and Chen 2014). However, a four-gram of paste bolus was used to study the influence of taste and temperature on the oropharyngeal stage of swallowing by Cola et al. (2012). Determining an appropriate bolus size of a food bolus is not only a fundamental aspect of safe and comfortable swallowing but also to standardise the swallowing experiments. These experiments involve a number of parameters such as the determining of bolus size per swallow, the number of swallows per bolus along with swallowing duration, and also magnitude of muscle strength capability as related to the bolus rheology (i.e. viscosity). However, until now, no written data has been collected regarding the exact size of a food bolus that can be swallowed. This is due to the practical difficulty of collecting the main portion of the bolus as it enters into the oral stage. This difficulty stems from the fact that orally chewed food particles are normally moved and cumulated at the back of the tongue surface and become non-recoverable in dysphagic and non-dysphagic subjects.

2.4 Coordination and Switching of the Oral-Pharyngeal-Laryngeal Track to Oral-Pharyngeal-Oesophageal Track

Food oral processing is an integrated biomechanical oral action involving oral forces and muscle coordination. This contribution is performed in a highly coordinated manner which enables a relative alteration in orofacial muscle coordination and tongue force generation in order to facilitate and reduce food to a consistency ready for swallowing. Therefore, bolus shifts from the oral stage to the pharynx, where a number of valves must open and close, directing the bolus into the oesophagus within several seconds. These valves include the soft palate, the base of tongue which must make contact with the pharyngeal wall in order to generate pressure to drive the bolus through the pharynx and into the oesophagus; the larynx which must close to prevent the bolus from entering into the air track (respiratory system); and the upper oesophageal sphincter. Previous studies have aimed to clarify the physiological mechanisms of tongue pressure generation in relation to the coordination of muscle contraction and bolus flow behaviours. In order to achieve such coordination, it was reported that combining oropharyngeal and oesophageal manometric measurements with other techniques (e.g. videofluorographic images, electromyographic signals and electromagnetic midsagittal articulograph) along with performing sets of repeated bolus swallows with different consistencies lead to a better understanding of swallowing mechanisms. These investigations highlight the possible relationships of the track switching from oral-pharyngeal-larynx track to oral-pharyngeal-oesophageal track among tongue and muscle activities during switching (i.e. submental, suprahyoid, jaw, pharyngeal and laryngeal muscle).

Surface electromyography (sEMG) has been used primarily to evaluate the muscle activity (specially timing and amplitude) associated with swallowing and to provide a valid biofeedback strategy in the treatment of swallowing disorders (Bryant 1991, Crary 1995, Crary et al. 2004, Haynes 1976, Huckabee and Cannito 1999, McKeown et al. 2002,

Vaiman et al. 2004). Perlman et al. (1999) concluded that the critical information of the submental region obtained from sEMG signals by evaluating specific muscles such as the anterior triangle of the neck (mylohyoid, geniohyoid, and anterior belly of the digastric muscles) during swallowing. Temporal and muscle activation patterns were also assessed in relation to laryngeal, pharyngeal and submental muscles. The obtained results revealed that both factors showed variations between individuals. Prior studies have also revealed that sEMG signal activity related to hyoid muscular elevation is strongly tied to laryngeal muscular elevation during swallowing (Crary et al. 2006, Kendall et al. 2003). However, Gay et al. (1994) concluded that the swallowing function varies from individual to individual in terms of the specific muscles used and how the various muscle activity patterns are coordinated.

The key limitations of these methods are that they are time-consuming, expensive and need experts to conduct and repeat such experiments. Hence there is a considerable need to develop simple, repetitive, reliable methods which can be easily adopted for studying sensorially perceived ease / difficulty of swallowing and perceived bolus flow behaviour as shown in Chapter 3, 4 and 5.

2.5 Bolus Formation prior to Swallowing

The purpose of the bolus formation is to modify food or liquid into a bolus form that can be swallowed easily and safely. In broad terms, this process involves the physical manipulation performed by the teeth, tongue and oral musculature to reduce the food particle size and to lubricate (moisture) the particles by saliva secretion to an optimal level (Chen 2009). Generally, the particle size of a solid food bolus category is thought to play a part in recognising food ready for bolus formation and swallowing. Food particles judged to be of an adequate size are squeezed to the back of the oral cavity by tongue-palate compression. Lucas et al. (2002) proposed models to support this theory and postulated that the

ability to sense and respond to texture is very important in food oral processing, in terms of safety and enjoyment experienced whilst eating.

However, the bolus formation is unlikely to be simple. It is more complex and the particle size is not the only factor to signify a food that is ready to swallow. The physical bolus properties alongside the particle size distribution were investigated for wheat-flake cereals (Peyron et al. 2011). Samples were chewed and boluses were collected at different times during the mastication process to be tested using texture profile analysis (TPA). Results show that along with particle size, hardness, the sensation of changes in cohesiveness, adhesiveness and springiness were also key factors in triggering a swallow. A recent study by Chen and Lolivret (2011) suggested that the oral residence time (ORT) is also an important factor to determine the oral effort for bolus swallowing. This factor is food type dependant where shorter or longer ORT is taken for thinner or more viscous foods, respectively. Authors also postulated a link between ORT and the extensional nature of the bolus. Thus foods more easily stretched have a shorter oral residency time and are easier to swallow than foods that are less stretchy. The ORT of bolus flow through the swallowing apparatus depends on both individual's physiological capability (tongue pressure) and bolus rheological properties as shown in Chapter 5. However, this parameter has not been tested on dysphagia patients.

In terms of the fluid bolus category, bolus will pass to the back of the oral cavity into the vallecular region of the tongue or the piriform fossa of the pharynx without teeth involvement and may only be in the mouth for around one second before a swallow is initiated (Lee and Camps 1991). Whilst a thin fluid bolus category is more easily deformed and flowed and does not require the high use of oral strength and orofacial muscular coordination but rather, agility and coordination for safe movement and swallowing (Leonard and Kendall 1997). Based on these studies of solid and semisolid food bolus and bolus formation, the primary goal of this project is to use a new methodology in constituting a ready-to-swallow

food bolus with different rheological properties and matched apparent viscosities at shear rates of 10 and 50 s^{-1} to eliminate other oral processing parameters such as salivary flow, influence of mastication (as presented in Chapter 3 and 5).

2.6 Approaches for Swallowing Studies

2.6.1 Oral Physiological Assessments

Although there are a large variety of oral physiological assessments aimed to study individual swallowing behaviour, bolus flow and oral movements as well as to detect dysphagia, it is unknown yet which of these assessments may have the best outcome in terms of the level of measurement, reliability, validity, and responsiveness of swallowing function. Therefore, it will become feasible for clinical and oral research studies, and nurses to provide important suggestions to the patients that allow them to practice safer swallowing (Steele et al. 2015). Studies of swallowing have traditionally been performed using radiographic and fluoroscopic techniques. However, the purpose of all oral physiological assessment techniques should not simply be to assess swallowing of disadvantaged groups, but also to explore and confirm the effectiveness of selected approaches to intervention of appropriate therapies. As a part of this thesis, a brief systematic review including a concise overview of several advantages and disadvantages of the common techniques that used to assess oral physiology related swallowing will be discussed.

2.6.1.1 Videofluoroscopy Swallowing Study (VFSS)

Videofluoroscopy swallowing study (VFSS) is one of the most dynamic and comprehensive method used for determining the nature and extent of oropharyngeal swallowing disorders, and testing swallowing ability. This method of assessment is considered as a gold standard

technique for revealing both the anatomy and physiology for both swallowing, and for demonstrating pathophysiology in people with dysphagia during swallows of saliva (dry swallow often conducted first to allow evaluation of structural movement), thin modified barium liquids (1, 3, 5 and 10 ml), cup drinking, pudding, and different bolus viscosities typically mixed with barium during the scan. This examination test enables the clinician to observe the muscle coordination during normal or abnormal swallowing (Beck and Gayler 1990, Chan et al. 2002, Logemann 1993). In the clinic, VFSS is often used to confirm the incidence and the absence of aspiration and also to directly observe physiology and important details that are not visible during bedside observation (Steele et al. 2013). However, this statement is not accepted universally due to the patient's condition and the degree of dysphagia (O'Donoghue and Bagnall 1999).

During the examination, sample preparation, the order of stimulus presentation (e.g. concentration and viscosity grade of the boluses) and the volumes to be tested are all critical aspects that must be considered. The standardised protocol of the videofluoroscopy requires that patients consume liquids or food samples whilst standing or sitting at a 45° to 90° angle (Figure 2.7). When the sample is swallowed, a video and images are taken in order to evaluate the function of the oral and pharyngeal swallowing phases and also to examine the oropharyngeal anatomic structures and swallowing time (Figure 2.8). However, VFSS procedures must be performed by a trained diagnostic specialist and have some degree of invasiveness such as exposure to radiation and intubation. VFSS procedures are necessary for accurate identification of swallowing impairments and determining treatment options that might alleviate impairments or lower the risks caused by the impairments (Leslie et al. 2004). Nevertheless, repeated diagnostic testing is inappropriate due to various reasons including, excessive exposure to radiation, long waiting lists at hospitals and the unavailability of specialist equipment (O'Donoghue and Bagnall 1999, Ramsey et al. 2006, Steele et al. 2007).

In relation to bolus rheology, a study by Linden et al. (1989) aimed to determine the bolus position at the point of swallow in two different consistencies: paste boluses versus thin barium boluses in dysphagic patients. They observed by VFSS that the head of the paste bolus was faster than the liquid bolus and reached into the pharynx before the swallowing onset. A relatively similar finding was reported by Saitoh et al. (2007) when subjects were asked to consume chewed, mixed consistencies (corned beef mixed with thin barium). These findings concluded that there are objective differences in the swallowing of viscous boluses allowing oral contents to spill into the pharynx. However, alteration of the bolus consistency showed that oral transit times (ORT) were longer for paste consistencies than for thin barium. Also multiple swallows by tongue pumping movements per bolus were greater when compared with the liquid bolus (Lin et al. 2011, Oommen et al. 2011, Troche et al. 2008).

Figure 2.7 Videofluoroscopy swallowing study (VFSS) station Scott et al. (1998)
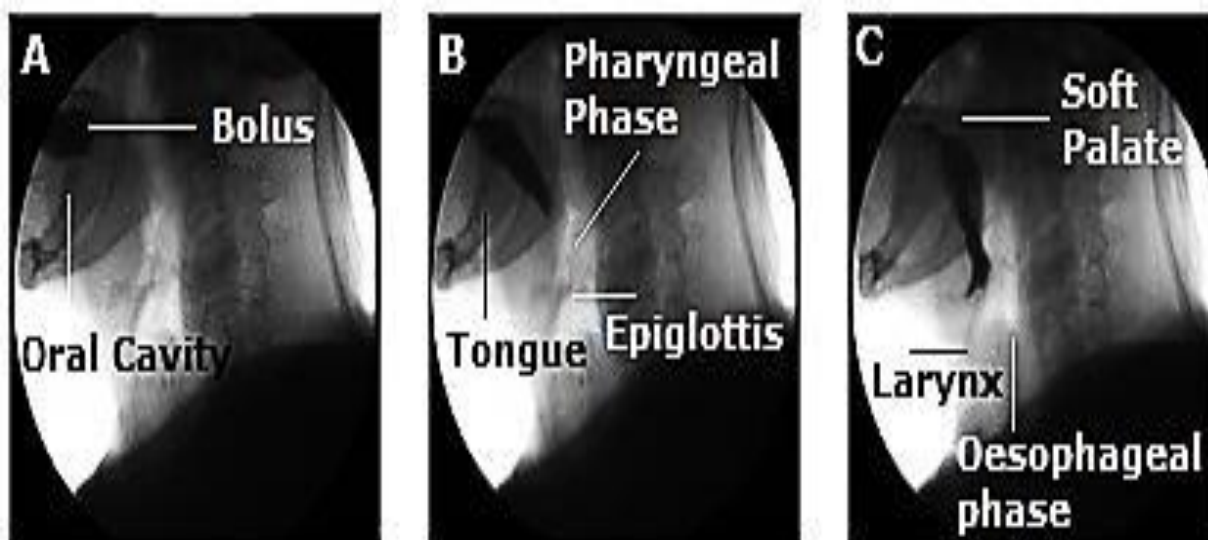
Figure 2.8 Videofluoroscopic photographs of swallowing stages of fluid bolus during (A) oral stage (B) oropharyngeal stage (C) pharyngeal stage, Reproduced from Singh and Hamdy (2006)

2.6.1.2 Surface Electromyography (sEMG)

Surface electromyography (sEMG) is a graphic record used to track the patterns of the orofacial and pharyngeal muscular performance. It is also used during the consumption and swallowing of different textural foods. The collection of information over targeted facial locations can be gathered via non-invasive surface electrodes attached to the skin surface where small electric currents are detected (Figure 2.9). Such signals can be amplified and quantified in order to line with the material properties of the food. sEMG has been proven reliable in numerous electromyographic studies over many years. Its biofeedback is used to progress patients with prominent dysphagia and more generalised weakness over time when compared with VFSS.
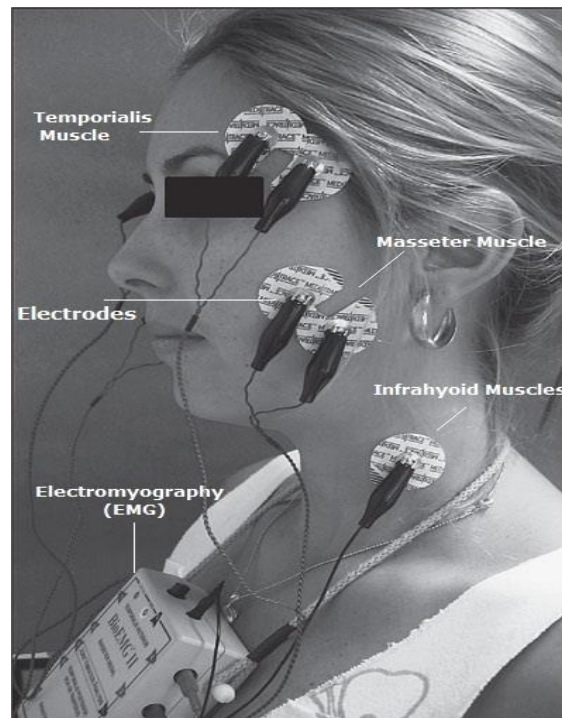
Figure 2.9 Arrangement of electromyographic electrodes placed in the facial and pharyngeal muscles (the anterior temporialis, masseter and infrahyoid muscles) for sEMG, reproduced from Pita et al. (2011)

The sEMG device consists of a transmitter unit which is strapped to a belt around a patient's waist or chest. The transmitter is small, lightweight and amplifiers with electrode leads that are connected to the transmitter. A further unit (the receiver) decodes the multiplexed signals from the transmitter. These decoded signals are displayed on a personal computer for sEMG data acquisition. During the oropharyngeal pattern of deglutition in normal and dysphagic people, a number of quantitative sEMG parameters, including peak frequency, peak length, amplitude, root-mean-square amplitudes, total work, and others are widely investigated. In alignment with VFSS, such biofeedback provides an interpretation of the correlation between textural properties (i.e. consistency and hardness) and sensory perceived of different food boluses during food oral processing and swallowing. However, oral and pharyngeal anatomic structures cannot be examine using sEMG.

Several studies were conducted to evaluate swallowing, swallow duration and/or oral processing behaviours across boluses with different

textures using sEMG. For instance, Butler et al. (2004) studied the effects of viscosity (honey-thick like vs. thin-like liquid) on swallowing. Results showed no alteration in swallow apnea duration in healthy adults. However, thicker paste consistencies elicited significantly longer swallow durations when compared to both liquids and thin pastes (Reimers-Neils et al. 1994). For consuming tougher and more adhesive foods (e.g. carrots, gum, apples, curd-type yogurts, puddings, cheese spreads, thickened water, soft and hard agar gel mixed with gellan gum, psyllium seed gum; and thick rice gruel), the amplitude of sEMG activity increased from liquid and thin paste to thick stimuli (Funami et al. 2012, Inagaki et al. 2008, Inagaki et al. 2009a, Inagaki et al. 2009b, Karkazis 2002, Karkazis and Kossioni 1997, Karkazis and Kossioni 1998, Kim and Han 2005, Ruark et al. 2002). These studies reveal that the rheological properties of a bolus (i.e. viscosity) change during chewing and oral processing, whilst the cohesiveness of the final ready-to-swallow bolus remains stable. A limitation of EMG recordings of facial movements as an index of oral processes is that the human face does not only display affective responses but also produces a large variety of activities unrelated to oral processes like emotional, speech, mental effort or mental fatigue, task involvement or performance motivation, anticipation of sensory stimuli, preparation of motor responses, orienting responses, and startle reflexes (Stekelenburg and van Boxtel 2002, Van Boxtel et al. 1996, Van Boxtel and Jessurun 1993, Veldhuizen et al. 1998, Waterink and van Boxtel 1994).

2.6.1.3 Ultrasound

Diagnostic ultrasound plays an important role not only in logopedics and phoniatrics but also in the study of swallowing normality and abnormality in terms of oral movements. The basic principle of ultrasound is an imaging procedure that visualises soft tissue by using high frequency sound waves. Although the oral cavity is the only portion of the swallow that can be clearly imaged with ultrasound, it is hard to truly

evaluate disorders of the pharynx which is the most critical part of the swallow when compared with VFSS. However, ultrasound provides a useful assessment opportunity when an individual patient has dysphagia particularly in oral stage of swallowing that can be regularly visualised with ultrasound to evaluate the oral function during swallowing. Nevertheless, repeated diagnostic tests for patient are appropriate as this technique and sEMG do not involve a radiation risk when compared to VFSS (de Wijk et al. 2006, Singh and Hamdy 2006).

Previous studies of swallowing have documented changes in tongue surface and tongue position using ultrasonic imaging and video-based images in order to explore tongue function and its role in transporting liquids of different consistency (Fuhrmann and Diedrich 1994, Shawker et al. 1984, Shawker et al. 1983, Stone et al. 2004, Watkin 1999). Other studies have revealed changes in the oropharyngeal swallow with increases in bolus viscosity. Reported findings concluded that liquids with increasing consistency and volume showed increased duration of swallowing, tongue base to pharyngeal wall contact, increased cricopharyngeal opening duration, increased oral and pharyngeal residues, and increased hyoid and laryngeal movements when compared to thin liquids in ultrasound (Chi-Fishman and Sonies 2002, Dantas et al. 1990, Lazarus et al. 1993).

2.6.1.4 Fibreoptic Endoscopic Evaluation of Swallowing (FEES)

Fiberoptic endoscopic evaluation of swallowing (FEES) has been proposed in recent years as a useful supplementary tool for studying the pharyngeal stage of swallowing and diagnosing dysphagia using imaging instrumentation (Bastian 1991, Langmore et al. 1988). It consists of a small diameter tube placed through the nose and into the pharynx to visualise the pharynx before, during, and after swallowing, as shown in Figure 2.10. However, this tool supplies limited information regarding its ability to identify or predict specific features of dysphagia or guide

intervention to alleviate risks associated with dysphagia compared to VFSS (Leslie et al. 2007). Nevertheless, it is one of the first choice tools for investigating swallowing in Europe as a result of its ease of use, well tolerated by dysphagic patients, possibility of bedside examination and diagnostic tests for patient can be repeated with no adverse effects when compared to VFSS (Aviv et al. 2000). Nacci et al. (2008) addressed the risks involved with performing FEES examinations. They proposed new, informed consent guidelines that stress the importance of informing patients of the possible risks involved. FEES examinations involve inserting an endoscope through the nasal cavity and can encounter adverse effects which may include: discomfort, gagging and/or vomiting, anterior epistaxis, posterior epistaxis, laceration of the mucosa, allergic reactions/hypersensitivity to topical anaesthesia or nasal sprays, adverse effect of methylene blue, vasovagal response and laryngospasm (Aviv et al. 2000, Fattori et al. 2006, Wu et al. 1997).
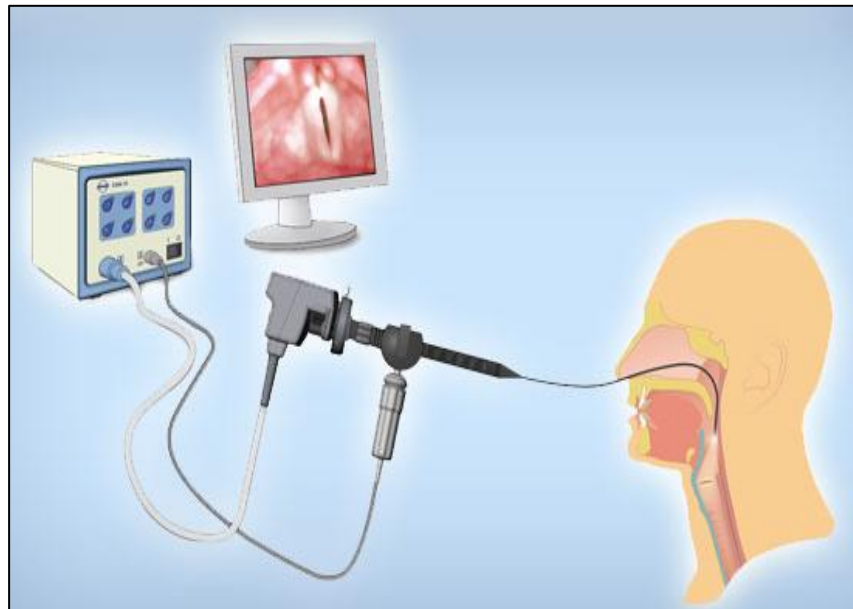
Figure 2.10 Fibre-optic endoscopic evaluation of swallowing (FEES) reproduced from ATMOS (2010)

2.6.2 Advanced Technologies in Biomechanical Simulations of Swallowing

In humans, the musculoskeletal biomechanics involved in mastication and swallowing have proved to be challenging to examine due to the fact that many structures are inaccessible. Additionally, the assessments used to record movement, forces and muscle responses are often invasive. These constraints led to the recent development of a number of biomechanical computational simulations both model and animation during bolus mastication and normal as well as abnormal bolus swallowing. These computerised simulations realistically emulate human swallowing providing an essential approach to evaluating and predicting human swallowing patterns in particular, 'what if' scenarios. Computerised simulations also allow for the understanding of the influence on an individuals' physiological capability (e.g. swallowing capability of muscular anatomy, saliva creation, bit force, chew cycles and mastication), bolus flow dynamic behaviours (i.e. pharyngeal wall contraction), and bolus characterisation (consistency, shape and size) (De Loubens et al. 2011).

Biomechanical computational simulation studies for modelling and animating the swallow process have been experiencing a continuous and rapid growth since the increased prevalence of dysphagia among the ageing population. A brief review on some of these studies will be highlighted. A study by Meng et al. (2005) was examined to simulate the pharyngeal wall movements, to time the swallowing duration and to analyse the influences of the liquid bolus rheology for Newtonian and non-Newtonian during bolus transportation using computer simulations. Harrison et al. (2014), Pileicikiene et al. (2007), Koolstra et al. (1988) and Koolstra and Van Eijden (2001) studied the possibilities of modelling a three-dimensional simulation of several complicated aspects of mastication involving the anatomical movements of the oral cavity (including the teeth, tongue, jaws, cheeks and palates), the breakdown behaviour of the food, bolus formation resulting from the interactions

between food particles and saliva, taste perception, aroma release and how these physical and chemical processes are perceived by a person.

2.6.3 Challenges and Future Studies on Swallowing

In recent years, various types of masticatory robots have been developed to measure the masticatory performance to better mimic the physical conditions encountered during food oral processing involving the muscles of mastication, the coordination of its displacement and forces and biological properties. These simulations give rise to a clear roadmap for development of advanced simulation technologies. Both Figures 2.11 and 2.12 are life sized mastication robots designed with human physiology in mind, and to be capable of mimicking the movements and forces of the human mastication process. The future applications of these challenging robots are to study, in detail, the chewing performance of real food in normal and abnormal swallowing. So far, such achievements show a promise for application of the robot to characterise food texture.

Figure 2.11 Motion control of a chewing robot of six parallel mechanisms (Tortora and Derrickson 2008)

Figure 2.12 Orofacial advanced masticatory robot (Cyranoski 2001)

Although the effect of food oral processing has been widely studied to service the disadvantaged population, additional studies are needed for a deeper investigation on the kinematics and spatiotemporal variability of tongue behaviours. Figure 2.13 shows three-dimensional electromagnetic articulography (EMA) that is a new feasible method providing unprecedented access to study the tongue (blade, body and dorsum) movements in detail during sequences of repeated discrete water swallows (Steele and Van Lieshout 2004b).
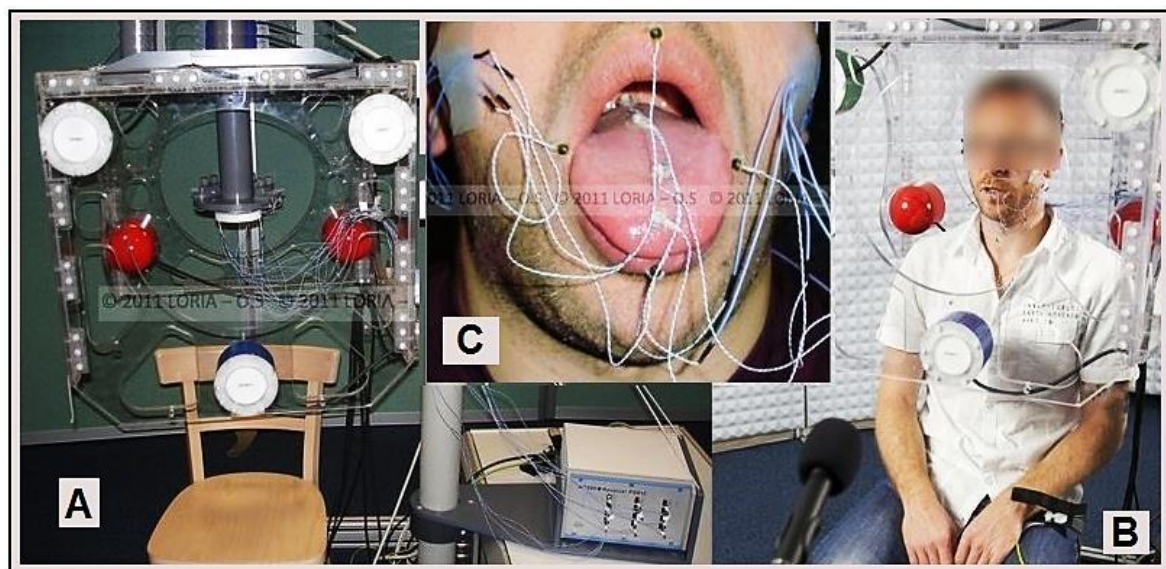
Figure 2.13 Three-dimensional electromagnetic articulography (EMA) device: (A) articulograph (B) volunteer setting position (C) 8 sensors on different orofacial positions reproduced from (Embarki et al. 2011)

The key limitations of these methods are that they are time-consuming, expensive and need experts to conduct experiments. Hence there is a considerable need to develop simple, repetitive, reliable method which is easily adopted for primary sensory of perceived ease / difficulty of swallowing and perceived bolus flow behaviour. This research project considered several methods described in Chapter 3, 4 and 5.

2.6.4 Bolus Physical Characterisations

The physical characterisations of a swallowable bolus have been progressively under-researched not only when studied by *in vitro* measurements (i.e. rheology and texture), but also during *in vivo* measurements. During *in vivo*, bolus charactrisation is mainly investigated during sensory panel experiments or treatments. Based on literature, bolus observation can fall into three broad categories. The categories involve chewing and spitting followed by bolus assessment, oral processing followed by swallowing observations or tongue pressing and food breaking. These assessments on the physical characters of a bolus incredibly enhance the understanding of the effects of boluses property variations on the oropharyngeal swallowing system. As a result, the potential to aid in the clinical evaluation and treatment of individuals with dysphagia is offered. However, these categories do not require medical supervision for healthy individuals.

2.6.4.1 Chew and Spit Bolus Assessment

The category of chew and spit bolus assessment is widely used as an approach to understand the influence of eating mechanics on a collected bolus in relation to food structure breakdown, particle size distribution texture, viscosity, adhesiveness, insalivation and lubrication. Such bolus assessment has resulted in a methodology that could help to design food for a safe and comfortable swallow according to a preferred dynamic sensory profile.

Several physical changes appear in a food bolus during mastication. To assess the physical bolus formation, chewing cycles, for example, need to prepare the food for swallowing by breaking down the food into small particles, and by food hydration (saliva) which facilitates the swallowing step. In this aspect, breads and cereals become typical food models to build the relationships between food breakdown in the mouth and its properties before swallowing (Le Bleis et al. 2013, Peyron et al. 2011, Tournier et al. 2012). In rheological terms, high degradation of bread particles showed a loss in the boluses physical structure when compared with a bolus structure made from spaghetti (Hoebler et al. 1998). Panouillé et al. (2014) reported that the rheological properties of a chewed bolus were mostly influenced by mastication time and saliva cooperation during consumption. Peyron et al. (2011) revealed that a bolus hardness rapidly decreased exponentially during the progress of the chewing sequence. While Chen et al. (2013) observed that boluses physically reduce in particle size as its hardness increases. However, studies have concluded that significant differences in bolus formation were observed between individuals due to the variation in chewing performance and food types. The wide variation in bolus formation between individuals could be due to many different reasons. In literature, the amount of salivary secretion is one factor that participates not only to bolus lubrication but also modifies the rheological properties of the bolus (i.e. consistency and viscosity) (Hutchings and Lillford 1988, van Vliet 2002). A preliminary study in dairy products by Drago et al. (2011) showed that salivary composition is an additional factor that affects bolus formation.

Solid food particle size (bolus granulometry) after oral processing is an interesting physical bolus parameter that has been intensively studied either after a particular number of chews, after a range of chew cycles or as a measure of masticatory efficiency for initiating a swallow. Collected boluses of various food products (e.g. cheese, nuts, raw vegetables etc.)

were evaluated to identify the particle size determination and quantification by wet and dry manual sieving, laser diffraction methods or by taking images and analyses using specific software (Chen et al. 2013, Dahlberg and Hannay-King 1942, Fontijn-Tekamp et al. 2004, Hoebler et al. 2000, Hutchings et al. 2011, Hutchings et al. 2012, Jalabert-Malbos et al. 2007, Jiffry 1981, Lucas and Luke 1984, Mishellany et al. 2006, Peyron et al. 2004, van der Bilt and Fontijn-Tekamp 2004, van der Bilt et al. 1993, Yurkstas and Manly 1950, Yurkstas 1965). Peyron et al. (2004) compared the particles of nuts and raw vegetables and concluded that the particles were much larger in vegetables than in nuts. However, particle size distributions were also similar among nuts and vegetables at the end of the chewing process. In addition, particle size distribution was significantly decreased at the beginning of the masticatory sequence (Peyron et al. 2011).

By contrast, Prinz and Lucas (1997) proposed that the property of bolus cohesiveness which is defined as:

"the degree to which the bolus holds together after mastication"

is more critical than particle size reduction at the swallowing threshold. This property was gradually increased at the initial chewing time by agglomeration of small particles together with saliva incorporation and later remained stable during chewing and oral processing (Ashida et al. 2007, Funami et al. 2012, Hoebler et al. 1998, Kim and Han 2005, Mioche et al. 2002, Peyron et al. 2011). This function of increasing the cohesiveness of a food bolus approved to prevent a bolus from being broken up into smaller fragments, which may prove equally life-threatening when entering the airway or may leave unwanted residue accumulation in the vicinity of oropharyngeal and/or oesophageal track during the swallowing process (Leonard et al. 2014). However, cohesive attributes vary between individuals and mainly depend on the bolus ingredients (Vilardell et al. 2014). In addition, the contribution of bolus cohesiveness to its flow or physiology remains unclear (Steele et al. 2015).

2.6.4.2 Oral Processing and Swallowing Observation

Oral processing followed by a swallowing observation is another approach to categorise bolus assessment during the swallowing process. This approach of assessment is widely applied, not only by clinicians but also by food scientists and technologists in industry and academia. Thus, it is often considered as case studies for swallowing tests to target individuals across all ages to decode the bolus physical flow behaviour and transition in terms of, tongue movement coordination, perioral muscle activities and also the bolus structure and its rheology prior to swallowing that is difficult to capture *in vitro*. Therefore, framing the positive contribution of such assessment leads to a clearer understanding of the dynamic food changes during oral processing and bolus formation. It is important to compare these changes with individuals' physiological capability (i.e. tongue and orofacial strengths) of swallowing either in healthy or impaired subjects and the implications for food provision.

For fluid bolus, some studies focused on the influence of thickened fluids on swallowing-related muscle movements and reported safe swallowing. A traditional behavioural approach for the treatment of dysphagia is to alter the physical properties (i.e. rheology) of a thin liquid bolus by increasing its consistency using commercial thickening agents (Clavé et al. 2006, Germain et al. 2006, Logemann 2007). As a result of increasing bolus consistency, sEMG, videofluoroscopy and videoendoscopy showed that a considerable increase was observed in the tongue movement in terms of pressing the bolus segmentally and sequentially against the hard palate with increased bolus viscosity (Corbin-Lewis and Liss 2014, Robbins et al. 1992, Steele and Van Lieshout 2009). To initiate the flow of such a bolus, the following sequence of events must occur: an increase in the tongue pressure production, increased orofacial, submental and infrahyoid muscle activities, increased exposure time of the oral bolus clearance and pharyngeal contraction for continuous flow of the thickened fluid bolus when compared with a thin one (Miller and

Watkin 1996, Nicosia and Robbins 2001, Reimers-Neils et al. 1994, Shaker et al. 1988, Shaker et al. 1994, Steele and Van Lieshout 2009). As a consequence, the recorded duration of bolus swallowing transition from the oral stage to the pharyngeal stage increases with increased bolus viscosity (Cook et al. 1994, Robbins et al. 1992). Logemann et al. (2000), Robbins et al. (2005), Doherty (2001), Tamine et al. (2010a) and Alsanei and Chen (2014) observed that ageing is associated with a significant reduction in the physiological capabilities of tongue pressure, oral volume and orofacial muscle strength in the swallows of older groups as compared to younger groups.

The capability of individuals dealing with bolus sizes (volume) is another important factor for eating and swallowing studies that can be observed using manometry (Butler et al. 2009, Perlman et al. 1993), videofluoroscopy (Cook et al. 1989, Dantas et al. 1990), electromyography (Perlman et al. 1999), high resolution manometry (Hoffman et al. 2010) and mathematical modelling (Kahrilas et al. 1996) in order to characterise the optimum bolus being swallowed of either a bolus of liquid drink, semisolid or from a masticated solid food. It is believed that the bolus size of various bolus types (i.e. presented in a drinking cup and/or spoons of increasing bolus sizes) have a significant influence on the physiologic changes in normal swallowing (Bisch et al. 1994, Jacob et al. 1989, Kahrilas and Logemann 1993, Kahrilas et al. 1992a, Kahrilas et al. 1992b, Lazarus et al. 1993, Perlman et al. 1993, Robbins et al. 2006). For instance Hoffman et al. (2010) reported that the movement of the hyoid bone showed a strong tendency to increase with increasing bolus volumes. Another change found by Hiss et al. (2004) concerns large boluses such that the initiated swallowing apnea onset appeared earlier than with small boluses.

Significant disparities in the relationship between swallow durations and bolus volumes are also investigated by Hoffman et al. (2010). They reported that the bolus volume per swallow decreases when the bolus viscosity increases. Another study by Hiss et al. (2004) found that there

was a delay in the initiated swallowing apnea onset as the bolus viscosity increased. Conversely, detecting an increase in the pressure along the pharynx length including the upper oesophageal sphincter as the bolus volume increased. However, tongue pressure showed a negative correlation at the same bolus condition (Hoffman et al. 2010). Moreover, the total duration of the swallowing process increased with larger bolus volumes. However, these studies also concluded that no changes were observed between males and females.

Several studies aimed to evaluate the characteristics of pressure produced by the tongue against the hard palate during saliva, thin liquid, honey-thick liquid, semisolid and solid bolus swallowing by using feeding and bolus assessment approach. Youmans and Stierwalt (2006) reported that the applied tongue pressures to swallow honey-thick liquid was slightly higher than that for thin liquids. While similar tongue pressures were recorded to swallow saliva and 12 ml of water (Alsanei and Chen 2014). But for only saliva swallowing, Steele et al. (2010) investigated that tongue pressure was greater during effortful saliva swallowing than habitual, non-effortful (normal) saliva swallowing. Ono et al. (2004) concluded that the pattern of tongue movement contacting the hard palate as well as the duration and pressure magnitude are coordinated precisely with the swallowing of 15 ml water.

The optimum liquid bolus being swallowed is of interest to both clinical practitioners and food oral processing researchers to carry out studies on diagnosing dysphagia and non-dysphagia swallowing behaviours. Studies showed that the volume of a liquid sample that is sipped or swallowed is influenced by a number of variables such as, oral volume, cup size, viscosity, taste, liquid temperature and a subject's age and gender (Alsanei and Chen 2014, Lawless et al. 2003). Generally, the frequently sipped water volume reaches an average of 9 to 20 ml during natural drinking conditions (Adnerhill et al. 1989, Alsanei and Chen 2014, Lawless et al. 2003, Steele and Van Lieshout 2004a). The water volume per sip decreased through sips (Lawless et al. 2003). They also reported

that the water-sipping volume increased as the cup size increased. However, gender difference in sip size showed that men consumed larger sips than women (Adnerhill et al. 1989, Alsanei and Chen 2014). In conclusion, the results of these studies have not always been congruous and also it is difficult to directly compare the studies. The reported variances are likely due to the different manometric and radiographic technical measurements which include bolus size, consistency, individuals' physiological oral capability, average ages, gender and degree of dysphagia (Robbins et al. 2006).

2.6.4.3 Tongue Pressing and Food Breaking

The tongue is a very active organ during food oral processing including taste and texture sensation, food mixing and transportation, as well as swallowing. Nevertheless, it is also the responsible for sensing the surface or geometrical properties of bolus because of its ability to perceive minute differences in particle size, shape, hardness and roughness. Tongue can also aid the food breaking down (e.g. jelly) during the tongue-palate compression. In a study by Alsanei et al. (2015) aimed to assess the individual's capability of tongue-only food breaking. During bolus assessment, it was found that the tongue muscle strength reveals one's capability in food oral handling and manipulation (i.e. food breaking without teeth involvement). This study also concluded that proper matching between one's oral physiological capability and the textural properties of food is critically important to ensure safe food consumption by vulnerable consumers. However, more studies are required with respect to the lack of matching between individual's oral physiological capability and the food textural properties in order to meet the challenge of designing foods that are characterised as the easy-to-break-easy-to-swallow in either the healthy population or dysphagic patients.

2.6.5 Models of Bolus Swallowing

A number of models on bolus swallowing has been performed which are three-degree food breakdown, maximum cohesiveness and adhesive food paste models. The findings of these models emphasise the relationship between swallowing and bolus characterisation such as particle size distribution, cohesiveness, surface lubrication of the bolus, physical properties of the bolus. These factors affect by food oral processing. A brief of these models focusing on the main principles will be discussed.

2.6.5.1 Three-Degree Food Breakdown Model

The above discussions show that the swallowing capability and oral muscle activities are considerably influenced by an individual (including consumption history, social background, age, gender, involvements of oral processing etc.) and also by the bolus properties. In fact each solid food has a characteristic, "breakdown path" in the mouth during mastication. Based on this fact a simple schematic model of a physical bolus was designed by Hutchings and Lillford (1988) in order to illustrate the bolus breakdown path and conceptualised swallowing. They suggested that a swallow is comprised of three-degrees of critical dimensions (structure, lubrication and time) to be achieved when food reduces to a certain degree of structure breakdown during mastication (i.e. ABCD in Figure 2.16) reaches a certain degree of lubrication (saliva - i.e. EFGH in Figure 2.16) and the time dependent as both mastication and saliva production which are gradual during the oral processing. Where structure breakdown refers to the comminution process of solid food as particle size reduction during the mastication process, the degree of lubrication reflects, to some extent, perceived lubrication of a food in the mouth. The later takes into account the combination of various factors, such as the amount of moisture (saliva) initially present in the mouth, free liquids liberated from the food, saliva released during mastication, and other factors such as the presence of fat, bolus rheology and bolus surface

properties that allow for swallowing. The duration of, "time" takes into account the fact that the breakdown of the food during the mastication process is a gradual process. Therefore, the time required for the breakdown of foods with different properties will vary.
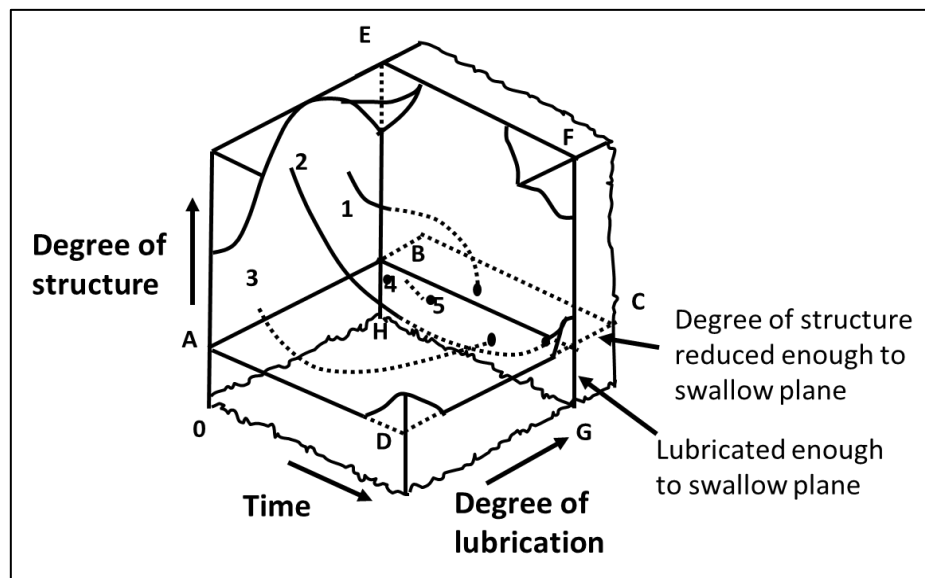
Figure 2.14 Illustration of the three-degree food breakdown model for solid food during mastication produced by Hutchings and Lillford (1988)

To simplify, the following studies show how this model can be used. During juicy meat oral processing of different meat textures that had similar overall moisture levels but different levels of fibre disorganisation at the end of the mastication, authors reported that the moisture level of the bolus is more important to the swallow threshold compared to the level of comminution of meat muscular fibres (Bornhorst and Singh 2012, Yven et al. 2006). Authors concluded that the meat may have sufficient levels of lubrication (high moisture level) upon entering the mouth. However, its structure must be significantly reduced at the end of the mastication process before it can be swallowed. In contrast, for a dry piece of cake, although the structure will be quickly broken down, it will require extra time for oral processing to reach a sufficiently high enough level of lubrication before it can be swallowed (Bornhorst and Singh 2012).

48

2.6.5.2 Maximum Cohesiveness Model

A further study by Prinz and Lucas (1997) attempted to produce a quantified model of the forces involved in bolus creation during mastication based on the produced model from Hutchings and Lillford. They suggested that as food particles are reduced in size and simultaneously wetted and glued by saliva cooperation, the oral processing forces in the mouth tend to form a bolus either cohesive or adhesive to the oral cavity (Figure 2.17). It seems that the optimum moment for swallowing is thought to coincide with the maximum cohesive force between food particles. Therefore, the bolus formation is more important than particle size reduction at the swallowing threshold. When the food is broken down into small particle sizes, it has been sufficiently moistened by saliva and a resulting bolus is formed. Nevertheless, this model assumed to release negligible amounts of liquid when it was deformed. Thus, saliva is the only wetting agent to be considered. As a result, the swallow action will be triggered when the cohesive forces in the bolus reach their maximum levels allowing the cohesive bolus to transports through the oesophagus. Cottrell (1964) and Bot and Pelan (2000) reported that bolus rheology (viscosity) is considered to provide the relevant force needed to initiate a swallow.
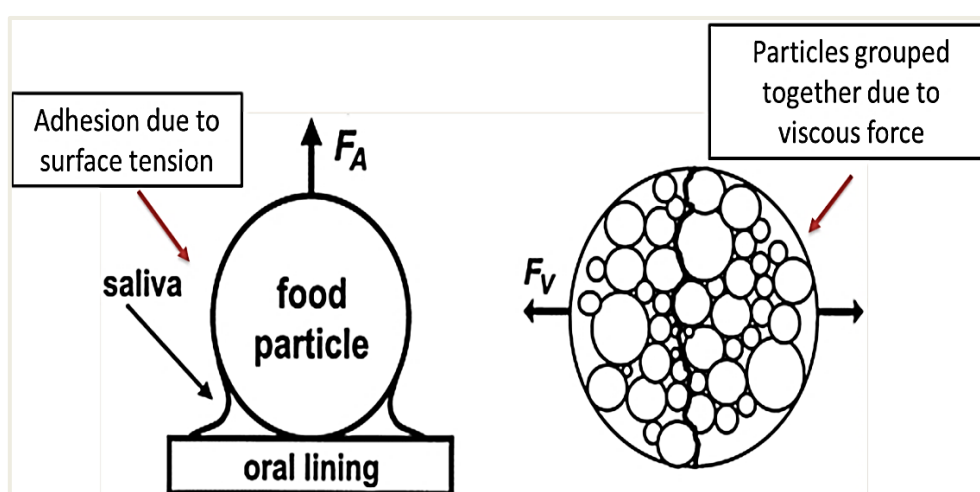
Figure 2.15 Illustration of the maximum cohesiveness model produced by Prinz and Lucas (1997)

2.6.5.3 Adhesive Food Paste Model

Following previous models, Rosenthal and Share (2014) and Rosenthal and Yilmaz (2014) used the model from Hutchings and Lillford and proposed that milled foods (e.g. peanuts, paste and sesame paste) will reduce the degree of structural breakdown (Figure 2.18). Therefore, a bolus of such attribute will require an increase in the degree of lubrication as excess saliva is secreted and formed into the bolus making it suitable to swallow. Based on the modification of three-degree swallowing model for dilatant food that exhibits shear thickening flow behaviour, the bolus structure degree of such attribute will require an increase in the degree of lubrication as excess saliva is required to enhance the bolus thinning down to the point of swallowing.
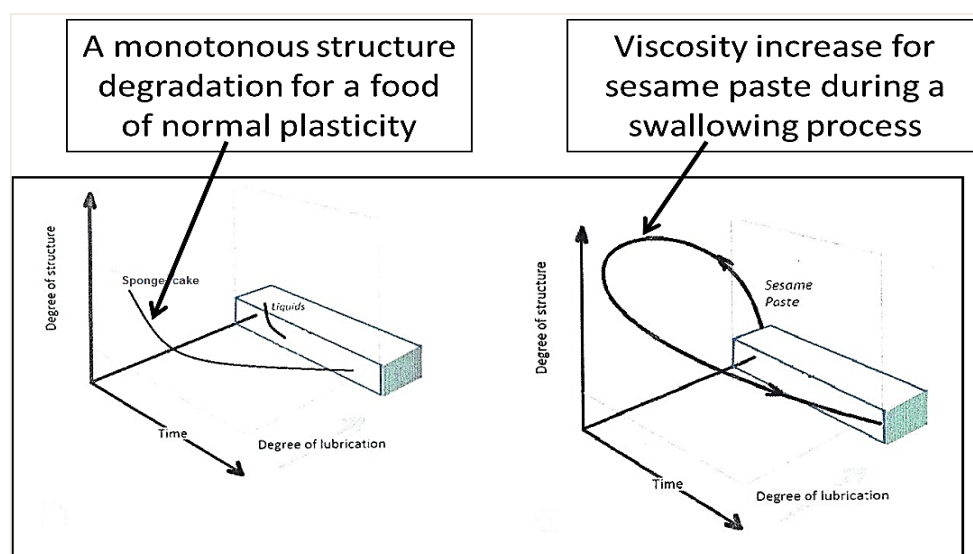
Figure 2.16 A modified 3D swallowing model for dilatant food produced by Rosenthal and Yilmaz (2014)

The key limitation of these models is that they involve saliva interaction, bolus breakdown, time-consuming and temperature effect during food oral processing. Hence there is a considerable need to design simple, repetitive, reliable and ready-to-swallow bolus. It will be easily adopted for primary sensory of perceived ease / difficulty of swallowing

and perceived bolus flow behaviour. This research project considered bolus type to be a ready-to-swallow in Chapter 3 and Chapter 5. During swallowing evaluation, subject will be asked to allocate ready-to-swallow food at the posterior one-third of the tongue in order to limit the time for the bolus to stay inside the oral cavity and to minimise saliva mixing and viscosity changes.

2.7 Hydrocolloids for Dysphagia Management

It is generally assumed that the safety and initiation of swallowing can depend on both the functions of the tongue and the physical changes in the food bolus properties as it was formed through mastication (O'Leary et al. 2010 and Peyron et al. 2011). A further belief is that texture modification (i.e. bolus mechanical properties) such as, rheological and surface properties as well as median particle size play an important role in triggering a swallow. Moreover, the uses of hydrocolloids as food thickeners and pre-thickened liquids for dysphagia sufferers are widely considered important for promoting safe and efficient swallowing. Additionally, these products have managed to reduce the bolus flow speed during swallowing. Therefore, such diet management has become an important aspect of the clinicians' treatment toolkit for stroke and dysphagia (Leonard and Kendall, 1997).

2.7.1 Thickeners

Most dysphagic diets found in the pharmaceutical, hospital and healthcare are often rely on thickeners. These products used to enhance the rheological properties of fluid formulations. With the innovative thickening agents, the swallow-safe bolus has become easier for some cases of dysphagic patients. These thickeners are commonly based on different classes of molecules dependent on its effect on the diet. For example, food thickeners are usually based on either polysaccharides or

proteins that have a wide array of functional properties in foods including; thickening, gelling, emulsifying, stabilisation and coating etc. Moreover, the main reason behind the ample use of thickeners in foods is their ability to modify the desirable rheological properties of food systems whilst remaining odourless and tasteless and without altering the mixing or mouthfeel of the foods. This includes two basic characteristics of food systems which are food flow behaviour (viscosity) and food mechanical property (texture) (Milani and Maleki 2012, Williams and Phillips 2009).

2.7.2 Raw Thickeners

Thickeners largely fall into one of two classes: high molecular weight polymers (e.g. xanthan gum) and particulate thickeners that have the ability to swell (e.g. starch) (Sereno et al. 2007). Dysphagia food products are predominantly starch based, but other products are commonly based on thickeners such as xanthan or guar gum. The polysaccharide molecules making up such thickeners have a high affinity for water. Due to the fact that a large number of hydroxyl groups noticeably increase their affinity for binding water molecules, rendering them soluble in water (hydrophilic substances). Thus they are hydrated to provide texture and viscosity control in food systems (Dongowski 1997, Milani and Maleki 2012).

Gel network formation of the thickeners depends on a three-dimensional gel network form through entwining and cross-linking of chains. The short sections of the separated chains align and form the aggregation of primary interchain linkages into, "junction zones" (Figure 2.19). These zones form the basis for the three-dimensional network of the gel that are not static but continually form and reform in different sections of the network. It may be that the gel is held together by long-range interactions and chain entanglements rather than larger discrete junction zones. Water molecules exist, in part, bound to the polysaccharides; the rest being trapped in pockets formed by the

polysaccharide network (Dongowski 1997). However, the mechanism by which this interchain linking occurs can vary (Djabourov 1991).
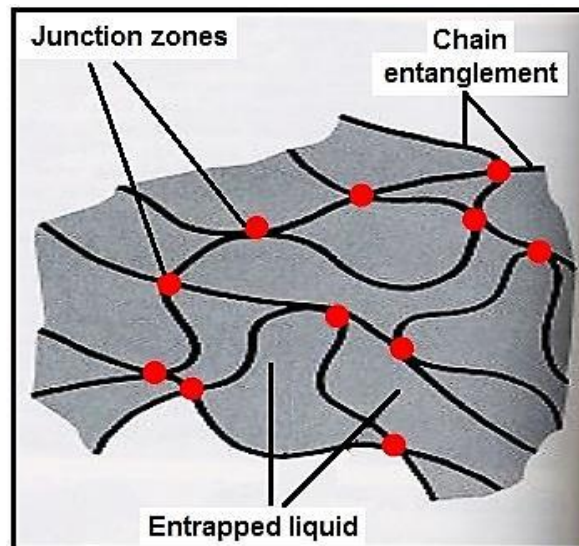
Figure 2.17 Schematic representation of three-dimensional gel network with junction zones, reproduced from (Song et al. 1999)

These networks provide the elastic properties for a material to behave partially solid-like. However, the continuous aqueous phases make them more viscous and behave partially liquid-like. Therefore, polysaccharides in solution with their complicated molecular entanglements are termed viscoelastic and thus can be studied using rheological methods (Gaylord and Van Wazer 1961).

2.7.3 Commercial Thickeners

Disadvantaged populations such as the elderly and hospital patients with food bolus obstruction typically display dysphagia. Dysphagic patients are particularly suffering from the symptoms of swallowing difficulties, choking, primary aspiration or even suffocation of thin fluids (e.g. water, milk, soup, coffee, tea and others). Thickeners (thickening agents) in their powder form are commercially available products in international markets and in particular United Kingdom such as Nutilis,

Thick & Easy and Recourse ThickenUp. These thickeners consist of starch-based, polysaccharide-based or mixture of both thickeners.

Regarding the dysphagia management diet, these thickeners are widely used as a diet treatment for the care of dysphagic patients as a result of their well-design thickeners to facilitate and help the safety of the swallowing process and also to combat swallowing disorders associated with dysphagia by modifying the texture and enhancing the rheological properties of thin fluid diets by increasing viscosity (Mills 1996, Pelletier 1997, Stahlman et al. 2000, Stanek et al. 1992). Thickeners are used for moderating viscosity ranges due to the ease of preparation, convenience, reasonable cost and suspending ability and volume stability of the thickened liquids. These sort of diets are generally described as liquids that cannot hold together well in the mouth and also can be easily passed into air pathway of disadvantaged population groups. Therefore, it is widely assumed that the thickening of such liquids plays a crucial role in the simple transportation of thickened liquids from the oral cavity into the stomach for further digestion. In addition, it is hypothesised that thickening agents are one of the positive ways that give symptomatic relief or potentially reduce the incidence of dysphagia symptoms which results from the swallowing of foods, fluids, or saliva (Scott and Benjamin 2010). As a result, it is considered that the food bolus can move around the mouth more slowly and allow a better control of swallowing at mealtimes. On the other hand, the effectiveness of thickened fluids in preventing above symptoms has not been well established as dysphagia varies between patients.

Table 2.2 describes three stages of thickened fluid textures used by clinicians and healthcare workers. Table 2.3 summarises the proposed terms of the consistency levels and their correlating viscosity ranges suggested by the national descriptors for texture modification in adults (Mills 1996, National-Dysphagia-Diet-Task-Force and American-Dietetic-Association 2002, Stanek et al. 1992). Selected characteristics of some thickeners in the powder form used for dysphagia therapy are obtained

from their companies' websites as shown in Table 2.4. However, starch-based thickener (Resource ThickenUp) was used to constitute food samples in Chapter 3 and gum-based thickener was used in Chapter 5.

Table 2.2 Descriptions of three stages of thickened fluid textures

Texture	Description of fluid texture
Stage 1	Can be drunk through a straw
	Can be drunk from a cup if advised or preferred
	Leaves a thin coat on the back of a spoon
Stage 2	Cannot be drunk through a straw
	Can be drunk from a cup if advised or preferred
	Leaves a thin coat on the back of a spoon
Stage 3	Cannot be drunk through a straw
	Cannot be drunk from a cup
	Needs to be taken with a spoon

Table 2.3 The viscosity ranges and consistency levels of defining thickened fluids at shear rate 50 s^{-1} and 25 $^{\circ}$C by the national dysphagia diet force and American dietetic association

Consistency Levels	Value	
	cP	**Pa.s**
Thin	1-50	0.001-0.05
Nectar-like	51-350	0.051-0.35
Honey-like	351-1750	0.351-1.75
Spoon-thick (pudding)	>1750	>1.75

Table 2.4 Selected characterisations of the most common thickened fluids used dysphagia therapy (Nutilis 2011, Thick&Easy™ 2015, ThickenUp™ 2013)

Product	Nutilis	Recourse ThickenUp	Thick & Easy
Suitability	Over 3 years old	Over 1 years old	Over 1 years old
Ingredients	Modified maize starch (E1442) Maltodextrin Tara gum Xanthan gum Gura gum	Modified maize starch (E1442)	Modified maize starch (E1442) Maltodextrin
Storage	In cool and dry place	In cool and dry place	In cool and dry place
Thickening time	Few minutes	Stir until desired consistency achieved	60 seconds
Quantities per 100ml	• Syrup 1 scoops (3.0g) • Custard 1.5-2 scoops (4.5-6.0g) • Pudding 2-2.5 scoops (6.0-7.0g)	• Syrup 1 tablespoon (4.5g) • Custard 1.5 tablespoon (7.0g) • Pudding 2 tablespoons (9.0g)	• Syrup 1 scoops (4.5g) • Custard 1.5 scoops (7.5g) • Pudding 2 tablespoons (9.0g)
Quoted viscosity range	• Syrup 0.45 ± 0.2 Pa.s • Custard 1.2 ± 0.4 Pa.s • Pudding 3.0 ± 1.0 Pa.s	• Syrup • Custard • Pudding	• Syrup • Custard • Pudding

2.7.3.1 Starch

2.7.3.1.1 Structure

Starch is produced by all green plants as an energy storage molecule and is a vital constituent of the human diet that found in abundance in many foodstuffs from potatoes to wheat and rice. Its structure consists of two molecules, amylose and amylopectin in varying molar ratios dependent on the plant species. Both molecules consist of glucose subunits linked by glycosidic bonds. Despite the common description of starch as a simple polymer of glucose, it in fact has a remarkably complex and heterogeneous structure over a range of scales (Gidley 2001).

2.7.3.1.2 Properties

Starch molecules are usually found as a semi-crystalline granule that is insoluble in cold water but becomes soluble upon heating where the granules swell and eventually burst. During breakdown the intermolecular bonds of starch molecules, called starch gelatinisation, amylose molecules diffuse from the granule, forming a gel-like network with various viscosity ranges in the presence of water and heat, allowing the hydrogen bonding sites (the hydroxyl hydrogen and oxygen) to engage more water. It is currently common practice to use starch-based thickening agents in the clinical management of dysphagia in order to change the physical properties of liquids for safe swallowing (Germain et al. 2006, Matta et al. 2006). Commercial food-thickening agents in their powder forms (Resource ThickenUp, Nestle, Nutrition, Germany) and potato flakes were used for thicker consistencies in chapter 3 to correlate between an individuals' oral physiological capability (tongue pressure strength) and their swallowing.

2.7.3.2 Xanthan Gum

2.7.3.2.1 Structure

Xanthan gum is one of the microbial hydrocolloids that was discovered in the 1960s. It is classified as an extracellular polysaccharide produced by Xanthomonas campestris which has bacterial species that grow on the leaf surfaces of various plant species and causes a variety of plant diseases (Becker et al. 1998). Xanthans primary structure consists of a cellulosic backbone of β- (1→4) linked D-glucose units substituted on alternate glucose residues with a trisaccharide side chain. This side chain is composed of two mannose units separated by a glucuronic acid (Melton et al. 1976). Approximately half the terminal mannose units are linked to a pyruvate group and the non-terminal residue usually carries an acetyl group. The carboxyl groups on the side chains render the gum molecules anionic. The pyruvic acid content of xanthan can vary substantially depending on the strain of xanthan campestris, resulting in different viscosities of xanthan solutions.

2.7.3.2.2 Properties

Xanthan (known as European food additive number *E415*) is a white to yellowish powder and is highly stable under many environmental conditions. It is practically constant, ranging from pH 1 to 13. Xanthan is also remarkably stable to heating and displays a constant viscosity from room temperature to 80 ˚C. From 80 to 90 ˚C, a structural transition occurs from ordered to disorder in water. Viscous solutions of xanthan exhibit marked non-Newtonian shear-thinning properties caused by parallel arrangement of the linear molecule chains. At low shear rate, it exhibits a high viscosity range even at very low concentrations and dramatically decreases at increasing shear rates (Jeanes et al. 1961). In addition to their desirable rheological properties, xanthan gum is widely

used in food products particularly for dysphagia diets due to a wide range of its functional properties making them ideal candidates for thickeners in the food industry (Sutherland 1998). For these reasons xanthan gum was used to constitute food samples with different consistencies in order to establish a link between the bolus flow behaviour and individuals' MITP capability in Chapter 5.

2.8 Mechanical Properties of Fluid Foods

2.8.1 Rheology Measurements

Rheology is the study of how materials deform and flow once subjected to a normal and tangential stress (Macosko 1994, Rao 2007). The word rheology originates from the Greek word *rheos* which means flow. Below, the rheological properties of food in terms of, the principle of flow behaviour, deformation, viscoelasticity, viscosity, elasticity and texture measurements of food systems have been briefly discussed.

2.8.1.1 Shear Stress

When a sufficient enough force is applied to a material's structure, it will break or flow. The size of the area upon which a force is exerted will affect the amount of deformation (flow rate) that occurs. Therefore, the word rheology is fundamentally defined as the relationship between stress (the amount of force per unit area acting upon and within a material) and strain (the amount of deformation induced by the stress) or rate of strain (Jobling 1991).

Determining the rheological property of solid and liquid is an important parameter such properties apply to all types of materials, ranging from gases to solids. In particular, food science has devoted considerable research to the food/liquid rheological properties since food frequently consists of solutions and biopolymers (i.e. proteins, carbohydrates and lipids) and these respond physically to any applied

forces. Processing conditions such as homogenisation, thermal processing and high-shear mixing may influence the rheological properties of food materials (Rao 2007). Owning to the fact that rheology of the foods is mainly influenced by forces being created in the oral cavity such as the comprision and squeezing forces of the tongue against the hard palate and intrinsic muscular conditions (Nicosia and Robbins 2001). In addition to the aforementioned, rheology also includes the study of starch-based and gum-based thickeners and their products for the infant and children with infantile cerebral, the elderly, patients with myasthenia gravis, head and neck cancers as well as those who have suffered strokes. Most of thickened products are non-Newtonian materials; therefore, the effect of shear stress (represented by MITP) may be an aid to produce acceptable products for disadvantaged populations.

2.8.1.2 Shear Rate

When comparing the viscosity of different foods the shear rates of 10 s^{-1} and 50 s^{-1} were chosen. It is thought that such shear rates are present in the oral cavities of both elderly individuals and adults respectively. Oral shear rates were quantified in studies dating from the 1970s and 1980s. Authors of such studies aimed to correlate instrumental viscosity measurements with sensory perceptions of viscosity (Shama et al. 1973, Shama and Sherman 1973). Twenty six healthy volunteers were recruited and the shear rates obtained may not correspond to values associated with older patients suffering from dysphagia. Subjects were provided with food samples (Newtonian and non-Newtonian). The samples consisted of items with varying viscosities such as golden syrup and lemon curd. The perception of viscosity was measured utilising three methods: tilting, stirring and orally manipulating the samples. Results obtained from the subjects were analysed and a relative viscosity ranking for each sample was recorded. Results were then transferred onto a shear stress-rate graph that had been instrumentally derived. The data obtained from the three tests was analysed separately. It was apparent that the

two non-oral sensory evaluation techniques were performed at different shear stress and shear rate levels. With regards to the thinner consistency samples, the shear rates were higher. For stirring, the shear rate was found to be constant at 90-100 s^{-1}, and for tilting the shear rate was found to be between 10-40 s^{-1}. In the case of oral sensory evaluation, subjects were asked to mention which sample felt most viscous whilst in the mouth. It was reported that the shear stress level remained constant between shear rates of 100-1000 s^{-1}, but decreased below this range. They concluded that the mouths shear rate upon sensory evaluation of viscosity varied according to the food type and is more commonly between 10-100 s^{-1}. It may however increase for viscous fluids and foods (Krumel and Sarkar 1975, Shama and Sherman 1973).

A more recent investigation proposed that oral perception of viscosity levels and its measurement should be at lower shear rates, especially for shear-thinning gel systems. Cutler et al. (1983) identified that a more realistic shear rate for weak-gel perception is approximately 10 s^{-1}. The investigation made use of golden syrup and chocolate spread (similar to types of food used in earlier experiments) in order to compare oral based sensory evaluations with instrumental viscosity measurements. Authors indicated that the difference in shear rate between their own study and that by Shama and Sherman (1973) may be due to the pairs of samples provided being too similar in their shear-thinning behaviours. Consequently distinction would have been complex, and perception scores would have been based on small margins. To account for such an issue, Cutler et al. (1983) opted to use magnitude estimation when performing their sensory analysis, based on ratio scaling proposed by Stevens (1975) for the perception of a sensation evoked by a stimulus where positive numbers are assigned to represent sensation ratios of one product to another or of a product to a standard. Unlike previous studies, magnitude estimation was used in conjunction with a trained panel of subjects with extensive experience of ratio scaling. Cutler et al. (1983) felt that such a

method would prove to be more accurate since a greater distinction between samples would be achieved, rather than simply concluding that one sample is more or less viscous than another.

Dickie and Kokini (1983) proposed that honey and mayonnaise would each possess a lower range of shear rates at between 14 s^{-1} and 10 s^{-1} respectively. However, this study did not take into consideration the squeezing force of the tongue. This test was done by placing balloon containing water in a subject's mouth and asking the subject to squeeze the balloon with their mouth. The ejected water was then measured and the flow rate of the water was obtained. The balloon had been calibrated using various weights and a syringe was used to give an indication of squeezing force in Newtonians. As previous studies, healthy volunteers below the age of thirty where used for the sensory panel. It can be assumed that a patient who struggles to manipulate a bolus and swallow properly would be able to generate a shear rate of 50 s^{-1} for a thickened fluid as assumed in the preparation of thickeners for dysphagic patients.

To further complicate the matter, the mechanics of bolus manipulation varies as the bolus makes it journey through the oral cavity via the pharynx and into the oesophagus. Such variables may also have a bearing on the shear rate. A recent study by Meng et al. (2005) focused on computer simulations of the pharyngeal bolus transportation for starch-thickened fluids. The study suggested that the shear rates generated for a non-Newtonian bolus were as low as 0.001 s^{-1}, and as high as 27 s^{-1} for a water bolus (Newtonian fluid). As the non-Newtonian bolus was propelled from the pharynx through the upper oesophageal sphincter into the oesophagus, the shear rate initially increased to around 0.3 s^{-1}. This caused the viscosity to drop from the original 6.0 Pa.s (6000 cP) to 1.0 Pa.s (1000 cP) at the junction point between the upper oesophageal sphincter and glossopalatal sphincter when they were open. Following this, the shear rate transiently decreased for around 0.1 s^{-1}, producing a significant increase in the viscosity to around 150 Pa.s (150000 Pc). However, the viscosity generally dropped back to around

4.0 Pa.s (4000 Pc) as the shear rate returned to higher levels to facilitate the movement of the bolus through the upper oesophageal sphincter as the circrophayngeal muscle remained relaxed. A mere 1.04 seconds elapsed during the completion of this entire process. This clearly highlights the potential impact of shear rate on the viscosity of the bolus as discussed in Chapter 5. Although the above study focused on the shear rates in the pharyngeal area and not within the oral cavity, it is worthy to note how shear rates can influence the bolus viscosity at the stage of swallowing in healthy individuals. Yet despite these later studies and the controversy over the use of the shear rate, the shear rates of 10 s⁻¹ and 50 s⁻¹ remain the accepted and often quoted shear rates for current literature.

2.8.1.3 Viscosity

The viscosity of foods can only be studied once shearing induces a stationary flow of the material. This flow occurs through the rearrangement and deformation of particles and through the breaking of a food material's structural bonds. A simple flow of food material can be established in a system by placing the material between two plates and pulling the plates apart in opposite directions. Thus the viscosity response of the material is detected by a rheometer. Such a force is called a shear force (Pa, Nm⁻²), and the rate at which the plates are pulled apart is described as the shear rate (s⁻¹) (Bauer 1967, Hatschek 1928, Rao 2007). Viscosity and apparent viscosity measurements were subjected to a range of shear rates in order to characterise food samples of thickened consistency.

The shear stress, σ, is given by:

$$\sigma = F / A \qquad \text{(Pa or Nm}^{-2}\text{)} \qquad (2.1)$$

where F is the force acting perpendicularly to the area A and the resulting shear rate, $\dot{\gamma}$, is given by:

$$\dot{\gamma} = \Delta V / h \qquad \text{(s}^{-1}\text{)} \qquad (2.2)$$

where *h* is the distance between the two parallel plates and ΔV is the velocity of the moving plate.

$$\eta = \sigma / \dot{\gamma} \qquad \text{(Pa.s or N m}^{-2}\text{ s)} \qquad (2.3)$$

where η is the shear viscosity.

2.8.2 Instruments

Characterising the rheological properties of fluid foods can be achieved by using many popular rheometry techniques. However, these varied techniques have many pitfalls too. Some of these benefits and drawbacks are briefly described below. One common technique utilises a rotational rheometer to measure the rheological properties of materials (i.e. viscosity and viscoelasticity) (Cichero et al. 2000, Garcia et al. 2005, Garcia et al. 2008, Mills 1999, Rao 2007, Wazer et al. 1964). The rotational rheometer is a superior choice over many rheometers, such as the glass capillary rheometer which is not able to measure non-Newtonian flow behaviour or time dependent data. Rotational instruments allow for time dependence and are the primary choice for determining viscoelastic behaviour (intermediates between that of solids and liquids) under various amplitudes and frequency of the applied strain for studying such behaviour (Steffe 1996). Rotational rheometers commonly incorporate a rotor and stator and a fluid food sample is placed between these two components (Barnes et al. 1989, Macosko 1994). Characterisation of the sample rheology depends on the relative rotation about a common axis of one of three tool geometries: concentric cylinder, cone and plate, or parallel plates as shown in Figure 2.20.
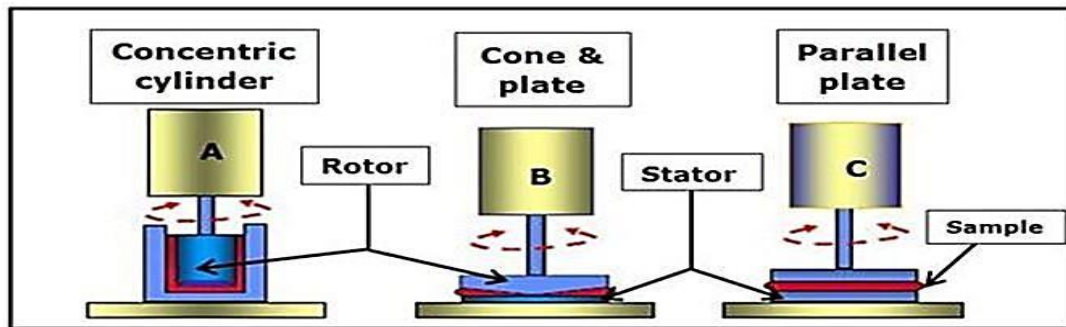
Figure 2.18 Schematic diagram of basic tool geometries for the rotational rheometer: (A) concentric cylinder, (B) cone and plate and (C) parallel plate (T.A.Instruments 2010)

2.8.2.1 Concentric Cylinder

In the concentric cylinder (i.e. cup and bob), the test fluid is maintained in the annulus between the cylinder surfaces (Figure 2.20A). The purpose of such a design is to allow a limited dimension of the annular gap in order to achieve values of shear stress and shear rate which are effectively constant throughout the sample volume. Concentric cylinders are widely used to determine the viscosity of thin fluids (Leonard et al. 2014, Popa Nita et al. 2013, Steele et al. 2003).

2.8.2.2 Cone and Plate

The cone and plate geometry offers an ideal geometry for viscous fluids that have moderate levels of shear-thinning such as hydrocolloidal solutions and dilute or semi-dilute colloidal dispersions. The cone and plate geometry consists of an inverted cone in near contact with a lower plate (Figure 2.20B). The cone measuring system is usually referred to by the diameter and the cone angle. For instance, a CP4/60 has a respective cone angle and diameter of 4° and 60 mm, respectively. The upper or lower surface may rotate depending on instrument design. This geometry was used in Chapter 3 and Chapter 5.

2.8.2.3 Parallel Plate

With a cone angle of 0º, the parallel plate geometry can be considered a simplified version of the cone and plate. The test fluid is

constrained in the narrow gap between the two surfaces as shown in Figure 2.20C. In the rheological literature, cone and plate (e.g. viscosity) and parallel plate (e.g. oscillation) geometries are preferred for highly viscous pastes, gels, and concentrated suspensions (Cichero et al. 2000, Iwasaki and Ogoshi 2014, Jobling 1991). Dynamic shear rheological properties (oscillatory measurement) is a standard experimental of rheological characterisation for studying such behaviour because by varying the amplitude and frequency of the applied strain, a wide range of timescales and behaviours can be studied (Anseth et al. 1996, Larson 1999, Macosko 1994). Therefore, these geometries were considered as measurement tool in Chapter 5.

2.8.3 Texture Measurements

2.8.3.1 Textural Properties

The texture of food materials is a complex stimulus embracing several textural properties. These properties are the group of physical characteristics that arise from the structural elements of the food, are sensed primarily by the feeling of touch, are related to the deformation, disintegration, and flow of the food under a force and are measured objectively by functions of mass, time and distance (Bourne 2002). Several studies have highlighted that consumers not only use a great variety of terms to describe a foods texture, but that trying to classify textural properties across different cultures and languages (i.e. English, German and Japanese) is very complex (Rohm 1990, Rosenthal 1999, Szczesniak and Kleyn 1963). The broad range of terms used to describe perceived texture in foods, lead to the creation of texture classification systems. Table 2.5 and Table 2.6 show the proposed classification systems by Szczesniak to link the rheological properties and terms popularly used in the description of textural characteristics. Classification systems were initially developed for semisolids and solids (Szczesniak and

Kleyn 1963) and later on for liquids (Szczesniak 1979). Undoubtedly, the use of such a system revolutionised the study of texture, and also viscosity, in the field of foods, liquids and in particular, the elderly (age ≥ 65) and dysphagic patients. Such groups are increasing in size and over the next few years numbers are expected to increase to over one million, worldwide. With the onset of old age there are many physiological changes that can affect how food texture is perceived. Consequently reducing a person's ability to consume foods of certain consistencies (Miura et al. 2000, Roininen et al. 2004, Takata et al. 2006, Walls and Steele 2004). Having teeth replaced with dentures is one such example of an oral physiological change (dysphagia). Such a change reduces the sensation derived from foods and also can result in food becoming trapped between dentures and gums. A further physiological change can result from a reduction in orofacial muscle activity and tongue strength, impairing an individual's ability to eat and swallow foods. Thus, in order to create and develop food products specifically tailored to protect the wellbeing of the elderly and dysphagic patients, then the effect of texture in foods and the physiological effects texture can influence must be understood.

Even there are other terminology of food texture that have been proposed by Sherman (1969) and Jowitt (1974), Szczesniak's classification of texture continues to be one of the most often used within food research studies and developments. Regarding solid and semisolid foods, the value of the classified terms was greatly increased with the arrival of the Texture Profile Analysis (TAP) instrument. Due to the fact that this instrument correlates the mechanical description terms obtained from instrumental tests with sensory terms Table 2.7. The TAP has been significantly developed, becoming an established aid in defining and assessing food textural parameters (Bourne 1978, Friedman et al. 1963, Szczesniak and Kleyn 1963).

Table 2.5 Classification systems of textural properties for solids, semisolid foods; adapted from Szczesniak and Kleyn (1963)

	Primary Parameters	Secondary Parameters	Popular Terminology
Mechanical Characteristics	Hardness	____	Soft, film, hard
	Cohesiveness	Brittleness Chewiness Gumminess	Crumbly, crunchy, brittle Tender, chewy, though Short, mealy, pasty
	Viscosity	____	Gummy, thin, viscous
	Springiness	____	Plastic, elasticity
	Adhesiveness	____	Sticky, tacky, gooey

	Class	Popular Terminology
Geometrical Characteristics	Particle size and shape	Gritty, grainy, coarse, etc.
	Particle shape and orientation	Fibrous, cellular, crystalline, etc.

	Primary Parameters	Secondary Parameters	Popular Terminology
Other Characteristics	Moisture content	____	Dry, moist, wet, watery
	Fat content	Oiliness Greasiness	Oily Greasy

Table 2.6 Classification systems of textural properties for liquid foods; adapted from Szczesniak and Kleyn (1963)

Category	Typical Words
Viscosity-related terms	Thin, thick, viscous
Feel on soft tissue surfaces	Smooth, pulpy, creamy
Carbonation-related terms	Bubbly, tingly, foamy
Body-related terms	Heavy, watery, light
Chemical effect	Astringent, buming, sharp
Coating oral activity	Mouth coating, clinging, fatty, oily
Resistance to tongue movement	Slimy, syrup, pasty
Afterfeel-mouth	Sticky
Afterfeel- physiological	Clean, drying, lingering, cleansing
Temperature related	Cold, hot
Wetness- related	Wet, dry

Table 2.7 Mechanical definitions of textural properties; adapted from Szczesniak and Kleyn (1963)

		Physical Properties	Sensory
Primary Properties	Hardness	Force necessary to attain a given deformation.	Force required to compress a substance between the molar teeth (in the case of solids) or between the tongue and palate(in the case of semisolids)
	Cohesiveness	Extent to which a material can be deformed before in ruptures.	Degree to which a substance is compressed between the teeth before it breaks.
	Viscosity	Rate of flow per unit force.	Force required dropping a liquid from a spoon over the tongue.
	Springiness	Rate at which a deformed material goes back to its undeformed condition after the deforming force is removed.	Degree to which a product returns to its original shape once it has been compressed between the teeth.
	Adhesiveness	Work necessary to overcome the attractive forces between the surfaces of the other materials with which the food comes in contact.	Force required removing the material that adheres to the mouth (generally the palate) during food oral processing.
Secondary Properties	Brittleness (Fracture ability)	Force with which a material fractures: a product of high degree of hardness and low degree of cohesiveness.	Force with which sample crumbles, cracks or shatters.
	Chewiness	Energy required masticating a solid food to a state ready for swallowing: a product of hardness, cohesiveness and springiness.	Length of time (in second) required to masticate the sample, at a constant rate of force application, to reduce it to a consistency suitable for swallowing.
	Gumminess	Energy required disintegrating a semisolid food to a state ready for swallowing: a product of a low degree of hardness and a high degree of cohesiveness.	Denseness that persists throughout mastication: energy required to disintegrate a semisolid food to a state ready for swallowing.

2.8.3.2 Texture Evaluation

Since the 1950s food texture has been studied towards the establishment of viable physical techniques and instruments that will allow for the characterisation and quantification of food texture properties. Such reliable objective methods would allow food scientists: to predict consumer's preferences in relation to food products, to design and manufacture food with textures that appeal to a broad range of consumer groups (i.e. aiding the development of food for elderly and dysphagic patients) and also to maintain consistent quality control of the food products during the manufacturing process across multiple manufacturing locations (Wilkinson et al. 2000). Currently various reliable techniques have been established, of which the texture analyser (TA) has been adopted by most research laboratories as well as industry. For example, the compression test is one of the common tests performed using TA. It is a conventional testing method to acquire flow stress (yield stress) data. Generally, cylindrical specimens are compressed and the resulting values for the required force subjected to the reduced height characterise the mechanical properties of the tested materials (Kopp et al. 2001). However, these instruments are not capable of mimicking the varying oral conditions that occur during food oral processing and swallowing as will be discussed in Chapter 2, section 2.9. This enormous variation is due to the dynamic nature of texture perception and the great variance between individual's in food oral processing and swallowing capabilities (Alsanei and Chen 2014, Alsanei et al. 2015, Engelen and Van Der Bilt 2008, Gambareli et al. 2007). Such a discrepancy often leads to low correlations between instrumental prediction and sensory evaluation. Sensory evaluation still proves to be an effective method (favoured by industry) in evaluating food texture. However, this approach has its disadvantages as it is a highly time-consuming and costly process. Furthermore, the sensory outcomes of such tests depends on the panellist's capabilities in transcribing their sensations into words and scores (Boyar and Kilcast 1986).

In order to overcome the aforementioned disadvantages, various physiological techniques have recently emerged providing a means to bridge the gap between objective characterisation and subjective perception. This is achieved by understanding a human's physiological response during oral processing. The recently developed Iowa Oral Performance Instrument (IOPI) is one of the more useful tools that enable to assess the physiological behaviour of tongue and lip strength in relation to swallowing capability of different food/fluid textures. A full review of this tool is presented in Chapter 2, section 2.3.1.1.3.1. Additionally, it was considered as a basis task in this project duo to the major application of this technique in determining an individual's tongue muscle strength (achieved by measuring the maximum isometric tongue pressure in Chapter 3, Chapter 4 and Chapter 5) and also to measure the pressure required for food breaking by combining the texture analyser and IOPI together for compression in Chapter 4.

2.8.4 Flow Behaviour Classifications of Fluid

2.8.4.1 Newtonian

Since different materials have different relationships between shear stress and shear rate as shown in Figure 2.21. The flow behaviour curve is a plot of shear stress versus shear rate, will therefore be a straight line with slope viscosity (η) for a Newtonian fluid. The flow behaviour of *Newtonian* fluids means that their viscosities are constant when subjected to a change in shear rates (independent of the applied shear rate) and dependent of temperature. It can be mentioned that such fluids have direct proportionality between shear rate and shear stress in laminar flow. The proportionality constant is thus equal to the viscosity measurements of the food material. The viscosity curve, which is a plot of viscosity versus shear rate, will show a straight line at a constant value equal to viscosity. Thus a Newtonian fluid flow behaviour can be defined by a

single viscosity value at a specified temperature (Hatschek 1928, Rao 2007).
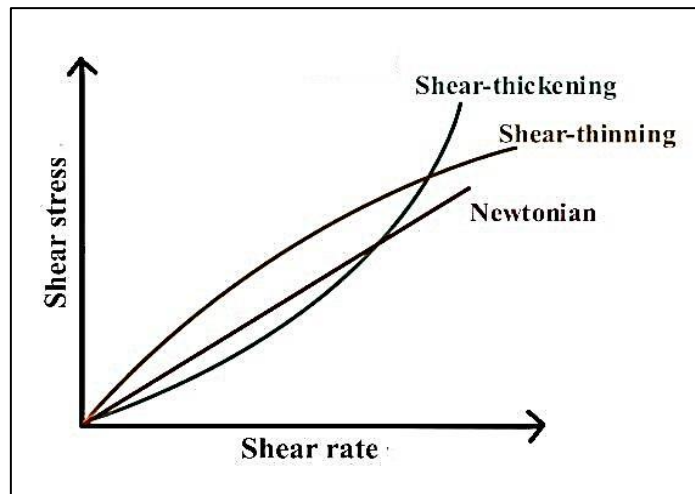
Figure 2.19 Viscosity classification curve of the fluid flow behaviours according to the relationship between the shear stress and shear rate (Steffe 1996)

2.8.4.2 Non-Newtonian

Materials which cannot be defined by a single viscosity value at a specified temperature and range of shear rates are called *non-Newtonian* flow behaviours. The viscosity of these materials must always be stated together with a corresponding temperature and shear rate. If the shear rate is changed the viscosity will also change. In general, a high concentration and a low temperature can increase non-Newtonian behaviour (Layec-Raphalen and Wolff 1976). Apart from being shear rate dependent, the viscosity of non-Newtonian fluids may also be time dependent, in which case the viscosity is a function not only of the magnitude of the shear rate but also of the duration and, in most cases, of the frequency of successive applications of shear (Vrahopoulou and McHugh 1987). Non-Newtonian materials that are time independent are defined as *shear-thinning*, *shear-thickening* flow behaviours (Figure 2.21).

2.8.4.2.1 Shear-Thinning

The viscosity of a shear-thinning flow behaviour (known as *pseudoplastic*) decreases as the shear rate increases. Majority of liquid food systems belong to this category of fluids. The shear rate dependency of the viscosity can differ substantially between different products, and also for a given liquid, depending on temperature and concentration. The reason for shear thinning flow behaviour is that an increased shear rate deforms and/or rearranges particles, resulting in lower flow resistance and consequently lower viscosity. Typical examples of shear-thinning flow behaviour fluids are gels, juice concentrates, thickeners and salad dressings. It should be noted that although sucrose solutions show Newtonian behaviour independent of concentration, fruit juice concentrates are always significantly non-Newtonian flow behaviour (as shown in Chapter 5).

2.8.4.2.2 Shear-Thickening

The viscosity of a shear-thickening fluid shows the opposite type of behaviour to pseudoplastic systems. It exhibits *dilatant* flow behaviour. As the shear rate increases, it gives rise to increasing apparent viscosity. Typical examples of a shear-thickening system are wet sand and concentrated starch paste. This type of flow behaviour is relatively uncommon, but found among suspensions of very high concentration (Bourne 2002).

2.8.4.2.3 Viscoelasticity

Studying the mechanical behaviour of food materials is complicated by the fact that their response is viscoelastic, intermediate between that of solids and liquids. Dynamic shear rheological properties (oscillation) is a standard experimental of rheological characterisation for studying such behaviour because by varying the amplitude and frequency of the applied

strain, a wide range of timescales and behaviours can be studied (Anseth et al. 1996, Larson 1999, Macosko 1994, Steffe 1996). Therefore, oscillatory measurement provides new insights about the physical mechanisms that govern the unique mechanical properties of soft materials. In this work, we limited our discussion to small amplitude experiments within the linear viscoelastic region (LVER) which allows an investigation of food sample responses without disruption of their structures. More information regarding LVER, small amplitude oscillatory shear and moduli of storage (G') and loss (G'') are presented in Chapter 5.

2.8.4.3 Apparent Viscosity

Apparent viscosity (η_{app}) is known as a one-point test. Since the shear rate of Newtonian fluid is directly proportional to the shear stress. A single point measurement is adequate to establish specific viscosity for the flow characteristics of a Newtonian fluid. For non-Newtonian fluids, apparent viscosity term implies a Newtonian fluid type measurement on a non-Newtonian fluid as many of these fluids exhibit nearly linear shear stress-rate behaviour at low shear rates. This behaviour is known as the 'Newtonian regime' (Bourne 2002). The apparent viscosity of food samples was the basis measurement in Chapter 3 and Chapter 5.

2.9 Limitations of Objective Measurements

In practice, instrumental tests do not always produce results which correlate well with sensory evaluations. This is due to the fact that instruments measure the physical properties of materials; they do not directly measure the sensory properties of bolus rheological properties experienced by the consumer during swallowing. In an effort to improve the correlation between objective measurements and sensory results, it is important to carefully set up the test in order to mimic the conditions found in real oral processing. Some factors obtained from literature and

some of these are valid in the current study that have rarely been considered in instrumental evaluations and are expected to be of significance are:

- **Mechanical Properties of Biological Tissues**

The mouth comprises of different types of tissues ranging from hard (teeth) and soft (oral mucosa) tissues. The latter possesses the ability to deform unlike the rigid probes used by the instrument. The mechanics of a system including soft deformable tissue must be considered. This is difficult to do with hard steel probes (Kohyama and Nishi 1997, Peleg 2006).

- **Temperature**

The temperature within the mouth typically tends to be a few degrees below the central body temperature (37 °C). The average range oral temperature in an adult is around 33.2 °C to 38.2 °C. This is mainly due to the mouth radiant, conductive and convective heat change occurs whilst the mouth is open. When food is introduced, the mouth undergoes a small change in its temperature which may lead to a change in bolus physical behaviour as illustrated in Chapter 5. No marked changes in temperature are assumed in the mouth within short periods of oral processing of ready-to-swallow bolus. However, there are some food products which are highly susceptible to fluctuations in mouth temperature such as gelatine, gel, chocolate, concentrated juice, margarine and ice cream which melt in the mouth (Ekberg et al. 2010, Engelen et al. 2003). Typical methodologies for instrumental tests thus involving the introduction of the sample leaving it to reach thermal equilibrium before the execution of the test (Rosenthal 1999).

- **Saliva**

Once food has entered the mouth, it is comminuted by the mastication process, which allows for a modified food texture promoting safe and efficient swallowing. As this breakdown proceeds, the coupling of

mechanical, thermal and chemical reactions as well as lubrication by saliva, leads to food bolus formation (Hutchings and Lillford 1988). For instance, mixing food with saliva has not only a diluting effect but also the amylase present in saliva catalyses the hydrolysis of starch into smaller carbohydrate molecules (e.g. maltose and glucose). By hydrolysing the starch of semisolid foods into sugar molecules the starch loses its ability to bind to water resulting in a decrease of a product's viscosity (Dunnewind et al. 2003, Engelen and Van Der Bilt 2008, Nordbö et al. 1984, Sakamoto et al. 1989). Generally, food oral process involves a combination of factors such as the threshold of bolus size distribution and lubrication (Lillford 2000), food type (i.e. solid) where its influence rather depends on the particle size reduction (Peyron et al. 2004) and lubrication and hydration (Bongaerts et al. 2007). Though all these studies suggest the interaction of saliva during food oral processing, this research project considered bolus swallowing as the ready-to-swallow bolus type. During swallowing, the subject was asked to allocate tested food at the posterior one-third of the tongue as it is medicine syrup in order to limit the time for the bolus to stay inside the oral cavity and to minimise saliva mixing and viscosity changes (Figure 5.5 in Chapter 5).

- **Food Samples**

Food is not a system in equilibrium. Therefore, its properties depend on the time when it is tested (Kohyama and Nishi 1997). Effects such as heat transfer and rates of hydration must be considered as factors that influence bolus during swallowing when performing measurements. Additionally, most food is heterogeneous and as a result the mechanical properties can vary significantly with the direction on which the force is being applied (van Vliet 2002). Application of force by most instruments during instrumental tests is confined to be uniaxial.

2.10 Thesis Summary and Literature Gaps

In the present chapter, current status of the literature had been further reviewed. As a summary, the food oral processing especially bolus swallowing studies have become more attractive to researchers in particular defining the terminology, measuring the physical and mechanical parameters of foods, and also understanding the relation between bolus swallowing and oral physiological measurements. This area of oral processing is researched mostly from a clinical point of view and thus knowledge in oral processing from sensory view point is currently limited. The investigation included a detailed evaluation of some existing clinical researches which were then extended using relevant techniques (such as MITP, oral volume, oral residence time). As a result, this chapter included a detailed evaluation of some existing clinical researches which were then extended using relevant techniques (such as MITP, oral volume, oral residence time). It has also led to the development of interesting new techniques to subjectively study bolus swallowing using relevant sensory approaches in healthy adults. Few examples are:

o Studying ready-to-swallow food samples (eliminating other oral processing parameters, such as salivary flow, influence of teeth)

o Using MITP measurements to study tongue only-food breaking systems

o Designing the perceived bolus flow behaviour study using trained sensory panel (training on video-fluoroscopic sheet), relating not only rheology but also individual food characteristics (such as sugar content, type of food) to swallowing perception.

Furthermore, this project designed to answer several questions as fallowing:

- What are the knowledge limitations in food oral processing from sensory view point? (Chapter 2, 3, 4 & 5)

- What are the bolus attributes that can be tested? (Chapter 2)

- How to characterise the physical properties of the bolus? (Chapter 2)

- Which methods can be used for measuring individuals' oral physiological capabilities and the mechanical property aspects of bolus swallowing? (Chapter 2, 3 & 5)

- What are the limitations of sensory perception of bolus (e.g. perceived ease of initiating swallowing, ease of break-swallow, bolus flow)? (Chapter 2, 3 & 5)

- Dose the initiating bolus flow depend on the tongue pressure to be at least matched by an individual's capacity? (Chapter 3)

- What is the relationship between individuals' oral physiological capabilities (MITP and oral volume) and gender and age? (Chapter 3)

- What is the relationship between individuals' oral physiological capabilities (MITP) and the perceived ease of initiating bolus flow? (Chapter 3)

- What is the relationship between individuals' oral physiological capabilities (MITP) and sensory perception of bolus manipulations (ease of food oral breaking)? (Chapter 4)

- Does the tongue muscle strength reflect one's capability in food oral handling and manipulation, e.g. food breaking without teeth involvement? (Chapter 4)

- To what extend proper matching between one's oral physiological capability and the textural properties of food is critically important to ensure safe food consumption by vulnerable consumers? (Chapter 4)

- Can healthy subjects report their subjective ease/difficulty when they break foods of different viscoelastic and pasty systems? (Chapter 4)

- What is the relationship between individuals' subjective ease/difficulty food oral breaking and their MITP? (Chapter 4)

- Can we measure the intra-oral pressures applied when breaking these foods *in vitro* and *in vivo* and then correlate it with the mechanical characterisation these foods? (Chapter 4)

- What is the relationship between individuals' oral physiological capabilities (MITP) and perceived ease of swallowing? (Chapter 5)

- What is the relationship between individuals' oral physiological capabilities (MITP) and perceived bolus flow behaviour? (Chapter 5)

- How the bolus flow behaviour can be subjectively measured by individual's MITP? (Chapter 5)

- How applicable is your method of tongue pressure measurement during swallowing particularly for elderly individuals, dysphagia patients? Can such method be utilized for food swallowing? (Chapter 4 & 5)

These listed questions will be answered in following chapters. Such information presented in this project could be a bridge between oral and food sciences, and also could be of interest to R&D researchers in both food manufacturing and pharmaceutical industries in trying to understand individuals' physiological capability of swallowing and the implications for food provision.

Chapter 3 Studies of the Oral Capabilities in Relation to Bolus Manipulations and the Perceived Ease / difficulty of Initiation Bolus Flow

3.1 Introduction

The tongue pressure generation plays a crucial role in propelling boluses through the oropharyngeal cavity. Therefore, the tongue has become the subject of intense attention resulting from its role in creating a pressure gradient that facilitates bolus flow (Clark and Solomon 2012, Kieser et al. 2011, Stierwalt and Youmans 2007, Yoshida et al. 2006). It has been also accepted that, during the tongue-palate compression, the tongue and its movements generate a pressure that squeezes a ready-to-swallow bolus in order to flow into the pharynx and then the bolus is pushed the further down into oesophagus by peristalsis waves (continuous rhythmical muscle contractions). The complexity and the dynamic nature of bolus swallowing and flow can be seen by recent numerical simulations and experiments for bolus tests (de Loubens et al. 2010, Nicosia 2013, Sonomura et al. 2011).

In relation to safely consumption and comfortable swallowing, bolus rheology and individual's oral physiological capability have been recently emphasised for their roles in triggering bolus flow (Nishinari 2009). Linden et al. (1989) and Saitoh et al. (2007) also suggested that bolus rheological properties are very important parameters for both the initiation of bolus flow and the ease of swallowing, not only for healthy individuals but more for vulnerable patients. One recent study involving various types of liquid foods with different consistencies confirmed the critical importance of bolus rheology in triggering bolus flow (Chen and Lolivret 2011). Findings established the positive correlations between the rheological parameters (i.e. the bolus flowability and stretch-ability) and

individuals' reported ease swallowing. It is currently common practice to use starch-based thickening agents in the clinical management of dysphagia in order to modify the physical properties of liquids for a safe swallow (Germain et al. 2006, Matta et al. 2006). Nevertheless, there is a general lack of understanding concerning the underpinning principles governing the initiation of bolus flow. More specifically, it is not clear what role the tongue plays in bolus flowability with respect to adjusting pressures to suit the properties of the bolus.

This chapter is motivated by the idea that bolus flow depends on two sets of conditions which are the oral physiological conditions (e.g. MITP) and the mechanical properties of the bolus (e.g. flow, rheology, and perceived ease / difficulty of initiation swallowing). As a minimal requirement for comfortable swallowing, the coordination of these two sets of conditions has to be properly matched. Resulting in that the tongue pressure required initiation of different boluses to flow through oropharyngeal track has to be at least matched by the oral tongue pressure produced by the swallower. In order to investigate the relationships between these parameters, five experimental tasks were designed and performed in this study. Each task was aimed as following: Task 1 and Task 2 aim to examine the influence of gender differences and age on MITP generation capacity using the IOPI and also compared participant's MITP with their maximum capacity of oral volume (i.e. cheek tension strength). Such comparison is not exist in previous literature between these two parameters across gender and age group; Task 3 aims to determine the optimum bolus size for comfortable swallowing to be used in the rest of the sensory tests for future investigation; Task 4 aims to measure tongue pressure generated during swallows of saliva and 12 ml water only using only the IOPI; and Task 5 aims to explore the relationship between individuals' MITP and the perceived ease / difficulty of initiating bolus flow. This investigation will be carried out to use ready-to-swallow bolus and to correlate between subjective ease or difficulty in

swallowing food bolus of different consistencies and their MITP in order to provide relevant information for designing food for vulnerable population.

3.2 Materials and Methods

3.2.1 Subjects

Healthy males and females of different ages and varied social/cultural backgrounds were recruited for these tasks as follows, 106 subjects for Task 1 and 2, 43 subjects for Task 3, 10 subjects for Task 4 and 21 subjects for Task 5. For the last three tasks, subjects who had previously participated in Task 1 and were familiar with the purpose and procedure, were invited to participate based on their MITP strengths thus a wide range of tongue pressures could be covered. The aims of Task 1 and 2 were to have large sample sizes for population statistics when compared with Task 3, 4 and 5. For Tasks 3, 4 and 5 were designed for smaller sample sizes in order to achieve specific aims.

For all tasks, subjects were screened for not suffering from any dysphagic symptoms. All subjects were non-smokers and were self-assessed as capable of independent living. They were either recruited from Leeds university campus or from local communities. During the first part of second task, subjects were involved in the measurements of MITP and the oral volume capacity. Before each test, a brief instruction of the overall purpose of the study, the test procedures, how long it would take, and what would be recorded during the test were given to the subjects. A consent form was signed by each subject before taking part in this study. Ethical approval was obtained from the Faculty Ethics Committee (FEC) at the University of Leeds. All experimental procedures were in accordance with the rules and regulations set by the University of Leeds.

3.2.2 Food Sample Preparations

For instrumental and sensory panel experiments, Smash (brand: Instant Mashed Potato (produced by Premier Foods PLC, UK)) used in Task 5 and ready-to-serve custard used in Task 3. Both materials were commercial products purchased from a local supermarket (Morrisons, Leeds, UK). Commercial food thickening agents in their powder form (Resource ThickenUp, Nestle, Nutrition, Germany) were purchased from a local pharmacy shop (Boots, UK). As shown in Table 3.1, modified starch (MS) solutions were thickened up by Resource ThickenUp to various consistencies to be used in Task 5, mixed for 4-5 minutes (until the powder had completely dissolved) and were consumed immediately to reduce the effects of temperature variability and time on the viscosity. Whereas, mashed potato (MP) samples of different consistencies as shown in Table 3.1 were made from mashed potato powder according to the, 'manufacturer's' guidelines.

3.2.3 Steady Shear Rheological Properties

The steady shear viscosity of these samples was measured by a Kinexus rotational rheometer (Malvern Instruments Ltd, Gloucestershire, UK). A cone-plate geometry CP2/60 (60mm diameter and 2° angle cone) was used for flow behaviour tests. Each sample was measured in triplicate. Table 3.1 shows the average apparent viscosity profiles as a function of a constant deformation (50 s^{-1}) and room temperature for 20 minutes. The idea of these concentrations (a range of apparent viscosities for mashed potato and modified starch samples) is to cover a range of viscosities and also to give a reasonable discrimination between the consistencies during sensory test of Task 5.

Table 3.1 Average apparent viscosity (Pa.s) and concentration (%) for both mash potato samples and modified starch thickened solutions coded from (1-8)

Sample code	Mash potato samples		Modified starch solutions	
	%wt/wt	Pa.s	%wt/wt	Pa.s
1	7.0	1.3	3.0	0.10
2	10	2.5	4.0	0.30
3	12	2.9	5.0	0.90
4	14	3.0	5.6	1.3
5	16	5.0	6.0	1.7
6	18	11.2	7.0	3.2
7	20	13.1	8.0	5.4
8	24	15.6	10	7.9

3.2.4 Experimental tasks

3.2.4.1 MITP Measurements (Task 1)

The Iowa Oral Performance Instrument (IOPI) device (IOPI Model 2.2, Medical LLC, IOPI Medical, Carnation, WA, USA) is a medical device available for studying tongue strength (i.e. tongue pressure production) during swallowing. Measurement procedure is discussed in Chapter 2 section 2.3.1.1.3.1.
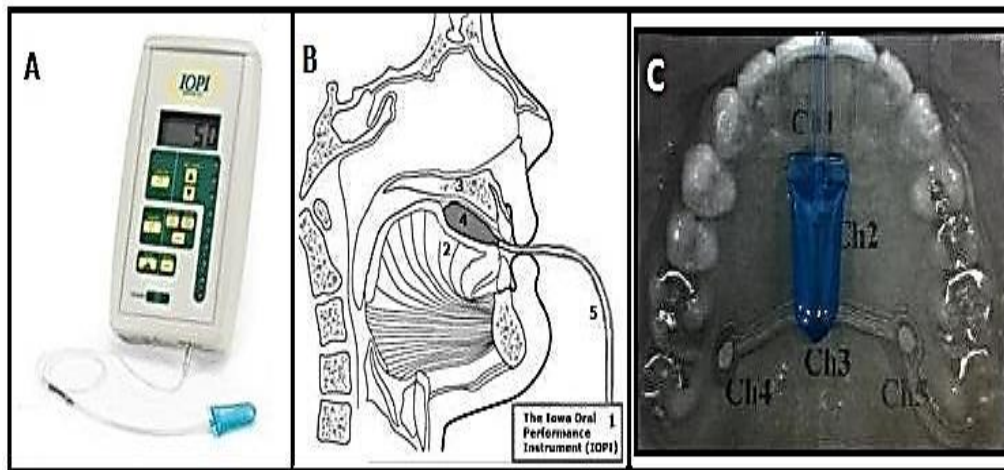
Figure 3.1 Illustration of the IOPI set-up for the tongue pressure measurement against the hard palate during maximum tongue generation and swallowing pressure; (A) IOPI device (B) measurement set-up: (1) IOPI (2) the tongue; (3) the hard palate; (4) the bulb inside the oral cavity and (5) the connecting tube (C) the location of the air-filled bulb during measuring MITP using IOPI. Described by figure used in the study of Tamine, *et al.* (2010); the bulb head located where is CH3: posterior median part; the bulb middle part, CH2: the mid-median part; the bulb end part was 2cm behind the front teeth where is CH1: anterior median part

In Task 1, the MITP of 106 healthy volunteers was measured (71 females with mean age of 49 ± 21 years and 35 males with mean age of 50 ± 23 years). To start this task, subjects were asked to sit naturally to avoid any physical strain and body stress. Following the picture provided in Figure 3.1A and B, subjects were trained to hold the IOPI bulb between the tongue and the hard palate and press as hard as possible with lip closure. The flat portion of the bulb was positioned 2 cm behind the participant's front teeth, as illustrated in Figure 3.1C. During the test, subjects were not able to view the LCD transmitter screen and data was recorded for five times to provide reliable pressures across repeated measurements for each subject on the same day. A short rest period of 30 seconds to 1 minute was given between measurements. The mean values were defined as maximum isometric tongue pressure (MITP). Their MITP were compared with their maximum oral volume in Task 2. Such

comparison is not exist in previous literature between these two parameters across gender and age group

3.2.4.2 Maximum Oral Volume Capacity (Task 2)

Task 2 aimed to measure the maximum oral volume (MOV) capacity. The purpose of this task was to assess the buccal muscular strength (i.e. cheek) as a likely reason to explore the possibility of age-related changes in the oral capacity of food handling. This was achieved by asking subjects to 'drink' water (without swallowing) from a cup and hold as much water as possible inside the mouth (whilst filling their cheeks). Subjects were then instructed to spit the water into a waste container. The cup initially contained 150 ml water and the remaining amount of water in the cup after drinking was then measured. Thus the MOV capacity was measured in ml as the difference between the initial volume (150 ml) and the remaining volume in the cup. This procedure was performed once for each subject.

3.2.4.3 Optimisation of the Bolus Size (Task 3)

Task 3 was designed to determine the natural comfortable swallowing volume. Two separate tests were conducted for this purpose: swallowing various amount of ready-to-serve custard (g) and sips of water (ml). For the former, the test was conducted in 43 healthy panellists aged between 22 years and 51 years (27 females and 16 males). As shown in Figure 3.2, task was designed by increasing the custard volume in spoons from 1 to 10 grams consecutively for each subject (Figure 3.2). The consistency of ready-to-serve custard used in this test was 1.5 Pa.s at shear rate of 50 s^{-1}. Based on this apparent viscosity value, the viscosity of this product falls within the range of honey-like consistency as categorised by the National Dysphagia Diet guidelines (NDD) published by American Dietetic Association for thickened dietary supplements (National-Dysphagia-Diet-Task-Force and American-Dietetic-Association 2002). Subjects were seated in an upright normal

position and a try consisted of 10 samples of custard were provided to the subject for self-feeding. Subjects had to follow specific instructions when swallowing the samples by placing each sample toward the middle-back of the tongue to facilitate bolus swallowing as when he/she swallows medicinal syrup. This approach of swallowing was designed to minimise the oral stay and oral exposure of the food so that the bolus swallowed had similar properties to that of food (detailed description is presented in Chapter 5, section 5.2.4.2.1). After each swallow, subjects were asked to validate the swallowing in categories of either, "too little", "little", "naturally comfortable swallowing", "too much", not comfortable", and finally "too much" which required 2 swallows. Subjects' decisions were based on the discretion of the natural comfortable swallowing volume when whole bolus is leaving oral structure substantially clear of residue within the mouth. This size of bolus will be used for further swallow studies. However, subjects were not asked to comment on taste and flavour or sensory preference. For all tasks, water was provided for subjects to rinse their mouths between evaluations and rest periods were given when needed.

Figure 3.2 Increasing the ready-to-serve custard sample size from 1 gram to 10 grams

3.2.4.4 Tongue Pressure Measurement during Swallowing (Task 4)

Task 4 was completed by 10 healthy subjects (6 females and 4 males; ageing between 24 and 56 years; average age: 36 ± 13 years). The average amount of sipped water for one comfortable swallow was determined by recording the difference (in weight) between the original volume of water (150 ml) prior to swallowing and the amount of water remaining after swallowing. Each subject performed five swallows and an average value was taken. MITP, pressures applied during the normal swallowing of saliva and the swallowing of 12 ml of water were also determined. MITP of the subjects were recorded five times using IOPI. Subjects were asked to swallow their saliva and 12 ml water while IOPI bulb in position that illustrated in Figure 3.1C. A short time from 30 seconds to 1 minute to rest was given between each swallow in order to regenerate saliva in the mouth. The objectives of Task 4 were to measure tongue pressure generated during swallows of saliva and 12 ml water only using one-bulb of the IOPI device, to compare intra-oral pressures when swallowing water and saliva boluses with their MITP, and finally to identify the differences between the applied tongue pressure for bolus swallowing and the MITP using one-bulb of the IOPI which scientifically refer to as the 'tongue-pressure functional reserve'.

3.2.4.5 Food Swallowing Capability (Task 5)

21 healthy subjects of both genders (9 females and 12 males) ageing between 24 and 80 years were invited to participate in a sensory swallowing experimental task. For this investigation, two food sets of ready-to-be-swallowed boluses were produced in a non-randomised design with increasing concentrations of mashed potato (MP) samples and modified starch (MS) thickened solutions. The concentrations of MP were 7.0, 10, 12, 14, 16, 18, 20 and 24 percentages; and MS thickened solutions were 3.0, 4.0, 5.0, 5.6, 6.0, 7.0, 8.0 and 10 percentages. The viscosity profiles for each concentration are shown in Table 3.1. From

Task 3 and 5, five gram bolus size was chosen for each bolus as this volume considered to be the most comfortable swallowing volume. Each tray consisted of 8 tea spoons coded from 1 to 8 referring to increasing concentration (%) and apparent viscosity grade (Pa.s) of the boluses. Samples were presented on spoons and displayed in a tray. Subjects were asked to swallow each sample as if it were medicine syrup. This way of swallowing has been described more clearly in Chapter 5. They were also asked to assess the bolus flowability by reporting the perceived ease or difficulty of swallowing each bolus. In the associated questionnaire, a table categorised with, "easy to swallow", "moderate to swallow", "difficult to swallow", and "very difficult to swallow" was used to rate the perceived difficulty of bolus flow for each sample. The viscosity level at which the participant reporting, "difficult to swallow" was then recorded in order to correlate with their MITP measurement.

3.2.5 Statistical Analysis

Summary of statistics such as mean and standard deviation values for age, MITP and MOV variables were calculated using SPSS 19. The median and interquartile range (IQR) was used as a score for the comfort level of swallowing custard as these scores were not normally distributed for males and females. The correlations between the physiological parameters (MITP and MOV capacity) were assessed using nonparametric Spearman's rank correlation coefficient. Differences between age and genders groups were evaluated for MITP and MOV respectively using Mann-Whitney U test. Correlations were found between the maximum consistency bolus swallowed with reported ease for the MP and MS thickened liquid samples and participant's MITP measurement using Spearman's rank correlation coefficient.

3.3 Results and Discussions

3.3.1 MITP

The function of the tongue strength is defined as the tongue muscle capability that exerts as a form of force during oral food processing. It is not known how much tongue strength is exerted by individual to accomplish certain important functions such as bolus swallowing. However, it is generally believed that the bolus of high viscosity requires somewhat more tongue force (strength) for clearing the oral cavity (Nicosia et al. 2000) and relatively higher levels of tongue strength is required for swallowing than the one required for producing speech (Barlow and Abbs 1986, Searl 2003). Therefore, tongue strength is one of the important oral physiological parameters to determine and document the individuals' MITP before swallowing tests.

In Figure 3.3, MITP is plotted as a function of age for both males and females. Obtained results give a general profile of MITP across populations for age groups and both genders. Careful analysis of the data distribution reveals a few important facts. Firstly, the maximum isometric tongue pressures are rather scattered in general. The range of the MITP is relatively large ranging from 10 kPa to 70 kPa. Secondly, the MITP profile seems to be very similar for both males and females (48 ± 14 kPa and 42 ± 11 kPa respectively with the *p-value* = 0.022). Table 3.2 summarise the average results and standard deviations of two age groups for both genders. Average MITP shows no statistical significance with the *p-value* < 0.05 between the two genders across the age groups. Thirdly, the ageing effect on the MITP is somewhat difficult to determine. In our study, an obvious pattern seems to emerge if populations are divided into two age groups: adult group (ranging between 22 to 64 years) and old age group (≥ 65 years). The MITP for the former scatters almost in a horizontal band, while a downwards distribution is clearly visible as age increases for the older subjects. This suggests that for elderly people (≥

65 years), ageing has a clear negative effect on their tongue pressure generation capability. The average MITP for the older group is significantly lower when compared with the younger age group (35 ± 11 kPa and 48 ± 10 kPa respectively with the *p*-value < 0.001).
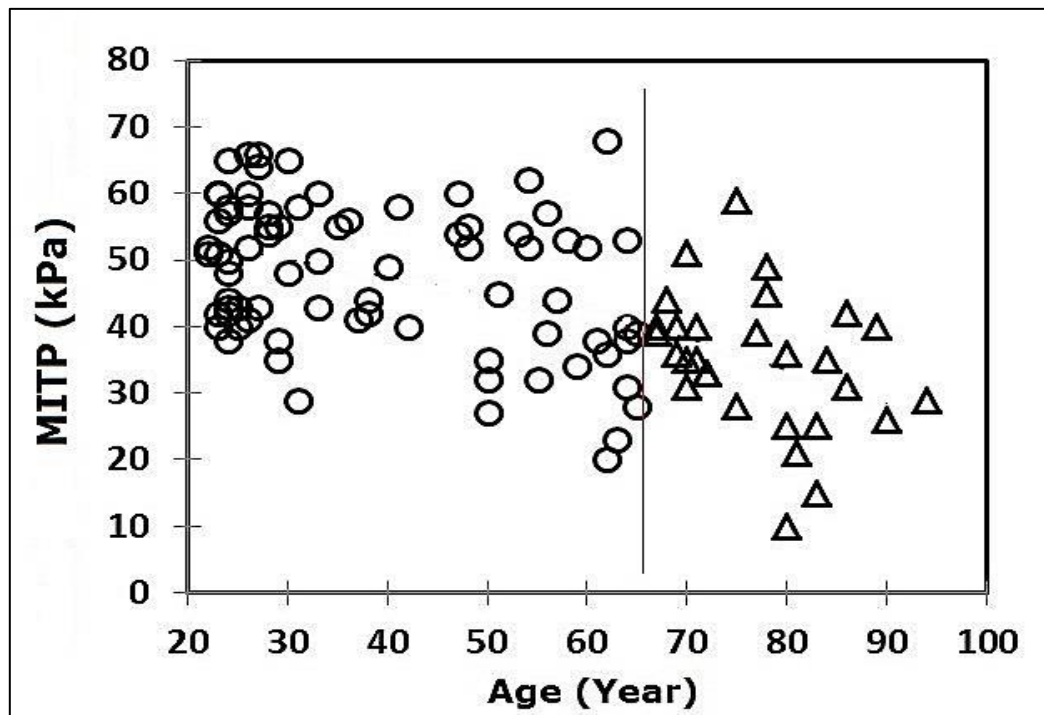
Figure 3.3 MITP performance of individuals as a function of age for both males and females ageing between 22 and 94 years). (**O**) Adults aged between 22 and 64 years and (△) old group aged 65 and over; r-squared values = 0.14 and 0.08 respectively. The red line is only to direct the reader eyes

From Table 3.2, it can be noted that the average MITP for different age groups in this study agrees well with Utanohara et al. (2008) who reported that average tongue pressure was about 50 kPa for young healthy adults and around 32 kPa for those in their 70s. On the other hand, indicated that a pressure of up to about 10 kPa in the midline of the tongue when the tips of the tongue thrusts against the anterior teeth (Ferguson 2006). The wide variation of MITP could be due to many different reasons. In literature, tongue pressure is often interchangeably used with the oral pressure even though the two terms could have different physical meanings and be measured by different

techniques/methods. Another important reason for tongue pressure differences could be due to the location of the pressure measurement. It has been indicated that the pressure at varying locations of the tongue will be different, highest in the anterior part, medium in the middle part, and lower in the posterior part (Ono et al. 2004). In this work, the maximum pressure was measured by pressing the tip of the tongue as firmly as possible to the anterior part of the hard palate which assumed that this process should be at the location of the highest pressure inside the oral cavity (Figure 3.1C).

Table 3.2 Average and standard deviation of the oral physiological properties (the maximum isometric tongue pressure (kPa) and the maximum oral volume (ml)) for both males and females in two age groups

Factors	N	Female N=71	Male N=35	Age group Year	N	Female	Male	Average
Maximum Isometric Tongue Pressure	106	42 ± 11	48 ± 14	< 65	77	45 ± 11	55 ± 9.0	48 ± 10
				≥ 65	29	36 ± 9.0	33 ± 13	35 ± 11
Maximum Oral Volume	106	68 ± 20	80 ± 21	< 65	77	74 ± 19	88 ± 17	81 ± 18
				≥ 65	29	51 ± 13	64 ± 19	58 ± 16

3.3.2 MOV Capacity

The maximum oral volume (MOV) capacity of an individual was measured by how much water can be contained inside the oral cavity. Since water is able to fill up every little corner space, the measured oral volume should represent the maximum void space of the oral cavity. Once a subject is asked to hold as much water as possible without swallowing or spitting, the subject has to seal off the pharyngeal opening, the nasal opening, the lips, and at the same time, expand the oral cavity by stretching out the side cheeks. In doing so, one has to have appropriate muscle strength and control of various orofacial muscles. For example, the *buccinator* muscles used for the control of cheek stretching (expansion) the *orbicularis oris* muscle for the proper sealing off of lips. Therefore, the MOV capacity of an individual would reflect the strength of relevant muscles as well as the oral geometry.

Figure 3.4 shows the decreasing trend of the maximum oral volume as a function of increasing age for both genders using a simple method as presented in Task 2. Obtained results are summarised in Table 3.2. Though MOV capacity was slightly higher for males (with a mean MOV of 80 ± 21 ml) than the females (with a mean MOV of 68 ± 20 ml), the difference between the two genders was small with no statistical significance (*p-value* = 0.005). On the other hand, the MOV was found to be significantly different between the young and old age groups 78 ± 20 ml for the young (22 to 65 years) and 56 ± 16 ml for aged groups (> 65 years). The difference was statistically significant for both genders using the Mann-Whitney test (the *p*-value = 0.005). The young male group had an average of 88 ± 17 ml against only 64 ± 19 ml for the older male group. However, the young female group had an average of 74 ± 19 ml against only 51 ± 13 ml for the old female group. If all subjects are divided into two age groups as shown in Table 3.2, the adult group (22 to 64 years) had a mean MOV of 81 ± 18 ml, whilst the old age group (≥ 65

years) had a significantly smaller mean MOV value of only 58 ± 16 ml with the *p-value* < 0.001.
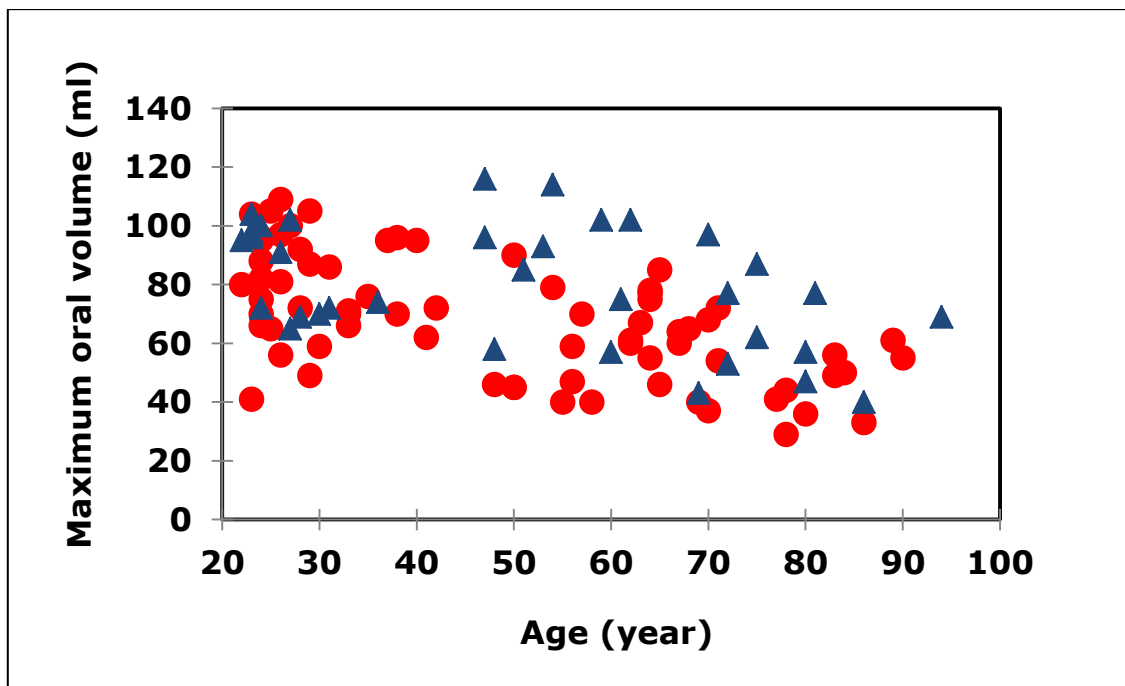
Figure 3.4 Maximum oral volume (MOV) capacity as a function of age for both males and females ageing between 22 and 94 years. (•) refers to females and (▲) refers to males; with r-squared values = 0.37 and 0.21 respectively

In terms of age-related changes, ageing seems to have very similar effects for both males and females on the capability in creating the MITP and the MOV by holding the large amount of water inside the mouth (Figure 3.4). In the young age group for both genders, the MOV appears to be in the same level of capacity, whilst the MOV for old subjects in both genders clearly declines as the impact of longevity, reflecting the weakening of the tongue muscles as well as other orofacial muscles, specifically the buccal muscular strength as a result of the natural ageing process. This pattern has a close similarity to that shown in Figure 3.3.

From Table 3.3, the Non-parametric Spearman's rank correlation coefficient gave a negative correlation between age and tongue pressure (for females −0.50 and males −0.62) as well as age and oral volume (for females −0.59 and males −0.47). During the test for old group, it was

clearly observed that some subjects dripped water from their mouths, indicating poor sealing of the oral cavity due to weakened orofacial muscles.

Table 3.3 Correlations obtained from non-parametric spearman's correlations between age, MITP and MOV for both males and females

Correlations	Male	Female
Age versus MITP	−0.62	−0.50
Age versus MOV	−0.47	−0.59

In order to compare MITP and MOV of individuals' capacity, Figure 3.5 is plotted for the two age groups (adult and old) and genders. The correlation between the two physiological factors is observed. Adult group had a distribution within a square of around 120 ml and 70 kPa (the light grey square). However, the old group have much compressed distribution within the range of only around 80 ml and 50 kPa, as shown by a dark grey square in the lower left corner in the same figure. Ageing seems to reduce the physiological capability of tongue strength and orofacial muscles in the old group. Therefore, elderly individuals will have significantly reduced functional muscle reserve in the tongue and orofacial muscles as a result of sarcopenia, or the deteriorating loss of tongue thickness and strength (Doherty 2001, Robbins et al. 2005, Tamine et al. 2010a). Age-related weakening of tongue and orofacial muscles seems to reduce an individual's capability of eating and oral handling of food.
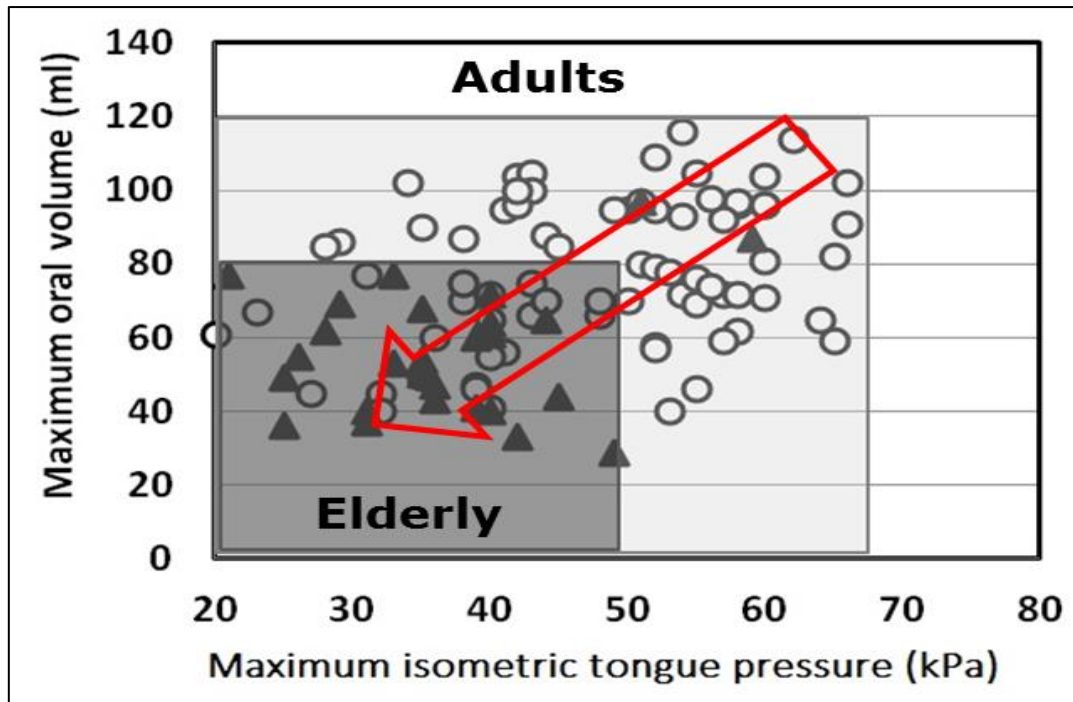
Figure 3.5 Correlation between the maximum isometric tongue pressure (MITP) and the maximum oral volume (MOV) capacity for both genders of (O) adult group and (▲) elderly group

3.3.3 Optimisation of the Bolus Size

The capability of individuals in dealing with the bolus size is another important factor for eating and swallowing research studies. In terms of bolus consistency, there are two different scenarios, a bolus of liquid drink and a bolus from chewed solid (or semisolid) food. For the former, the comfortable size (volume) of liquid bolus can be conveniently determined by monitoring the amount of water sipped during a single swallow. It was reported that the frequently sipped water volume reaches roughly 10 – 12 ml during natural drinking conditions (Macrae et al. 2011). In this task, 10 healthy subjects (4 males and 6 females) were invited to sip water from a pre-weighted cup of 150 ml for natural drinking and swallowing whilst recording tongue pressure generation for a swallow using IOPI. By weight difference, the amount of sipped water was then determined before and after each drink. It was found that the water average amount for one comfortable swallow was on average 14 ml (16 ml for females and 12 ml for males) which is slightly higher than that observed by Macrae et

al. (2011) and Bennett et al. (2009). This difference between the two experimental studies is relatively small and is probably acceptable. However, the difference observed between males and females is slightly surprising. It is not apparent what causes this difference and how important this difference is. Finding from a prior study by Lawless et al. (2003) could be used to explain these slight differences in the amount of water. They reported that the water-sipping volume increases as the cup size increases.

On the other hand, individuals have a much lower capability in dealing with solid or semisolid food. When consuming a mouthful of food, individuals would normally need at least two or more interval swallows (van der Bilt 2012). However, there is so far no literature data about the exact size of a food bolus one can swallow due to the practical difficulty in collecting real boluses (this is due to the fact that orally chewed food particles are normally moved and cumulate at the back of the tongue surface and become non-recoverable). In this work, ready to consume custard samples with apparent viscosity of 1.5 Pa.s in various amounts were fed to healthy subjects. They were asked to swallow the food with a minimal oral exposure and were then asked whether the amount of the food was "too little" or "too much" for a natural comfortable swallow. Results are summarized in Figure 3.6, where the percentage of subjects is plotted against the optimum bolus size.

The normality test shows that the comfortable level of swallowing for males and females with median ± interquartile range (IQR) (5 ± 3) (mean: 5.72; SD: 1.89) are following normal distribution and the p-value (1.00) of Shapiro-Wilk normality test confirms the normality of this data. Thus, since the highest percentage of subjects felt that a bolus amount of 5 gram would be the most comfortable level for a natural swallow. This size of bolus was considered for further swallow studies in this work and also in Chapter 3 and Chapter 5.
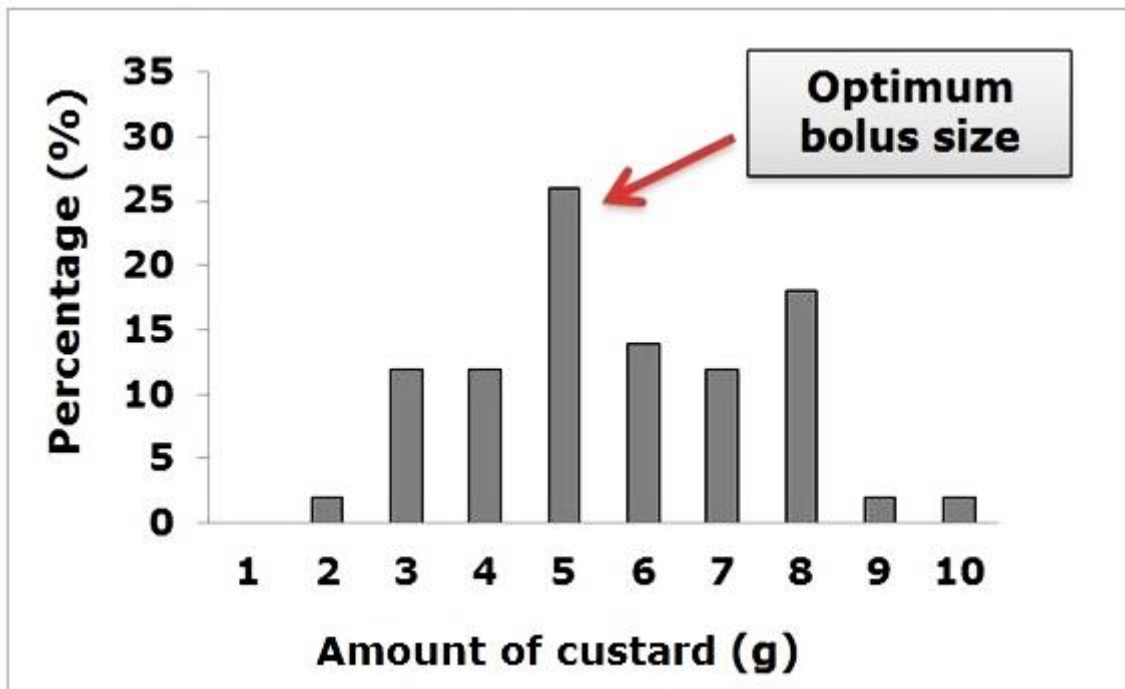
Figure 3.6 Percentage profile of custard bolus amount for naturally comfortable swallow

3.3.4 Tongue Pressure Generation during Swallowing

A number of studies has been evaluated the tongue pressures generated during swallowing by using different types of boluses such as saliva, thin liquid, honey-thick liquid, semisolid and solid boluses. It was reported that the tongue pressure required to swallow honey-thick liquid was relatively higher than that for thin liquids (31.4 kPa and 29.5 kPa, respectively) (Youmans and Stierwalt 2006). In another study by Steele et al. (2010), peak tongue pressure was greater during effortful saliva swallow (around 60 kPa) than the normal saliva swallow (30 kPa). Same procedure was used in this work to measure the tongue pressure for subjects swallowing saliva normally and 12 ml water. The average obtained results (as presented in Figure 3.7) illustrate that the applied tongue pressures for these swallows were in similar range for males and females (for saliva swallowing: females 36 ± 8.7 kPa; males 36.3 ± 5.2 kPa; for water swallowing: females 34 ± 7.2 kPa; males 36.5 ± 6.1 kPa). These figures are slightly higher than those reported in literature but are

significantly lower than the MITP applicable by both genders (females 51.3 ± 8.3 kPa; males 53 ± 2.4 kPa). The differences between the applied tongue pressure for bolus swallowing and the MITP is referred to as the 'tongue-pressure functional reserve' (Ney et al. 2009, Steele 2013). It was indicated that the tongue pressure generated during a normal swallowing should fall below 50 % of the MITP capacity. In this study, subjects used on average around 66 % of their maximum muscle strength for normal swallowing, higher than the 50 % threshold of functional muscle reserve. The exact reason for this difference in results is not clear, but the presence of the bulb inside the mouth is one possible cause.
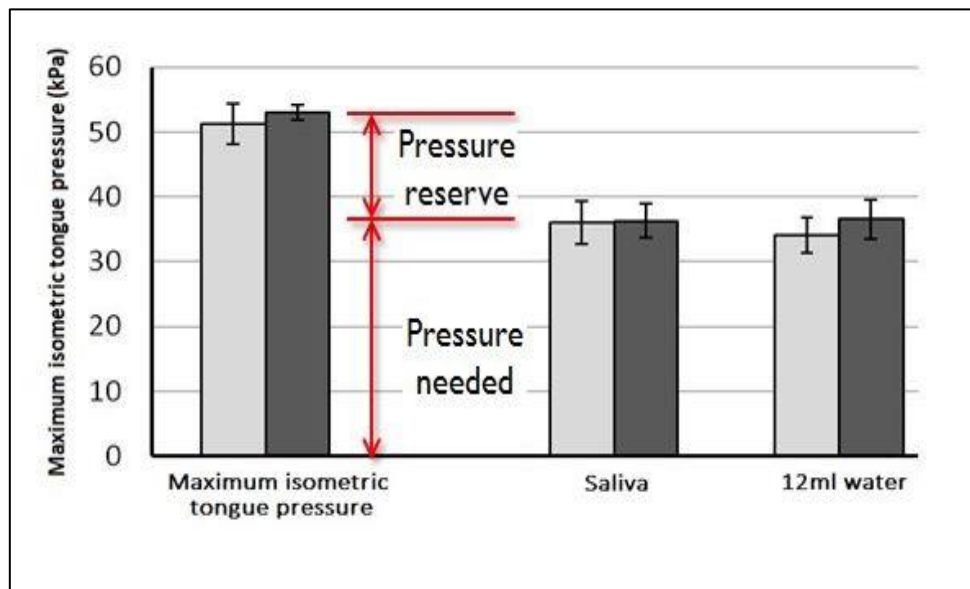
Figure 3.7 Average maximum isometric tongue pressure (MITP) and the average tongue pressures for normal saliva swallowing and 12 ml water for both genders. Light grey column refers to females and dark grey column refers to males. The red arrows illustrate the pressure needed for swallowing saliva and 12 ml of water and the pressure reserve

3.3.5 MITP and Swallowing Capability

The critical criteria used in triggering a bolus flow have long been of interest to food scientists and oral physiologists. Various theories have been proposed in literature, from three-degree food breakdown model

(Hutchings and Lillford 1988) to a maximum cohesiveness model (Lucas et al. 2002) and adhesive food paste model (Rosenthal and Share 2014, Rosenthal and Yilmaz 2014) which have been discussed previously in Chapter 2, sections 2.6.5.1, 2.6.5.2 and 2.6.5.3. Individuals naturally adapt different oral strategies when consuming food of different texture to ensure appropriate size reduction for solid and semisolid foods (as studied in Chapter 4 about food oral breaking) or saliva mixing for fluid food (van der Bilt 2012). An earlier study by Chen and Lolivret (2011) from our group suggested that rheological properties and particularly the stretchability of the food bolus are critically important in triggering bolus flow. A critically important question is: what limits an individual's capacity to initiate bolus flow? A logical speculation is that an individual's capacity in tongue pressure generation needs to exceed a certain limit in order to perceive ease in swallowing bolus.

To examine this hypothesis, Task 5 was designed to involve 21 subjects who had already participated in the MITP measurements of Task 1. They were invited to swallow boluses of increasing apparent viscosity. Figure 3.8 is plotted in order to correlate between the swallowing capability of the maximum consistency swallowed with ease for mashed potato (MP) samples and modified starch (MS) thickened solutions against MITP. The consistency level of the MP samples and MS solutions had been simplified by using the sample code as given in Table 3.1.
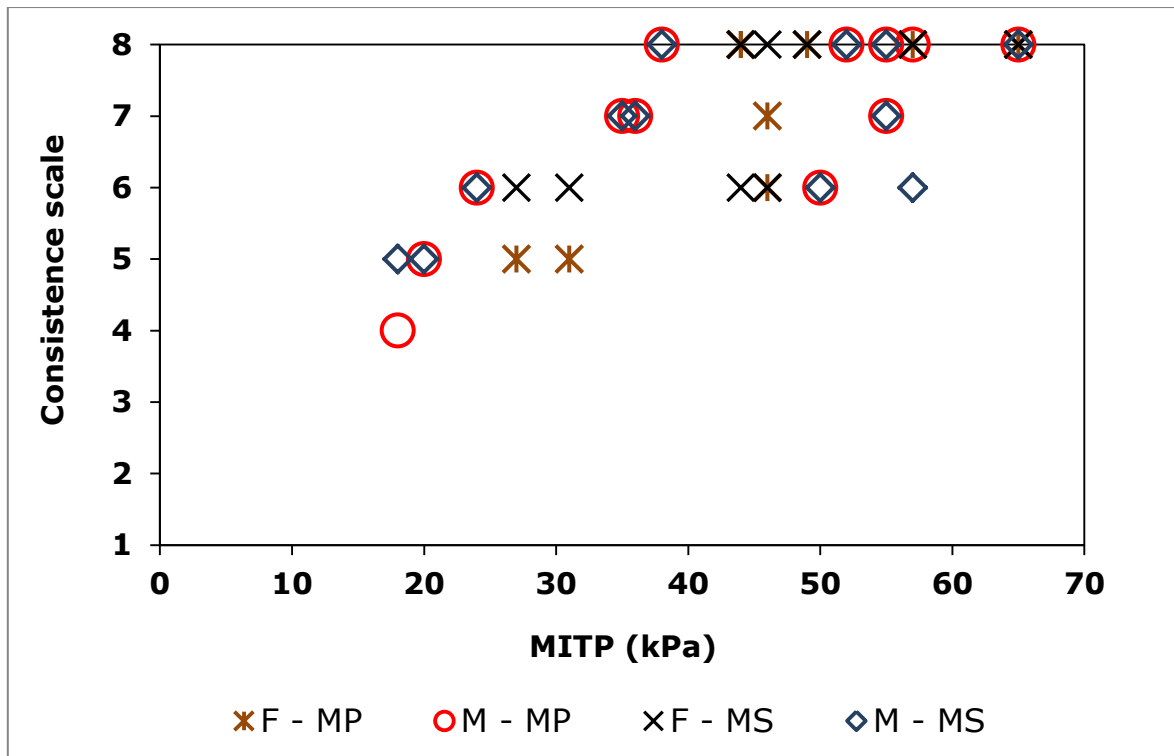
Figure 3.8 Correlations between an individuals' MITP and their perceived difficulty of swallowing referring to the maximum bolus viscosity of mashed potato (MP) samples and modified starch (MS) solutions (r values = 0.61 and 0.46 respectively). Consistence scale from 1-8 refers to sample code of increasing viscosity presented in Table 3.1. Some values of individuals' perceived difficulty of swallowing are overlap
*F: females and M: males

From Figure 3.8, a positive correlation was observed when subjects reported ease of swallowing bolus of thicker consistencies and their MITP. It is observed that for subjects whose MITP exceeds 40 kPa, it appears that their capability in swallowing food (bolus) easily does not depend on their MITP. However, for whose MITP falls below 40 kPa, a positive correlation is observed between an individual's capability of tongue pressure generation and the maximum bolus consistency swallowed with ease for boluses of both types. Highly concentrated samples (24 % MP (15.6 Pa.s) and 10 % MS solutions (7.9 Pa.s and above) were reported to be difficult to swallow for all subjects, regardless of an individual's capability to generate a very high MITP. This seems to agree with the muscle (i.e. pressure) reserve theory that only a measured amount of effort will be applied to tongue pressing (Ney et al. 2009, Steele 2013).

Therefore, even though an individual may have very strong tongue muscles and is capable of creating a high tongue pressure, it is not beneficial to produce such high tongue pressure for normal swallowing. We suggested that there are two possible explanations: firstly, to create a high tongue pressure means to exert a greater effort and, in this case, swallowing will become a highly conscious and uncomfortable oral action. Secondly, and probably more importantly, a very high tongue pressure application would cause a problem to the following swallowing stages. A high pushing force for swallowing means a high velocity of bolus flow and this would cause a problem for muscle coordination to timely seal off the pharyngeal-laryngeal track as well as open up the pharyngeal-oesophageal channel. Therefore, a measured tongue pressing against the hard palate would be most appropriate in triggering a safe bolus flow.

Since the data for all variables (MITP, MP samples and MS solutions) were not normally distributed across age groups as evaluated by Shapiro-Wilk's, the Spearman's rank correlation coefficient was calculated. Table 3.4 shows very good correlations between the MITP and the reported ease of swallowing MP samples and MS solutions for the old group 0.791 and 0.949 respectively. This means that decreasing the capability of MITP is an indicator for increasing perceived difficulty in swallowing for both thickened samples. Correlations for the adult group were moderate (0.498 and 0.409 respectively) giving inconclusive associations.

Table 3.4 Correlations obtained from non-parametric spearman's correlations between age, the MITP (kPa), the maximum consistency of food boluses of MP and MS boluses (% w/w) across aged groups

Correlations	Adult (24-64 years)	Old (> 65 years)
Mashed potato versus MITP	0.498	0.791
Starch solution versus MITP	0.409	0.949

*MITP: maximum isometric tongue pressure

Further data analysis has been conducted across the population between MITP and an individuals' reported ease of swallowing MP and MS

samples. Positive correlations were obtained from Spearman's rank correlation coefficients with r-values = 0.69, and 0.55 for MP and MS samples respectively. Because of this, it can be concluded that there is a statistically significant correlation between MITP capacity and the ease of swallowing thicker consistencies. R values indicate that about 61 % and 45 % of the variation can be explained by the regression models for MP and MS samples respectively.

3.4 Conclusions

This part of the research investigated a number of oral physiological parameters for a collection of healthy human subjects over a wide age range (including elderly subjects) and gender. These parameters include the MITP, the MOV capacity, the optimum bolus size of liquid water and a semi-liquid food (custard). The analysis of these parameters against age and gender reveals little gender difference in the creation of MITP. Age was also found to have little influence on the age under 64 years. However, an ageing effect becomes evident for those over 65 years. The average MITP was significantly different between two age groups: 48 ± 10 kPa for the adult group ageing between 22 and 64 years and 35 ± 11 kPa for the old group ageing 65 years and over. The MOV capacity was also significantly different between the two groups: 81 ± 18 ml for the adult group and 58 ± 16 ml for the old group. The MITP and the MOV show a close interesting correlation, both decreasing with the increase of age for the elderly population. It was further observed that an individual's sensed ease in swallowing boluses of increased consistency correlated with their capability in generating MITP. However, this correlation was not seen for subjects whose MITP were higher than 40 kPa. These results support the premise that both the oral physiological conditions (MITP and oral volume capacity) and the rheological properties of the food (bolus) are important factors that influence the bolus manipulations and the ease of initiating bolus flow.

The physiological capability of tongue strength seems to influence an individual's capability of bolus manipulations and oral handling of food. Therefore, following chapter will establish, in a more precise manner, the correlations between an individuals' tongue muscle strength and oral capability of tongue-only food breaking.

Chapter 4 Food Oral Breaking in Relation to Tongue Muscle Strength

4.1 Introduction

The oral physiological capabilities (i.e. tongue strength) associated with eating and swallowing play a crucial role throughout the entire food oral processing. These processes include assessing food texture, oral food handling and manipulation and finally bolus swallowing. The strength of various oral/facial muscles and their capability for coordinated actions are crucial during the eating process. While healthy people maintain normal oral physiological capabilities for eating and swallowing, many disadvantaged individuals such as elderly and dysphagia patients experience a significant reduction in their oral physiological capabilities, due to the natural longevity or health problems. These reduced capabilities are made by the weakening of tongue muscles as well as other orofacial muscles, and declined masticatory efficiency (Alsanei and Chen 2014, Crow and Ship 1996, Fei et al. 2013, Humbert and Robbins 2008, Nicosia et al. 2000, Perlman et al. 1993, Robbins et al. 2007, Steele and Van Lieshout 2009). With the predicted continuous growth of the aged (older) population (≥ 65 years) and the prevalence of dysphagia in developed countries and even some fast developing countries in the coming decade, the provision of healthy tasty food for safe consumption by these populations is becoming a major challenge in the modern society. To overcome this challenge, a proper understanding of the relationship between: (1) the oral capability of food handling (MITP) and the mechanical properties of food and also (2) individuals' oral physiological capabilities (MITP) and sensory perception of bolus manipulations (ease of food oral breaking) are urgently needed by the food industry.

The tongue is a major skeletal muscle in the floor of mouth and plays a central role in eating and swallowing. Apart from its sensory roles for

taste and textural sensation of foods, the tongue functions as a versatile mechanical device. It aids the food movements around the oral cavity and helps to secure food (bolus) in place. The tongue's muscular strength also helps to break up food particles, and to mix and hydrate them with saliva in order to form a proper cohesive bolus. More importantly, the tongue generates a major compressive force against the hard palate to initiate sequential swallowing actions forcing the bolus through the oral-pharyngeal-oesophageal track (Heath and Prinz 1999, Logemann 2006). When food is soft enough for tongue-palate compression, the tongue continues pressing until bolus is broken or fractured. By contrast, if the food is too hard for this process, oral strategy changes to mastication by teeth in order to reduce bolus size (Boyar and Kilcast 1986, Chen 2009, Lucas et al. 2002, Mishellany et al. 2006, Miura et al. 2000).

In recent years, there have been a growing number of clinical documents reporting the influences of oral physiological functionalities (as affected by oral illnesses, oropharyngeal dysphagia, reduced functional muscle reserve and weakened orofacial muscles) on the behaviour of food oral processing (Clark et al. 2003, Ono et al. 2003, Robbins et al. 2005, Roy et al. 2007, Steele et al. 1997, Stierwalt and Youmans 2007, Yoshida et al. 2006). IOPI is a rehabilitative technique that was developed in the 1990's not only for dysphagic patients but also for people across age groups who used their tongue normally. The device has been used as a reliable technique to assess tongue strength particularly the tongue-palate compression and the tongue endurance. More detailed information on the IOPI measuring system and applications is presented in Chapter 2 and Chapter 3. Previous studies showed that positive correlations exist between MITP and the bolus physical properties (bolus size and rheology) (Alsanei and Chen 2014). Noteworthy, there is only limited literature on tongue strength and its capability of food handling (breaking and smashing food without teeth involvement).

Many elderly, who edentate or have lost some of their natural teeth, have to adopt a 'tongue-only' strategy for food oral breaking and

handling. Thus they have limited food choices due to restrictive oral capabilities. In an effort to design an artificial tongue, a group of Japanese scientists observed that the tongue can only deform to a certain extent (Ishihara et al. 2013). Beyond its limit, pain will be felt and no further tongue deformation will be made in order to prevent permanent damage to the soft tissues. Therefore, choosing the right texture of food is critically important for the health and well-being of the disadvantaged elderly population.

Oral food handling means a wide range of oral actions are combined for the purposes of proper bolus formation and safe bolus swallowing. The oral breaking of soft foods by tongue-only compression is the focus of this work. The assumption is that in order to deform and break food under the tongue stress, we propose that a proper matching of food mechanical strength in particular textural properties by MITP is critically essential for tongue-only oral food processing. That is, the need of oral stress for food breaking must be met by the available tongue capability. Gels and mashed potato samples were chosen for this study because of their common availability and easy preparation. Such foods are also categorised as, 'Level 1 Dysphagia Pureed Diet' as found in the National Dysphagia Diet (NDD). These types of foods are usually recommended for people suffering from age-related tooth loss, reduced chewing ability, swallowing difficulties and for people who are under the risk of choking as a result of weakened oral/facial muscles. A series of gels (viscoelastic material) and mashed potatoes (pastry food material) ranging from soft to hard with increasing consistency were constituted and their mechanical/textural properties were characterised by an instrumental texture analyser. Three main experimental tasks were designed: to measure the maximum isometric tongue pressure (MITP) using IOPI device in order to characterise an individual's physiological capability of oral food handling (Task 1); to assess an individuals' capability for tongue-only food breaking (Task 2); and to measure the intra-oral pressures applied when breaking these food materials (Task 3). The main

purpose of the present study is to establish, in a more precise manner, the correlations between an individuals' tongue muscle strength and oral capability of tongue-only food breaking.

4.2 Materials and Methods

4.2.1 Subjects

Thirty four healthy, male and female subjects of different ages and sociocultural backgrounds were recruited for these tasks. Table 4.1 summarises the general profile of sample sizes, age distributions, and their MITP. Criteria of subject selection were non-smokers, self-assessed as capable of independent living, not under any medical treatment, and not suffering from any oral and dental diseases. Before the tests, subjects were briefed about the aim, objectives, methods, and safety issues of the experiment. Informed consent was obtained from all subjects. Each test session lasted about 40 minutes and no longer than one hour. After each session, a five-pound shopping voucher was awarded to each subject. Ethical approval has previously been granted by the Faculty Ethics Committee at the University of Leeds.

Table 4.1 Demographic features of subjects regarding sample sizes, age ranges, the averages and standard deviations (SD) of age and the oral physiological property (MITP; kPa) for both male and female subjects recruited for different tests in this work

Task	Sample size (N)	Gender (N)			Age (Years) (Average ± SD)			*MITP (kPa) (Average ± SD)		
		Male	Female	Age	Male	Female	Average	Male	Female	Average
1 & 2	34	11	23	17-62	41 ± 17	31 ± 13	34 ± 15	51 ± 17	49 ± 12	50 ± 14
3	30	11	19	21-60	40 ± 14	31 ± 9.0	33 ± 10	48 ± 14	49 ± 9.0	49 ± 10

* MITP: Maximum Isometric Tongue Pressure

4.2.2 Food Sample Preparations

Vege-gel powder (Dr.Oetker, Leeds, U.K.) was purchased from a local supermarket (Morrison, Leeds, UK). The product is made from vegetable sources of carrageen (seaweed) and locust bean gum, capable of forming a semi-rigid, transparent, elasticised, and thermally reversible jelly. From Table 4.2, altogether a total of 13 gel samples of varying strengths were constituted into various consistencies according to the manufacturer's written instructions. The powder was first dissolved in cold water, and then heated to above 65 °C for 4-5 minutes. The completely dissolved solution was poured into cylindrical ice moulds (15mm diameter and 15mm length). Samples were then left to set in a refrigerator at 7°C for up to 2 hours, allowing for gel formation. The gel samples were then carefully moved to a room temperature environment and thermally equilibrated before being tested.

Packed, commercial dehydrated potato flakes (Instant Mashed Potato [Smash brand], Premier Foods PLC., St Albans, Hertfordshire, UK) were also purchased from a local supermarket (Morrison, Leeds, UK) and a pastry food (mashed potato) was prepared according to the manufacturer's instructions. From Table 4.2, altogether, 10 mashed potato samples of varying strengths were prepared by mixing potato powder in boiling water for 5 minutes. Mixtures were then compressed into the same ice matrix multi-mould used for gel gelation and then stored at room temperature (25°C) for 1-2 hours until firm. All test samples were prepared on the day of the test and were used fresh. From Table 4.2, the formulation of both gel and mashed potato was based on the constituent concentrations, by increasing concentration (0.2 % and 4.0 %, respectively).

Table 4.2 Two sets of foods (gels, coded as G_n and mashed potato samples coded as P_n) with various ranges of concentrations (% wt/wt)

Sample code	Concentration % wt/wt
G_1	1.4
G_2	1.8
G_3	2.0
G_4	2.2
G_5	2.6
G_6	2.8
G_7	3.2
G_8	3.6
G_9	4.0
G_{10}	4.2
G_{11}	4.6
G_{12}	5.0
G_{13}	5.2
P_1	8.0
P_2	12
P_3	16
P_4	20
P_5	24
P_6	28
P_7	32
P_8	36
P_9	40
P_{10}	44

4.2.3 Food Sample Mechanical Characterisations

A compression test was performed to determine the mechanical strength of both gel (fracturability and elasticity) and mashed potato (deformability) by using the TA XT-Plus texture analyser instrument (Stable Micro Systems Ltd., Surrey, UK) equipped with a 25 kg load cell. The obtained results were calculated using the Exponent software provided by the instrument manufacturer. For the gel samples, a compression test was applied in order to investigate three mechanical properties of gel fracturability, including the maximum fracture force (hardness), fracture work and elasticity. As shown in Figure 4.1, a test sample was placed on a stationary platform and compressed by a flat-

ended, 40mm diameter, cylindrical aluminium probe at a speed of 2.0 mm/s. For the mashed potato samples, the same test conditions were used to characterise sample deformability including the maximum force (hardness) and deformation work. All tests were performed at a room temperature of around 22 ± 2 °C. Five replicates were conducted and analysed per sample to ensure accurate measurements.
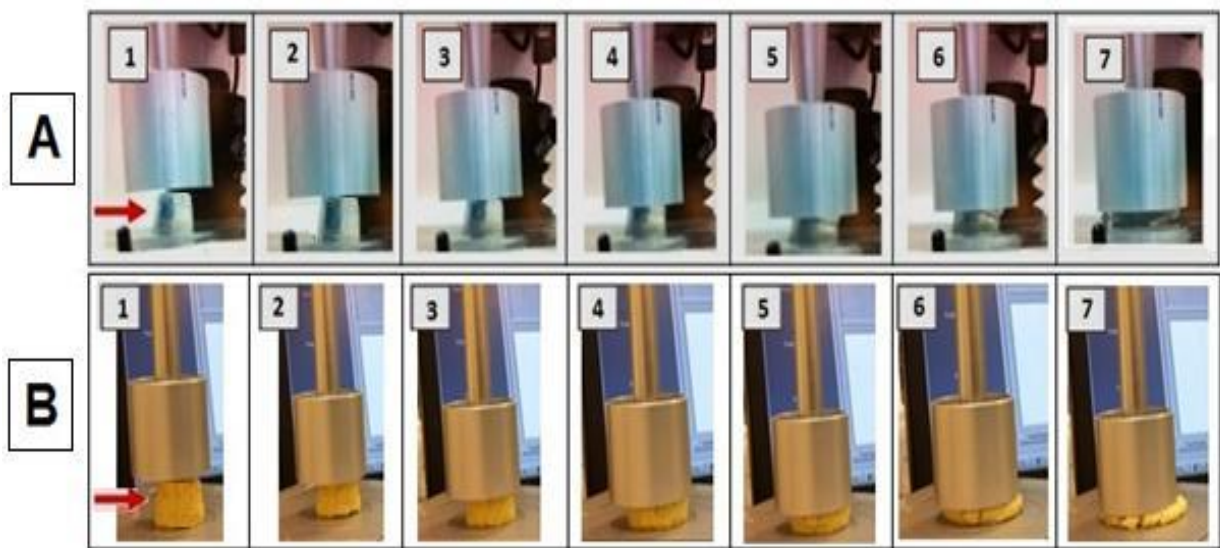
Figure 4.1 Seven frames extracted from a representative video during compression test to measure the strength and fracture behaviours for both (A) the breaking pressure of 4.8 % gel (A1 before compression, A2-A6 during compression, A7 just before breaking) and (B) compressing pressure of 38 % mashed potato (B1 before compression, B2-B5 continue to deform during compression, B6-B7 deform until flat) using a texture analyser compression test

4.2.4 Optimisation of the IOPI Bulb Location during Gel Oral Breaking

Two different methods were carried out to determine the optimum IOPI bulb location during gel oral breaking and pressure generated by tongue-palate compression. The first method was performed by placing an IOPI bulb on top of the gel sample, and subjects were asked to place them onto the middle of their tongues as shown in Figure 4.2 (1A). The

second method was conducted by placing the bulb in the gel sample (gelled bulb) during the preparation process as shown in Figure 4.2 (1B).
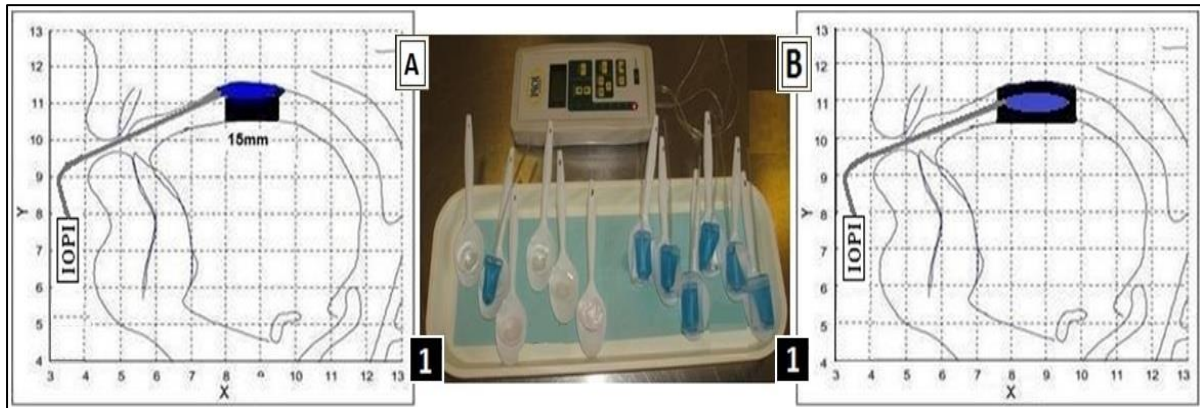
Figure 4.2 Illustration of two methods used to determine the optimum air-filled IOPI bulb location during gel oral breaking and pressure generated by tongue-palate compression using three different concentrations of gels (2.6, 4.8 and 5.6 %). A1 describes the IOPI bulb location on the top of the gel surface, and B1 describes the IOPI bulb location in the middle of gel. The face template reproduced from Serrurier et al. (2012)

During the test, subjects were instructed to gradually elevate their tongues against their hard palate (whilst their mouths remained closed) in order to break the sample. Once the gel broke, subjects were immediately asked to relax their tongues. To record the gel oral breaking pressure, the bulb was linked to the IOPI transducer. Data obtained from the IOPI transducer shows that the average amount of pressure required to break gels (2.6, 4.8 and 5.6 %) when the IOPI bulb located on the top is slightly higher (22, 30 and 40 kPa) than that in the middle of the samples (18, 27 and 36 kPa) with standard deviation of ± 4.0 kPa and r^2 values of 0.995 and 0.999, respectively. This can be referred to the thickness of the gel around the IOPI bulb which made the gel easy to fracture. Thus, the optimum IOPI bulb location (on top of the food sample) to measure oral breaking pressure will be considered for further investigation.

4.2.5 Pressure Measurement of the Food oral Breaking

A compression test was also performed to measure the required pressure for gel breaking (2.6, 4.8 and 5.6 %), and potato smashing (19, 25, 33 and 38 %) by combining the texture analyser and IOPI together during compression test. In this case, an IOPI bulb was carefully placed on top of the sample before the test (Figure 4.3). A thin layer of paper tissue (5 mm X 10 mm dimensions and 0.07 mm thickness measured by dial gauge micrometer, Mercer of St Albans, England reading 0.01 mm) was placed between the surfaces of the gel sample only and the bulb to avoid bulb slipperiness. The compressing pressure at the point of gel fracture and mashed potato compression can be recorded by IOPI. Same test conditions were used in section 4.2.3 sample characterisation.
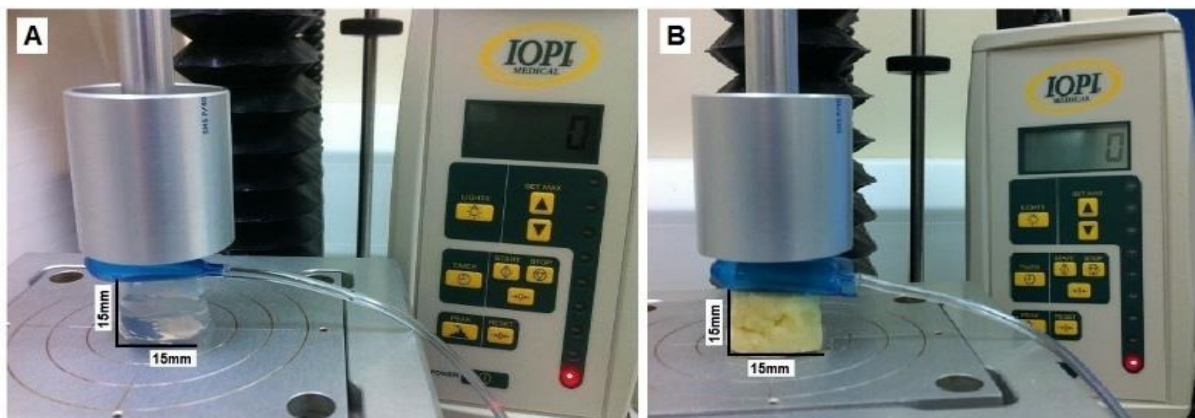
Figure 4.3 Illustration of the measurement combining texture analyser and IOPI together for compression test (A) gel breaking pressure and (B) potato smashing pressure

4.2.6 Experimental Tasks

4.2.6.1 MITP Measurement

In Task 1, the maximum isometric tongue pressure (MITP) of thirty-four healthy subjects, of both genders, was measured. Subjects were asked to sit in the most relaxed manner, with their heads in an upright position and their eyes focused on a horizontal level as a target. The subjects were instructed using a graphic illustration to place the air-filled

tongue bulb centrally on the top of tongue and then to lift up their tongues and compress as hard as possible with the closure of their lips to reach peak values (Alsanei and Chen 2014). The generated tongue pressure was recorded and displayed on a numeric LCD screen in kilopascals. More information can be found in Chapter 2, section 2.3.1.1.3.1. Each participant was tested 5 times, with about one minute interval between tests. The mean value of these tests was obtained to define an individual's MITP. The obtained MITP value was used as an indication of an individual's capability for breaking and smashing without teeth involvement.

4.2.6.2 Assessment of Individual's Capability in Tongue-only Food Breaking

In Task 2, subjects were provided with a total of 12 samples (six gels and six mashed potato samples). Gel samples were categorised into three groups (depending on gel hardness) as per the following: easy (from G_1 to G_4), medium (from G_5 to G_8) and hard (from G_9 to G_{13}). Each participant was given two samples from each group. Similarly, mashed potato samples with portion sizes measuring 5 grams were classified to three groups, depending on their hardness (easy from P_1 to P_3, medium from P_4 to P_7, hard from P_8 to P_{10}) and two samples were selected from each group. Samples were served in ascending order, based on their mechanical strengths, with a minimum of 1-2 minutes rest between sets. Subjects were instructed to use tongue compressing alone to decide whether the samples were easy, medium or hard to break/compress (Figure 4.4). Subsequently, the sample was spat out into a container for disposal. No swallowing action was involved. Water was provided subjects allowing them to rinse their mouths between evaluations.
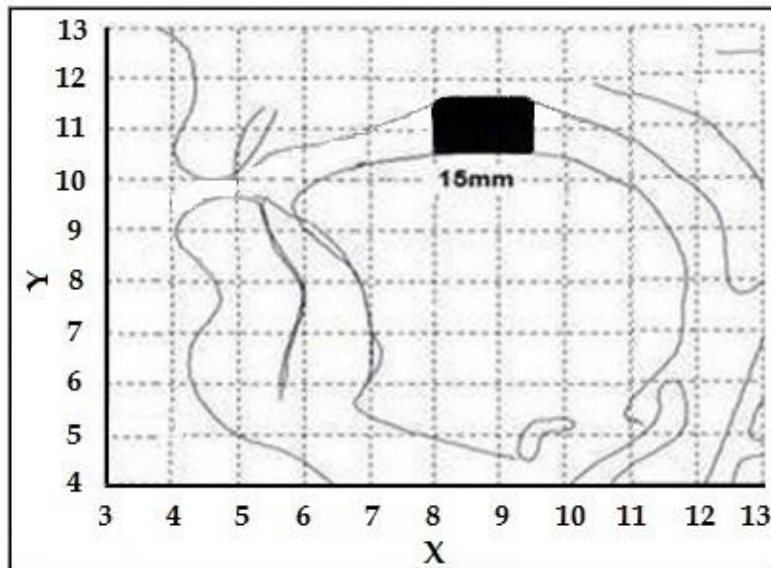
Figure 4.4 A graphic illustration showing the location of the food sample for tongue-only compressing, modified from Serrurier et al. (2012)

4.2.6.3 *In Vivo* **Measurement of Tongue-Palate Pressure required for Food Oral Breaking**

In Task 3, IOPI was used for *in vivo* determination of the oral pressure for tongue-only food breaking. There were a total of thirty subjects and each participant was provided with a tray containing two sets of food samples. In this test, an IOPI bulb was incorporated and placed on the top of each sample. As shown in Figure 4.5, *Set A* consisted of duplicated gel samples of three concentrations (2.6, 4.8 and 5.6 %). *Set B* consisted of duplicated mashed potato samples of four concentrations (19, 25, 33 and 38 %). Samples were provided in a random order using code numbers. The test procedure was exactly the same as in previous tasks.

Figure 4.5 Presentation of (A) duplicated gel sample sets of three concentrations (2.6, 4.8 and 5.6 %) and (B) duplicated mashed potato sample sets of four concentrations (19, 25, 33 and 38 %)

To start the test, subjects were instructed to gradually elevate their tongues against their hard palate (whilst their mouths remained closed) in order to break/smash the samples. As soon as the breaking/smashing occurred, subjects were asked to relax their tongues. During the test, the air bulb was linked to the pressure transducer of IOPI to record the tongue–palate pressure of food breaking/smashing (Figure 4.6). Between each sample, subjects were given a short period of rest, ranging from 30 seconds to 1 minute.
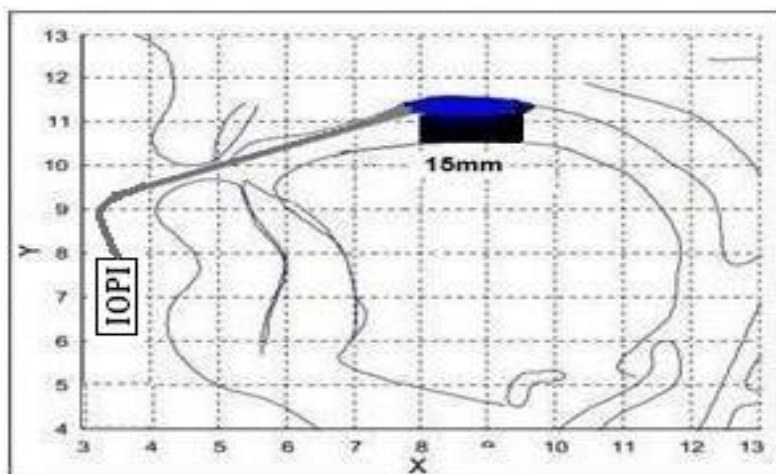
Figure 4.6 A graphic illustration showing the location of IOPI bulb and the food sample during the measurement of tongue-palate pressure generation for food oral breaking, modified from Serrurier et al. (2012)

4.2.7 Statistical Analysis

Statistical analysis was performed by using a Statistical Package for the Social Sciences (SPSS) 21 (SPSS Inc., Chicago, IL). Mean, standard deviation (SD), the correlation coefficient (r^2) values for age and MITP were calculated. A correlation study of MITP and the threshold gel strength for tongue-only food oral breaking were also assessed.

4.3 Results and Discussions

4.3.1 Food Mechanical Strength

Mechanical/textural properties of all gel samples and mashed potato samples have been properly tested using a texture analyser under controlled conditions. Figure 4.7, 4.8 and 4.9 summarise the mechanical property profiles (including fracture/deformation force, fracture/deformation work and gel elastic module, respectively) of the gels and mashed potato samples based on the force-displacement curves obtained from compression tests.

Examples of force-displacement curves, for the gel and mashed potato, are shown in Figure 4.10. The gel sample exhibits a clear fracture point, a typical feature of a viscoelastic material (Figure 4.10A). The mashed potato behaves like a typical pasty material, with a monotonous increase of the deformation force/stress due to continuous yielding deformation of the material under the applied stress. The sudden force drop shown in Figure 4.10B was not caused by any structural damage of the sample, but due to test ending. There are many different ways and different terms used for describing the mechanical strength of food samples. In this work, the maximum force (F_1) reached prior to the gel's breaking point is used to represent the *gel hardness* (or firmness used in many literatures) of the gel sample. The Young's (elastic) modulus was calculated for *gel elasticity*, which is defined as the initial slope curve of stress-strain ratio, at which the force-displacement curve shows a linear

viscoelastic region (selected at the strain range of 20 % for all gels). For mashed potato samples, the term *hardness* refers to the maximum force necessary to deform a product with a given strain, causing deformation. *Plastic deformability* is a term that represents the ability of a mashed potato sample to be deformed continuously and permanently without rupture; it is called yield stress (Bourne 2002). The work required for the fracture of gels (*fracture work*) and the work required for deformation of mashed potato samples *(deformation work)* is defined as the energy absorbed by the material during compression which is calculated from the area under the force-displacement curve. These parameters will be used to investigate the relationship between an individual's threshold of perceived difficulty during tongue-only food breaking/smashing and their MITP.
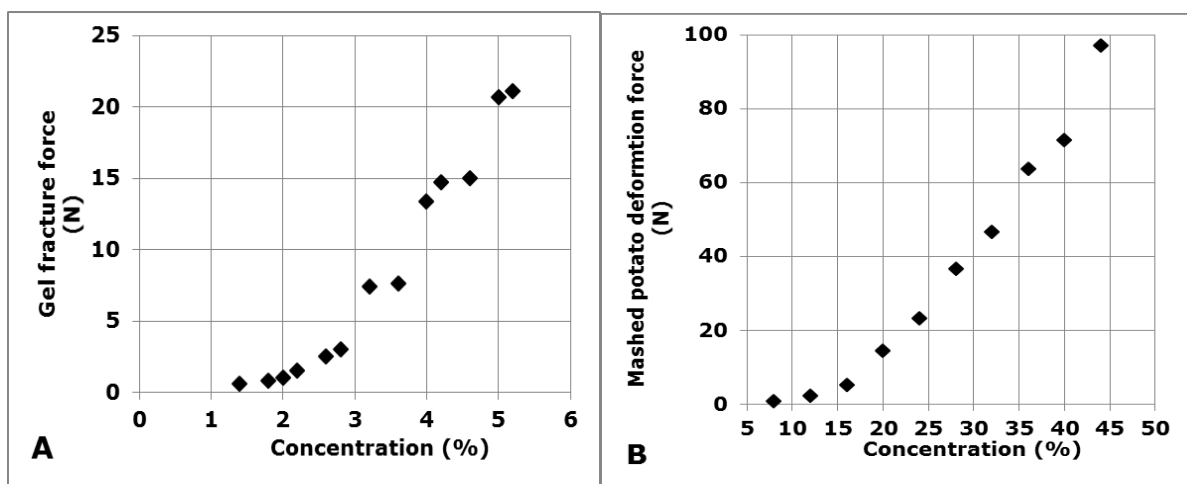
Figure 4.7 Mechanical properties of gels and mashed potatoes: (A) the fracture (breaking) force (N) of Vege-gels and (B) the maximum deformation forces (N) of the mashed potatoes as a function as a function of concentration (%)
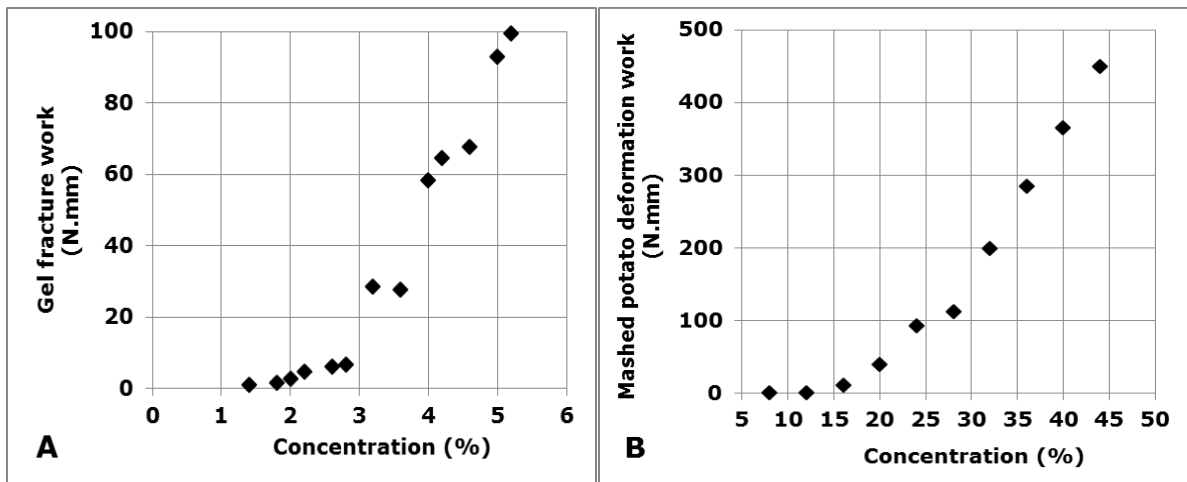
Figure 4.8 Fracture work (N.mm) of gels (A) and the deformation work (N.mm) of mashed potatoes (B) as a function of concentration (%)
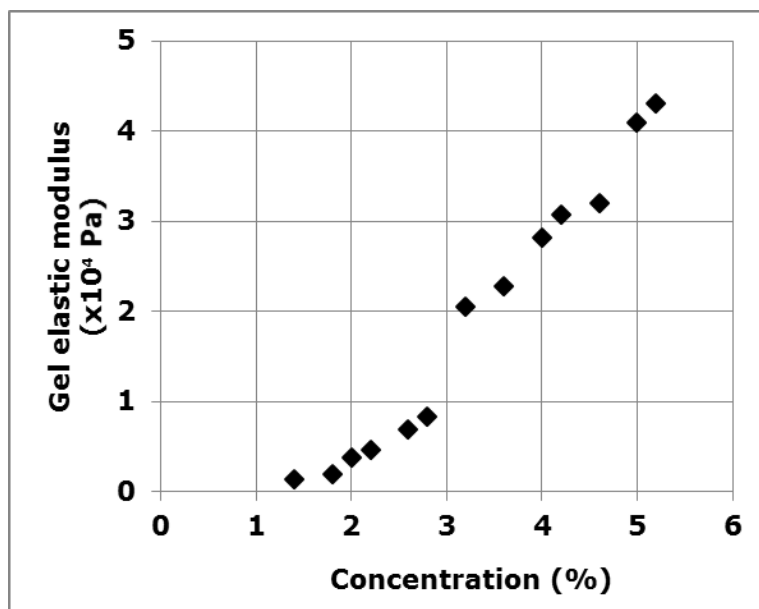
Figure 4.9 The elastic (Young's) modulus profile ($\times 10^4$ Pa) of Vege-gels measured at 20 % strain
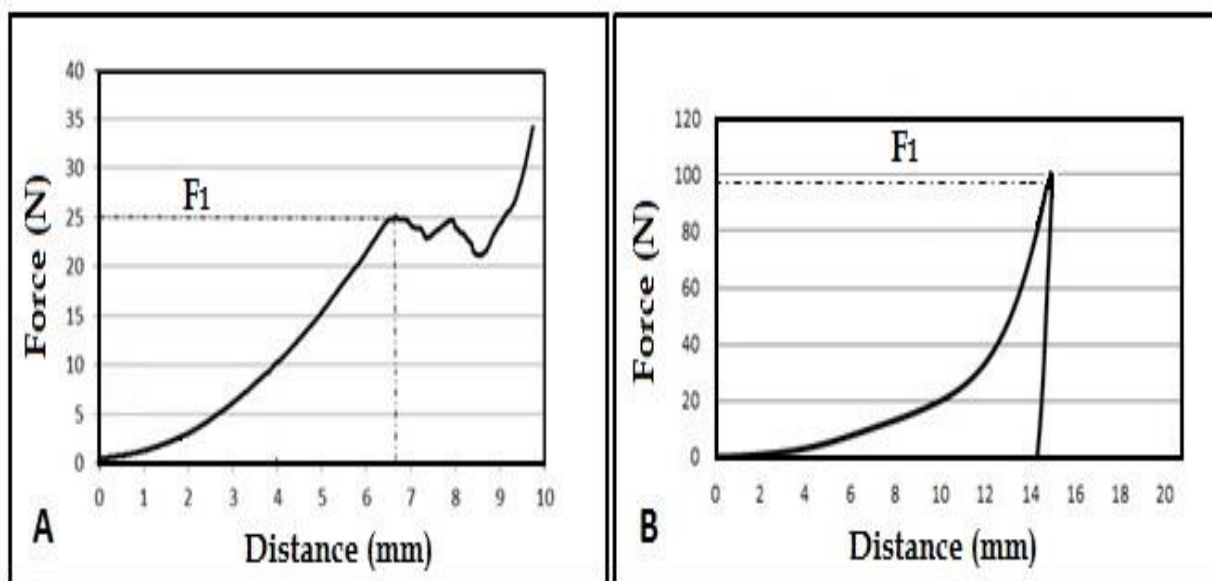
Figure 4.10 A typical force-displacement curve of 5.2 % Vege-gel sample (A) and 44 % mashed potato sample (B) obtained from a single compression test. F_1 shows sample hardness. Gel fracture work and mashed potato deformation work were presented by the area under the curve

From Table 4.2, the formulation of both gel and mashed potato was based on the constituent concentrations, by increasing concentration (0.2 % and 4.0 %, respectively). The main goal was to produce a series of well-defined food test samples, which provide a sufficient coverage of mechanical strength for oral handling, ranging from 'very easy' to 'very difficult' to break and also to give a reasonable discrimination between the consistencies during sensory tests. Since the mechanical strength does not behave in a linear relationship with the constituent concentration for both gel and mashed potato samples, it proved very difficult to have sample sequences with exactly the same ratio change of the mechanical strength as shown in Figure 4.7, 4.8 and 4.9. Statistical analysis shows that the gel hardness has a good relationship with concentration with an r^2 value of 0.94. The hardness of mashed potato also showed a positive

relationship with concentration with an r^2 value of 0.95. The gel fracture work and mashed potato deformation work also showed good correlation with constituent concentrations with r^2 values of 0.92 and 0.91, respectively.

4.3.2 MITP

Demographic features of participating subjects, including the general profile of subject sample sizes, gender, age distribution, as well as the average MITP for both genders are given in Table 4.1. The results again confirm the great variability of tongue muscle strength among healthy individuals, with the highest MITP reaching 75 kPa and the lowest at only 17 kPa. Our subjects unintentionally appeared in two age groups, below and above 30 years. However, statistical analysis showed no significant difference between youth with an average MITP of 53.4 ± 11.4 kPa and the older adult group with an average MITP of 45.5 ± 16 kPa (*P* value = 0.13). Additionally, there was no significant difference in MITP between male subjects (N = 11, 51 ± 17 kPa) and female subjects (N = 23, 49 ± 12 kPa, *P* value = 0.90). A plot of MITP against age showed a scattered data band within a horizontal band between 20 and 70 kPa. The MITP average for all ages was 50 ± 14 kPa in this study, a figure which is consistent with the findings in a previous study by (Alsanei and Chen 2014) in which the average tongue pressure of the young healthy adult group (22–64 years) was around 48 ± 10 kPa. Utanohara et al. (2008) also reported a similar result at around 50 kPa of tongue pressure.

The tongue pressure is directly related to the strength created by tongue muscle contraction and is commonly used as a useful indication of the oral physiological status and/or capability in food handling. This oral capability could be influenced by many chronic conditions (e.g. age, illness), but is more importantly determined by an individual's

physiological condition. A number of experimental evidences show that individuals vary greatly in this capability. It has also been demonstrated that the tongue pressure and age relationship was only evident for elderly populations as weakening of the tongue muscle became more significant as a consequence of the natural ageing process (Alsanei and Chen 2014).

4.3.3 MITP and Tongue-only Food Breaking

In order to determine the correlation between tongue strength and perceived ease / difficulty food breaking, participating subjects with known MITP were invited to assess the ease of tongue-only food breaking/smashing. Each subject was provided with two sets of samples (gels and mashed potatoes), both with increasing consistencies. The transition from easy to difficult was taken as the threshold of an individuals' tongue capability. A subject's capability of tongue-only food breaking was then compared against their oral physiological functionality (MITP). Results are shown in Figure 4.11 and Figure 4.12. In Figure 4.11A and Figure 4.11B, the gel hardness and elasticity is respectively plotted against MITP. Though data is somewhat scattered, a positive correlation is clearly evident with the *P value* <0.0001. Statistical analysis shows a meaningful correlation coefficient (r^2 of 0.4) for both cases, suggesting a moderate correlation between the two factors.
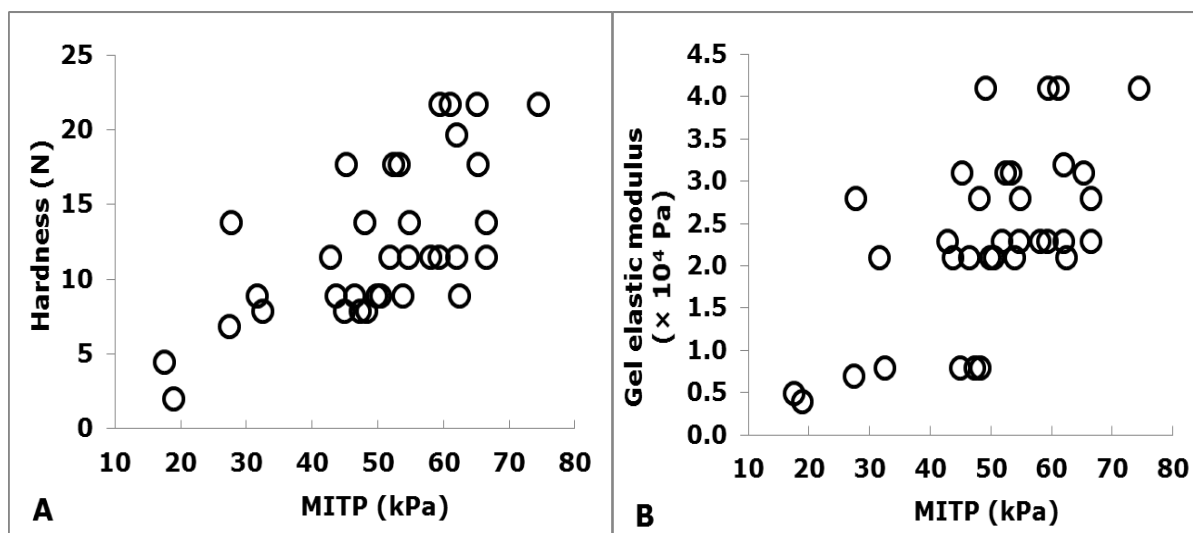
Figure 4.11 Correlations between an individuals' threshold of perceived difficulty during tongue-only food breaking of Vege-gels and their MITP: (A) hardness threshold as a function of MITP; (B) elasticity threshold as a function of MITP (r^2 = 0.4 for both cases); (N = 34; 11 males, 23 females; aging between 17 and 62 years)

The correlation between an individual's threshold of perceived difficulty during tongue-only food smashing and their MITP for the mashed potato samples are presented in Figure 4.12A and B. They show that the measured food hardness has correlated with the subjects' MITP. In this case, the threshold hardness is plotted against MITP. Again, a positive correlation with the *P* value <0.0001 (r^2 value 0.5) between the two factors was obtained. Work of deformation has also shown a positive correlation with subjects' MITP as demonstrated in Figure 4.12B.
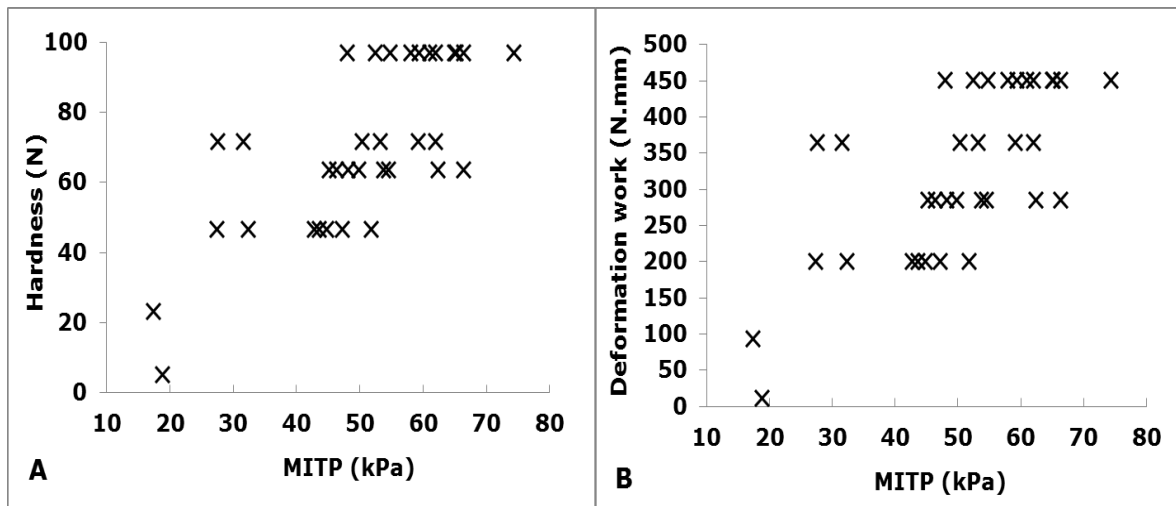
Figure 4.12 Correlations between an individual's threshold of perceived difficulty during tongue-only food smashing mashed potato samples and their MITP: (A) hardness threshold and (B) deformation work threshold as a function of MITP ($r^2 = 0.5$ for both cases) (N = 34; 11 males, 23 females; aging between 17 and 62 years)

However, the breaking of the gel and mashed potato sample (within the mouth) occurs in very different manners. As an elastic material, the gel fractures only when the applied stress exceeds its mechanical limit (the breaking/fracturing point as shown by the maximum force in Figure 4.7A). However, mashed potato, as a plastic material, has different deformation behaviour. During the compression of mashed potato between the tongue and hard palate, the sample begins to be deformed continuously and permanently from its original height. This behaviour is due to the energy imparted to disintegrate the mashed potato, which yields a state of size reduction under the increasing applied force. This plastic deformation continues further, as the applied force increases, and eventually, plastic deformation ends, as the sample is completely flattened out (Figure 4.10B).

The aforementioned positive correlations between oral physiology functionality and the capability of tongue-only food breaking suggest that strong tongue muscle strength is advantageous for oral food processing. This could be particularly important for consumers who have lost the full functionality of chewing and masticating, such as the elderly and

dysphagia patients. This could also be the case for those whose chewing and masticating functions are still developing, such as infants. Although the tongue is a soft tissue, it can become very firm when contracted. Tongue-only food breaking involves soft, solid food being compressed by another soft, solid material, as has been indicated by Peleg and Corradini (2012). The tongue will have to deform itself when used to deform a soft, solid food by breaking or smashing process. However, the deformation of the tongue has a certain limit for self-protection. It is generally believed that a deformation of 20 % strain could be the maximum limit for the tongue before it becomes painful (Ishihara et al. 2013). Healthy individuals adopt very different oral strategies for food oral breaking and bolus formation. For very soft foods, the tongue-only strategy can be conveniently used. However, if a food is too firm for the tongue to handle (break or smash), teeth involvement will become inevitable. Arai and Yamada (1993) demonstrated that 12 % strain of agar and gelatine gel is the critical point for change in the oral processing strategy from tongue-palate compression to teeth mastication.

A moderate correlation between the oral physiological capability and tongue-only food breaking is not surprising. There are many factors that could cause the deviation of experimental data. Most obviously, sensory perception from human subjects is always subjective, dependent on the mode and environment. The changing perception from easy to difficult is a gradual transition process rather than an abrupt switch over. A large variation is therefore expected from individuals in deciding this threshold point. Temperature differences between the food sample and the human body is another important influencing factor. In this study, all food samples were stored and characterised for their mechanical properties, at room temperature. However, all sensory tests will have to be tested inside the mouth at body temperature. Though the temperature difference creates an uncertainty, the practice is commonly adopted in literature for food texture and sensory studies. Temperature uncertainty could be

avoided in the future by applying necessary temperature controls. Allowing for samples to be stored and characterised at body temperature.

4.3.4 *In Vivo* Measurement of Tongue-Palate Pressure required for Food Oral Breaking

In vivo measurement of tongue-palate pressure generation was made possible by incorporating the IOPI bulb into the food sample. Samuels and Chadwick (2006) and Steele et al. (2015) emphasise the importance of matching a person's tongue strength capability (i.e. simple tongue compression) with the food provided. Once the gel is compressed by the tongue, the pressure generation can be recorded instantly by the IOPI handset. The main purpose of this test is to assess the real tongue pressure for food oral breaking and to confirm its agreement with the breaking pressure obtained *in vitro*. Three gel samples and four mashed potato samples, of different mechanical strength were used for this test and the results are shown in Figure 4.13. Not surprisingly, almost a linear increase of the breaking pressure with the increased strength (concentration) is clearly evident for both sample systems with r^2 value 0.991 and 0.960, respectively. This is consistent with the general principle that the higher the mechanical strength of a food, the harder the food is to break. However, the most interesting observation is the coherence between the real pressure of food oral breaking and estimated oral pressure, obtained from *in vitro* measurements using the texture analyser. For the gel samples, the coherence between the two methods is evident (Figure 4.13A). For the mashed potato samples, the agreement between the two sets of data is still satisfactory, though not as good as for the case of gels (Figure 4.13B). The reason of the increased discrepancy between the two measurements for mashed potato samples is probably because of the yielding nature of such samples under the applied stress. There is no sudden fracture for such materials. This makes judgement of the breaking point even more subjective.
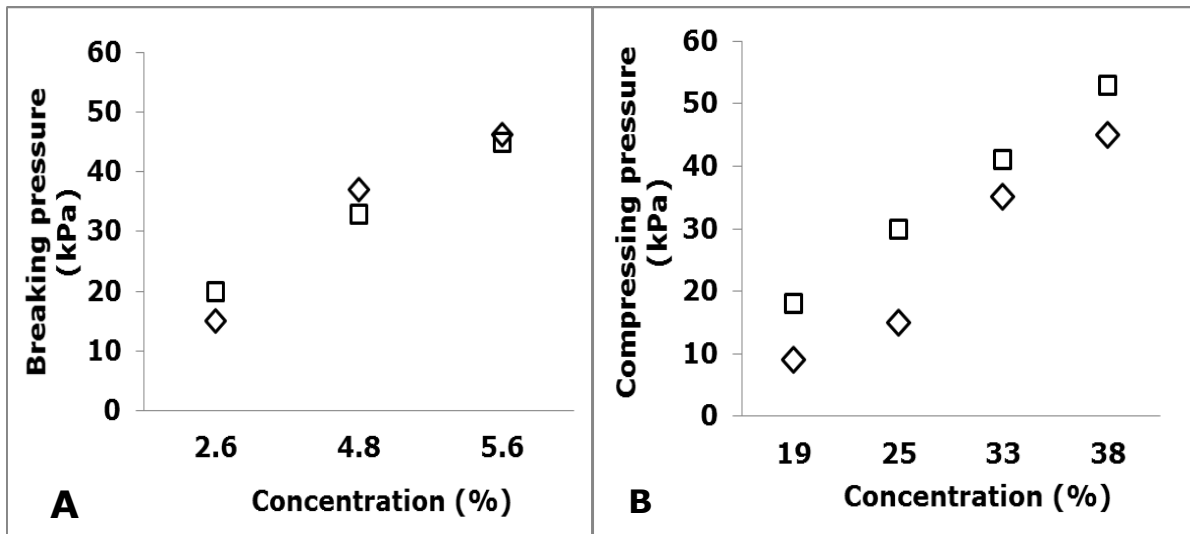
Figure 4.13 Agreement of the *in vivo* measured tongue-palate pressure (◇) with the estimated breaking pressure obtained from panellist sensory tests (□); for (A) gels and (B) mashed potatoes

The *in vivo* oral pressure measurement provides a new feasible method for eating studies, especially when relating the oral physiology capability to the physical and textural properties of food. The main challenge or difficulty of *in vivo* oral pressure measurement for food breaking is the sample preparation. The IOPI bulb has to be incorporated properly into the sample, either within the centre or on the top of the sample. Sample sizes will also have to be properly adjusted. Sample sizes that are too large will be inconvenient for oral handling. Though a small sample size could be ideal for oral handling, it may have a risk of sample slippery due to the contact with the pressure bulb.

4.4 Conclusions

During this study, the important roles of oral physiological capability in oral food handling have been investigated. The MITP was used as a representative of oral physiological capability and tongue-only food breaking was chosen as the typical example of oral food handling. Two sets of food samples (gel and mashed potato) with a wide range of mechanical strength were prepared. Their mechanical properties were

characterised using a Texture Analyser. A total of thirty four subjects participated in sensory tests of food oral breaking. Data analysis showed that a positive correlation existed between oral physiological capabilities and oral food handling capabilities. Results suggest that strong tongue muscle strength is advantageous for oral handling (break/smashing) of viscoelastic and pastry foods. Individuals with a low tongue pressure (or tongue muscle strength), either caused by natural ageing or due to illness, could have a limited choice of food for comfortable oral handling. Results from this work provide a useful guidance of food choice for those disadvantaged consumers such as the elderly, dysphagia patients and infants. From our results, we can conclude that individual's capacity in tongue pressure generation needs to exceed a certain limit in order to break and smash food. This fact leads to investigate the relationship between individuals' oral physiological capabilities (MITP) and perceived ease of swallowing and also and perceived bolus flow behaviour. Additionally, to answer how the bolus flow behaviour can be subjectively measured by individual's MITP?

Chapter 5 Perceived Bolus Flow Behaviour during Normal Swallowing in Relation to Bolus Rheological Measurements and Tongue Strength

5.1 Introduction

Bolus flow behaviour is an important feature for swallowing. It involves the coordinated activities of three elements (oral, pharynx and oesophagus). In physiological concept, bolus flow has influenced by the action of the tongue against the palate as a bolus is ejected from the mouth and into the pharynx during a swallow (Matsuo and Palmer 2013, Nicosia 2013, Rosenbek and Jones 2008). It provides also a complex moving platform which in turn provides a driving force to initiate the bolus flow. In rheological concept, the tongue acts like a constant stress tool in the oral cavity (Mackley et al. 2013). Hence tongue plays a major role in both sensory and motor aspects of the oral stage of swallowing, particularly for transporting the bolus with different rheological properties. Earlier studies agree that tongue strength capability (i.e. MITP) of healthy individuals reduced with advancing age (Alsanei and Chen 2014, Crow and Ship 1996, Fei et al. 2013, Youmans et al. 2009). As a result, such physiological change can place people with weak tongue at higher risk of swallowing difficulties (dysphagia) (Nicosia et al. 2000, Tamine et al. 2010b). Nicosia et al. (2000) reported that not only swallowing but also bolus flow outcomes are influenced by tongue strength capability. To this point, the influence of bolus rheological measurements (i.e. viscosity and viscoelasticity) and tongue strength on changing the bolus flow behaviours during swallowing remain unstudied due to the complication of the bolus assessment in such process.

Along with the tongue strength capability presented in Chapter 2, 3 and 4, the rheological characterisation of food bolus (i.e. viscosity) is an important factor for swallowing. Previous research studies emphasise that

bolus flow properties are a part of several approaches to address swallowing disorders in dysphagic patients and also to provide compelling evidence of both spatial and temporal data analysis on the influence of bolus viscosity on the oropharyngeal swallowing using videofluoroscopy, endoscopy and electromyography (Butler et al. 2009, Chi-Fishman and Sonies 2002, Garcia et al. 2005, Leonard et al. 2014, Perlman et al. 1999, Scott et al. 1998, Wu et al. 1997). Pouderoux and Kahrilas (1995) Miller and Watkin (1996) Nicosia et al. (2000) reported that significant increases in tongue force amplitude were observed with increasing bolus viscosity when compared to fluid bolus. In fact to understand this behaviour of swallowing, there is a general agreement on the restriction of the fluid dynamics with no-slip condition for viscous flow, likely due to bolus stickiness to the tongue and oropharyngeal surfaces and therefore prevent slip (Batchelor 2000, Day 1990, Ferziger and Peric 2001). Consequently, individuals most likely apply their maximum bolus propulsion capability to overcome perceived bolus stickiness and perceived swallowing difficulty of viscous bolus.

Perceived ease of swallowing is one of the frequent terminologies that found in the food oral processing literature to describe a bolus attribute during swallowing evaluation. This terminology needs to be studied and clarified (Steele et al. 2015). During a single swallow, perceived ease of swallowing (perceived comfortable swallowing) means that the ability of individual to swallow food or/and liquid bolus by leaving their oral structure substantially clear of bolus residue (Alsanei and Chen 2014). We rely on the assumption that the physical properties (i.e. rheology) of swallowed bolus will change under individual's MITP. This change demonstrates by the viscosity decrease upon the bolus surface which implies the reduction of friction force relative to the solid surface (oropharyngeal walls). Hence, individual's tongue pressure will exceed a certain limit to enable perception of ease swallowing of bolus with higher viscosities.

It is widely accepted that bolus type can be categorised into three types as following: (1) fluid bolus (e.g. water), (2) semifluid bolus (e.g. gel and pudding-like bolus), or (3) semisolid bolus (e.g. chewed mushroom and chewed oyster). On the other hand, the literature emphasised the need to also classify the bolus flow behaviours in the context of the swallowing process (Steele et al. 2015). In the case of a fluid bolus, laminar flow of such bolus occurs under stress or force. It is described as a linear stretched flow deformation when fluid's layers slide over each other at different shear rates with the maximum velocity at the central line (Figure 5.1A). While sliding bolus flow can be divided into two flows either as an apparent slip flow (e.g. rubbery amorphous form). Apparent slip flow describes as a layer of high shear rate upon the surface creates low viscosity phases which then result in a large velocity gradient near the wall (Figure 5.1B and Figure 5.2B). Or under high shear rate upon the bolus surface, the bolus flow is uniform as a plug flow (e.g. chewing gum). It is likely due to bolus property of being high elastic and limited deformation (Figure 5.1C). However, there is no study that links between perceived bolus flow behaviour; subjective ease of swallowing and individual's MITP in food science, sensory literatures, rheology and flow of materials.

Perceived bolus flow behaviour
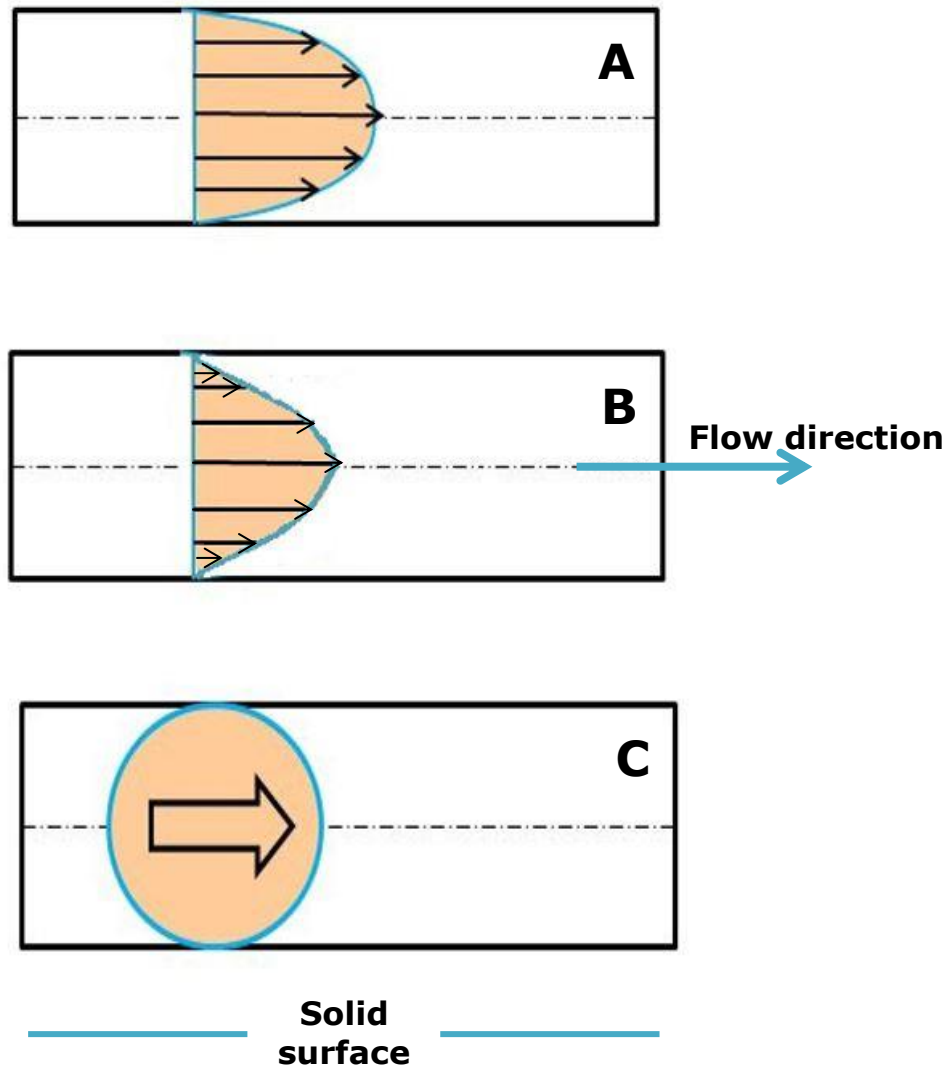
Figure 5.1 Illustration of bolus flow behaviours during swallowing (A) a laminar flow described as a linear stretched flow deformation when fluid's layers slide over each other at different shear rates with the maximum velocity at the central line. Sliding bolus flows can be divided into two flows either as (B) apparent slip flow which describes as a layer of high shear rate upon the surface creates low viscosity phases which then result in a large velocity gradient near the wall. Or (C) a plug flow of the bolus which describes as uniform flow under high shear rate upon the bolus surface, likely due to bolus property of being high elastic and limited deformation

Food and swallowing related literature strongly suggests that there are several relevant properties of food for swallowing, including

cohesiveness, hardness and slipperiness (Steele et al. 2015). In the literature of rheology and slippery flow mechanics of a material, slip phenomenon is divided into two concepts either *true slip* or *apparent slip* (Figure 5.2A and 5.2B). To define these terminologies, the former is described as a discontinuous of the velocity field across the fluid-solid interface which means that the fluid close to the wall moves with a different velocity than the wall itself. While in the case of apparent slip, it is describes a layer of high shear rate upon the surface with different rheological properties than the essential homogeneous bulk of fluid flow giving a situation similar to slip. This layer of high shear rate creates low viscosity phases which then result in a large velocity gradient near the wall to facilitate fluid movement (Aral and Kalyon 1994, Barnes 1995, Chakrabarti 1995, Cohen and Metzner 1985, Goshawk et al. 1998, Lam et al. 2007, Lauga et al. 2007, McCarthy and McCarthy 2013, Meeker et al. 2004, Peters 2008, Salmon et al. 2003, Yeow et al. 2004). As apparent slip phenomenon has been reported to occur in polymer solutions and concentrated materials (Chakrabarti 1995, Steffe 1996), the phenomenon of slipperiness will be highlighted in this study regarding individual's MITP, bolus rheological measurements, perceived ease of swallowing and perceived bolus flow behaviour.
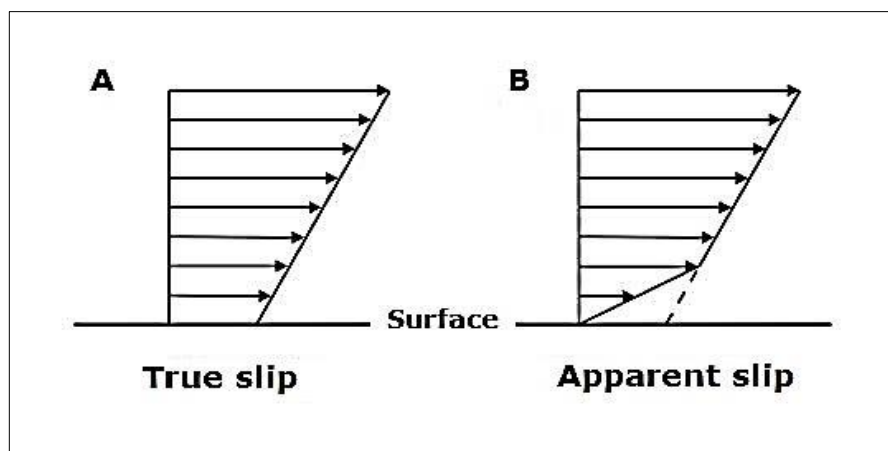
Figure 5.2 Illustrations of (a) true slip and (b) apparent slip mechanisms on a solid surface, adapted from Peters (2008)

Thus, with this background, the goal of the current study was to investigate the hypothesis that if tongue pressure exceeds a certain limit, it will then enable individual to perceive bolus flow behaviour and also to perceive ease of swallowing bolus with higher consistencies compared to individuals with low tongue strength capability. In order to explore this hypothesis, 23 healthy subjects of both genders were invited to experimental tasks to investigate the relationships between individual's MITP and their perception of bolus flow behaviour, perceived ease / difficulty of swallowing and also oral residence time (ORT) of different food bolus consistencies. We utilised simple, repetitive, reliable methods which are easily adopted for primary sensory of perceived ease / difficulty of swallowing and perceived bolus flow behaviour.

5.2 Materials and Methods

5.2.1 Preparation of Ready-to-Swallow Food Samples

Materials used in this work were: Lyle's golden syrup (Lyle's Golden Syrup Tate and Lyle Nottinghamshire, United Kingdom), mashed potato (Instant Mashed Potato [Smash brand], Premier Foods PLC., St Albans, Hertfordshire, United Kingdom) and super-concentrated orange juice (Sunquick - Orange Drink Concentrate, Co-Ro Food, Ellekaer Frederikssund, Denmark). They are commercial products purchased from a local supermarket (Morrison and Tesco, Leeds, U.K.). Xanthan gum (One On Internet Company Ltd., Bristol, United Kingdom) was online purchased from One On Company.

Four sets of ready-to-swallow food samples were prepared for swallowing test which are golden syrup (GS), mixture of concentrated orange juice xanthan gum (COJXG), super concentrated orange juice (SCOJ) and mashed potato xanthan gum ratio (7 grams of MP to 3 grams of XG; MP:XG). Different water temperatures were used (at 25 °C to

dilute GS and 100 °C to constitute MP:XG mixture). In order to producing concentrated orange juice (COJ) in amorphous state, a steam jacketed kettle (Food Technology Lab at Leeds University) was used for evaporating process at 100 °C as a function of time (minutes). At this temperature, the COJ sugar remained in the solution during water removal processes (evaporation). Therefore, the SCOJ samples recognised as supersaturated sugar solutions.

5.2.2 Rheological Measurements of Ready-to-Swallow Food Samples

5.2.2.1 Constant Shear Measurements

This work was built up on the steady shear rheological measurements of four food samples featuring different properties by a Kinexus rotational rheometer (Malvern Instruments Ltd., Gloucestershire, U.K.). To obtain steady shear data, a cone-plate geometry CP2/60 (60 mm diameter and 2° angle cone) was used in order to study the flow viscosity of the samples. Apparent viscosity as a function of a constant shear rate of 10 per second was also measured at 25 °C for 10 minutes. The reported results were expressed as an average of the three measurements. As summarised in Table 5.1, the matched apparent viscosity ranges was categorised for Newtonian and non-Newtonian thickened liquid/food samples by considering a range of consistencies between adjacent stimuli which is an appropriate approach to cover a range of viscosities and also to give a reasonable discrimination between the consistencies during sensory tests. Selective samples were used based on matched viscosity ranges from 1.5 – 48 Pa.s (as highlighted in light grey in Table 5.1). Below or above these ranges, samples become too liquid or too solid to be swallowed as ready-to-swallow bolus. Thus matching apparent viscosity of the food samples at the swallowing point can be compared with individual's swallowing capability (the tongue pressure).

Table 5.1 Selective matching apparent viscosity ranges used during swallowing test (light grey rows) as a function of concentration (%) and evaporation time (minute) for Newtonian (GS) and non-Newtonian food samples (COJXG, SCOJ and MP:XG). Sample code from 1-6 was used in the questionnaire (Appendix 2)

Sample Code	Matched apparent viscosity	Food samples			
		GS	COJXG	SCOJ	MP:XG
	at shear rate (10 s^1)	%	%	Minute of evaporation at $100°C$	%
	0.8	89	0.1	1	0.5
	1.2	90	0.2	5	1
1	1.5	92	0.3	10	2
2	3	94.5	0.45	20	3
	5	95.9	0.6	29	4
3	6	96.5	0.7	35	5
	9	97.4	1.2	46	7
4	12	98.2	1.5	50	8
	18	99	2.2	55	11
5	24	100	2.7	60	14
6	48	-	5	85	36
	50	-	8	97	44

5.2.2.2 Dynamic Shear Measurements

Studying the mechanical behaviour of food materials is complicated by the fact that their response is viscoelastic, intermediate state between that of solid and liquid. Dynamic shear rheological (oscillatory) measurements is a standard experimental of rheological characterisation for studying such behaviour because by varying the amplitude and frequency of the applied strain, a wide range of timescales and behaviours can be studied (Anseth et al. 1996, Larson 1999, Macosko 1994, Steffe 1996). Therefore, oscillatory measurement provides new insights about the physical mechanisms that govern the unique mechanical properties of soft materials. In this work, we limited our

discussion to small amplitude experiments within the linear viscoelastic region (LVER) which allows an investigation of SCOJ and MP:XG samples responses without disruption of their structures.

5.2.2.2.1 Linear Viscoelastic Region (LVER)

Prior to the dynamic shear rheological measurements, the applied shearing must be very gentle in order to study the structure of food materials without destroying. One way to achieve this is to apply an oscillating shear to the material with low amplitude level at a fixed frequency (ω) (1.0 Hz). Within the LVER, the materials response is independent of the magnitude of the deformation and the food materials' structure is maintained intact (undamaged). Therefore, an undamaged structure can be studied. Characterisation of the foods within the linear region yields a "fingerprint" of the food structure and it can be measured using a strain sweep test. In a strain sweep test, the frequency of the test is fixed and the amplitude is incrementally increased. The LVER of SCOJ and MP:XG were to strain amplitude of 0.1 and 1.4 % respectively. The dynamic shear rheological measurements were conducted in triplicate. The reported results were expressed as an average of the three measurements.

5.2.2.2.2 Small Amplitude Oscillatory Shear

Once the LVER is determined, a frequency sweep at a stress in this area can be used to determine the nature of food materials. In a dynamic experiment, when a sinusoidal force is driven into a material with small amplitude, the resulting stress and strain fields will also be sinusoidal and differing by the angel phase (δ). δ usually refers to the ratio of viscosity's contribution to elasticity's contribution within the system (Figure 5.3). A purely elastic material will have a phase shift of δ equals 0°, whereas a purely viscous material will have stress and strain perfectly out of phase,

or δ equals 90°. If the material is viscoelastic, which means that the phase shift will be between 0° and 90°, and the stress is maintained within the LVER, useful parameters such as the storage modulus (G') and loss modulus (G'') can be derived from the material responses stress and strain output which will be studied.
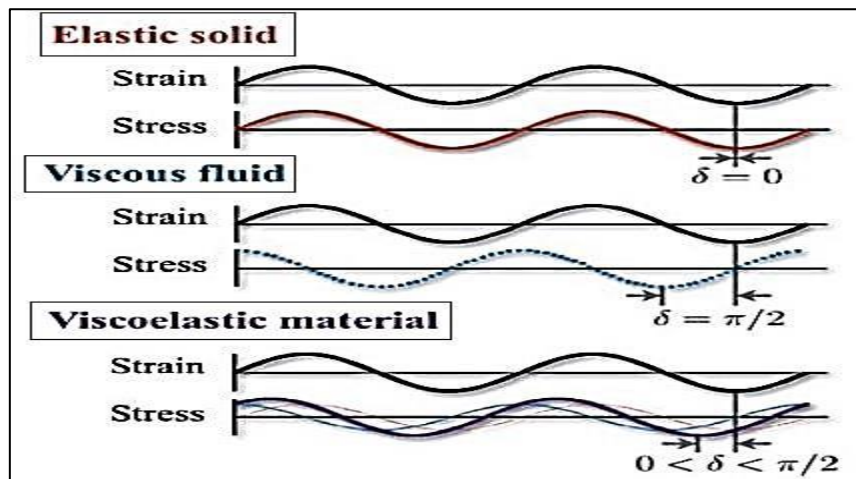
Figure 5.3 Schematic picture of phase angle between stress and strain for elastic solid, viscous fluid and viscoelastic materials (Wyss et al. 2007)

5.2.2.2.3 Moduli of Storage (G') and Loss (G'')

In general, the food materials can respond to the frequency sweeps of the deformation through two standard viscoelastic properties: the storage (elastic-like) modulus (G') and the loss (viscous-like) modulus (G''). G' refers to the material's ability to store energy per unit volume due to the material transfers the applied stress with no storage of the energy. Similarly, G'' is related to the dynamic dissipation of energy per unit deformation rate per unit volume when stress and strain shift 90° from each other. Additionally, G' is proportional to the extent of the elastic component (contributed by crosslinking, entanglement, and/or aggregation) of the system, and G'' provides information on how much portion of the energy investment for food deformation in order to understand the food flow behaviour.

In order not only to determine the LVER but also to investigate the storage modulus and the loss modulus in small frequency sweep measurements were firstly performed for all prepared SCOJ and MP:XG of different apparent viscosities by using a Kinexus rotational rheometer equipped with a parallel-plate geometry with a diameter of 50 mm and a gap size of 3.0 mm. These sweep tests were carried out at an isothermal condition of 25 °C and covered the frequency sweep range from 0.01 to 10 Hz with a logarithmically increasing scale at a fixed angular frequency of 1.0 Hz. At a suitable strain so that G' and G'' were still within the LVER. Each measurement was repeated in triplicate.

5.2.3 Sugar Content

A hand refractometer (range 0-80 % Bellingham and Stanley Ltd, Tunbridge Wells, UK), which is optical instrument that measures the amount of light refracted as it passes through a liquid, was used to determine the amount of sugar (solid) content in percentage Brix for golden syrup (GS) and super concentrated orange juice (SCOJ) samples (Table 5.2). SCOJ samples of higher sugar concentrations are recognised as a rubbery amorphous (non-crystalline) food form in which their molecules have a lack of organised crystal structure (such as lollipops, taffy, and caramel candies) (Brown 2010, Labuza et al. 2004, Mcwilliams 2007).

Table 5.2 Total sugar content of golden syrup and super concentrated orange juice samples. Numbers from 1 to 6 refer to the apparent viscosity values from 1.5 to 48 Pa.s. Sample code from 1-6 was used in the questionnaire (Appendix 2)

Sample Code	1	2	3	4	5	6
GS	31	42	54	59	65	—
SCOJ	56	63	76	High (>80)	High (>80)	high (>80)

5.2.4   Sensory Evaluations of Swallowing

5.2.4.1 Subjects

23 healthy consenting adults, who do not have a problem with their swallowing, of both genders (9 males and 14 females) with different ages (32 ± 9.0 years; aging between 21 and 60 years) were recruited. Before informed consent and taking part in this study, subjects were given a brief instruction regarding the overall purpose of the study, procedures, how long it would take, and what would be recorded during the test. Additionally, a ten-pound shopping voucher was awarded to each subject for participating in this study. Ethical approval for the study was obtained from the Faculty Ethics Committee at the University of Leeds.

5.2.4.2 Test Procedures

At first, classification of individuals' MITP was measured using IOPI (Figure 5.4A). Secondly, subjects were self-handed teaspoons for each sample in a set, moving from right to left, of increasing apparent viscosity (1.5, 3.0, 6.0, 12, 24 and 48 Pa.s) indicated by the numeric labels 1, 2, 3, 4, 5 and 6 respectively. Except GS samples were only 5 samples. As shown in Figure 5.4B, sample presented in positions 1 and 2 on the lower row of the tray for GS and COJXG, and in positions 3 and 4 on the upper row of the same tray for SCOJ and MP:XG. Subjects were appraising their perceived ease / difficulty of swallowing using questionnaire (Figure 5.4D and appendix 2). They were allowed to describe their perception of the bolus flow behaviours during swallowing supported with a videofluoroscopic image-describe sheet of bolus entry in the oral-pharyngeal-oesophageal track (Figure 5.4E and Figure 5.6). However, subjects were not asked to comment on taste, colour and flavour or sensory preference. They were also instructed to expectorate the sample that cannot be swallowed into a waste container. They then used the cup of water provided to rinse mouth between evaluations and rest periods were given when needed. Followed sections are a detailed description of each task.
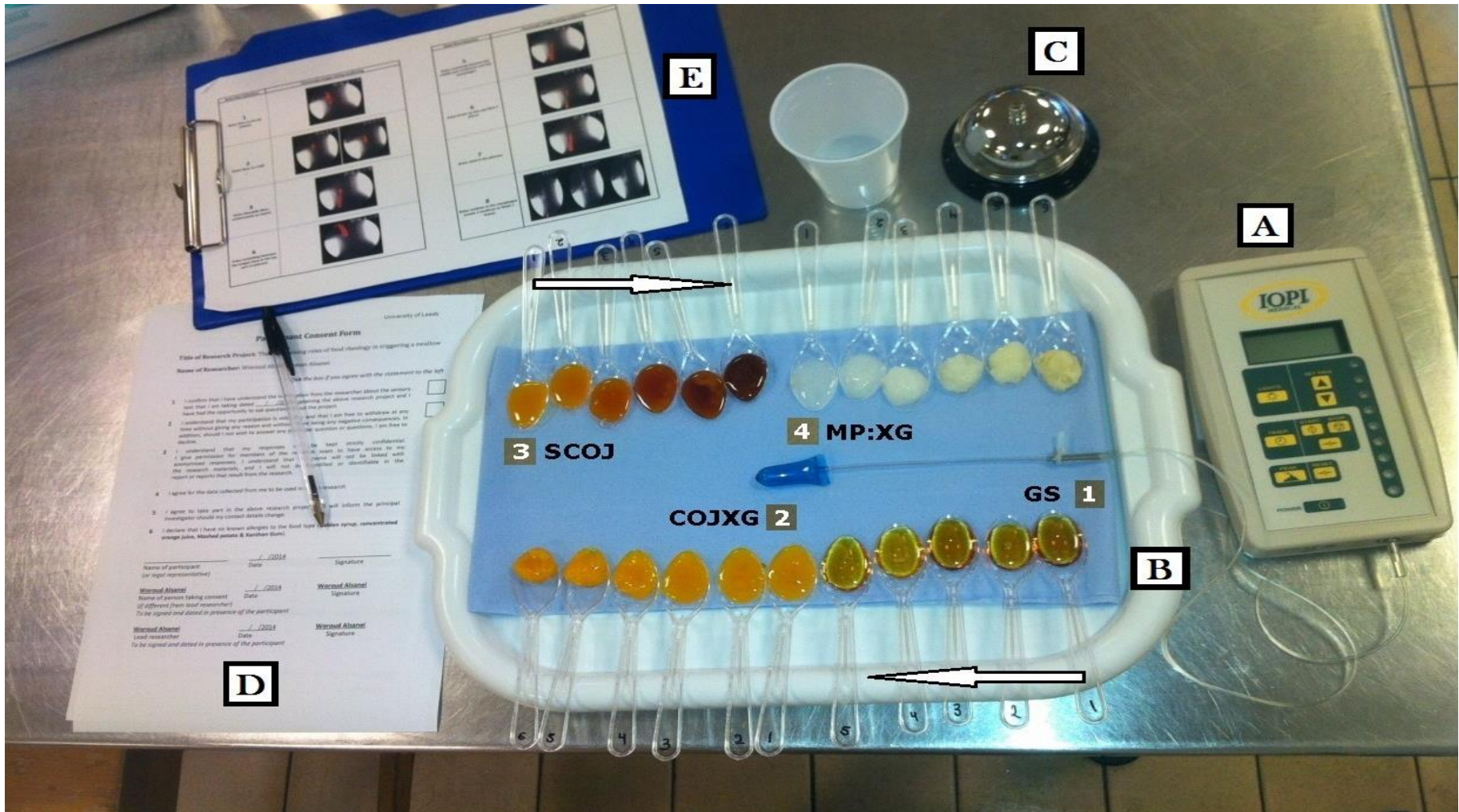
Figure 5.4 Presented photo of the experimental setup of swallowing tests for Newtonian and non-Newtonian food samples (A) IOPI device (B) four sets of food samples (C) a hand bell (D) evaluation questionnaire form and (E) a videofluoroscopic image-describe sheet. Sample code from 1-6 was used to name the spoons and also used in the questionnaire (Appendix 2)

5.2.4.2.1 Tongue Strength Capability

Tongue strength in the form of pressure was recorded five times with a short rest period of 30 s to 1 minute between measurements for each subjects using IOPI technique (Figure 5.4A). The mean values were defined as maximum isometric tongue pressure (MITP).

5.2.4.2.2 Perceived Ease / Difficulty of Swallowing

Each subject seated comfortably at a table containing a tray of tested samples and swallowing evaluation questionnaire that designed to assess their capability to swallow with ease. As shown in Figure 5.4B, the tray contained two rows of teaspoons with each containing a five-gram of test sample volume. This volume was chosen based upon our previous study that indicates the most comfortable volume to swallow by leaving oral structure substantially clear of bolus residue (Alsanei and Chen 2014). The test was organised so that the bottom row contained GS and COJXG, and top row contained SCOJ and MP:XG. Subject was instructed to take the sample in increasing order from the spoon into their mouth. To be familiar with the taste of the samples, subject was given a random sample of each set to taste. For swallowing, the subject was asked to allocate each sample at the posterior one-third of the tongue as it is medicine syrup to limit the time for the bolus to stay inside the oral cavity and to minimise saliva mixing and viscosity changes (Figure 5.5A and 5.5B). He/she was asked to describe his/her perceived ease / difficulty of swallowing using questionnaire provided in appendix 2.
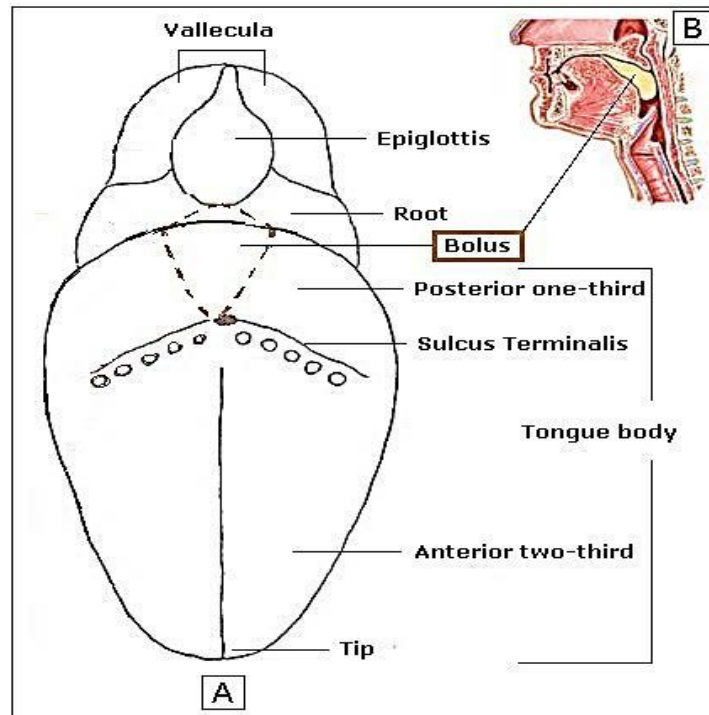
Figure 5.5 Schematic illustration of the ready-to-swallow bolus position as it is medicine syrup (A). (B) A cross-sectional view of the bolus position during the swallowing reflex when the tip of tongue in contact with anterior part of hard palate; reproduced from Dowdey (2007) and Massey (2006)

For each bolus in each set, subjects were observed from the side and the number of swallows. The later was counted by observing the movement of laryngeal elevation. After swallowing each bolus, the subject was asked to assess the bolus flowability through their oropharynx by reporting their perception of ease / difficulty swallowing using the questionnaire provided. The associated questionnaire was designed with a table of five categories which are *easy to swallow*, *moderate to swallow*, *difficult to swallow*, *very difficult to swallow* and finally *cannot swallow*. These categories were used by subject to rate his/her perceived ease / difficulty of bolus flow for each sample. In the event that the subject felt and reported that he/she is facing difficulty in swallowing. This means that the bolus is difficult to swallow and the bolus viscosity at this level defines as a cut-off point of perceived difficulty in swallowing. Further analysis of these results will correlate with individual's MITP (Alsanei and Chen 2014).

5.2.4.2.3 Perceived Bolus Flow Behaviour

After each swallow, subject was asked to describe the flow pattern of each bolus as the bolus moves through the oropharynx into the oesophagus. The description based on subject's sensation supported with a videofluoroscopic image-describe sheet of bolus entry in the pharynx designed by the researcher for non-specialists (Figure 5.6). In the associated sheet, two tables categorised with "bolus flow pattern" and "bolus flow position" during swallowing to facilitate their discretion. The possible patterns of the bolus flow were coded by numbers with briefly descriptions. Each number refers to a specific image. According to the subject, these categories mirror the sensation of bolus flow pattern as well as the potential for defining the bolus flow behaviour along oral-pharyngeal-oesophageal track for each sample.
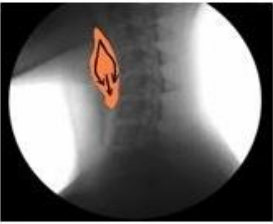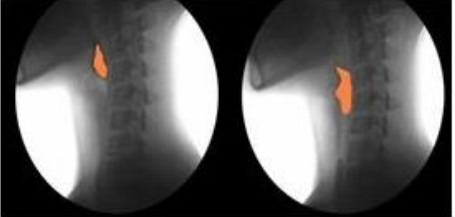
Bolus flow pattern	Bolus flow position	Bolus flow pattern	Bolus flow position
1 Bolus flow as water		**5** Bolus stick in the pharynx and in the oesophagus (needs more swallows to finish one bolus)	
2 Bolus sliding with slip sensation		**6** Bolus flow as a ball	
3 Bolus stretching between the tongue base & the top part of pharynx		**7** Bolus slip very fast as mushroom and oyster	
4 Bolus stretching between the middle part of pharynx and the oesophagus		**8** Bolus break up and flow as pieces	

Figure 5.6 A videofluoroscopic image-describe sheet of bolus entry in the oropharynx (Smoupnhoize 2010)

5.2.4.2.4 Oral Residence Time

Trained subjects were asked to place the bolus on the posterior one-third of the tongue as shown in Figure 5.5. They were also trained to ring the hand bell provided as an indication of the time to swallow from starting until finishing. Thus a stopwatch was started and stopped, respectively by the researcher for timing the oral residence time (ORT). In this study, ORT per swallow defined as the number of seconds needed after placing the ready-to-swallow bolus on the posterior one-third of the tongue until the completion of swallowing.

5.2.5 Statistical Analysis

Summary of statistical analysis was made by using statistical package for the social sciences (SPSS) 21 (SPSS Inc., Chicago, IL). Mean and standard deviation (SD) values for age and maximum isometric tongue pressure were calculated. Correlations between the tongue strength and the cut-off point of perceived difficulty in swallowing with increasing viscosity for tongue pressure groups were also assessed. The correlations were obtained between the maximum consistency swallowed with reported ease for GS, COJXG, SCOJ and MP:XG samples and individual's MITP.

5.3 Results and Discussions

5.3.1 Tongue Strength Capability

From Figure 5.7, MITP of 23 healthy subjects aging between 21 and 60 years was plotted as a function of age for both genders. The range of the MITP is relatively varying, from as low as only 18 kPa to as high as 75 kPa. The MITP profile indicates that no statistical significance in the capability of tongue pressure generating with the *P* value <0.05 for both male and female subjects (50 ± 13 kPa and 51 ± 12 kPa) respectively.

Consistent with our previous investigation, there has been relatively similar findings about the MITP as a function of age under 65 years old using IOPI (Alsanei and Chen 2014).
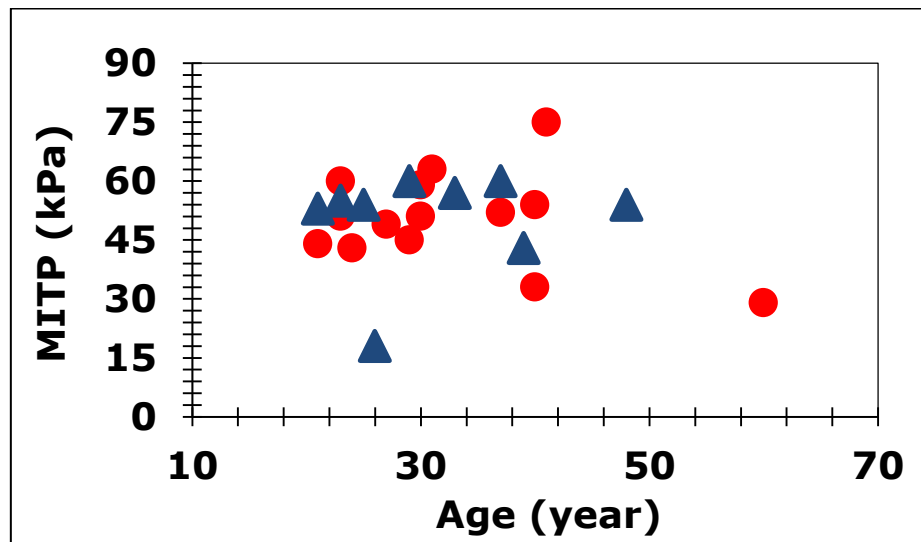
Figure 5.7 Maximum isometric tongue pressure (MITP) performance for both males (▲) and females (●) aging between 21 and 60 years)

5.3.2 Perceived Ease / Difficulty of Swallowing in Relation to Viscosity

From Figure 5.8, the individuals' cut-off point of perceived difficulty in swallowing of various boluses for Newtonian GS and non-Newtonian foods COJXG, SCOJ and MP:XG were plotted and evaluated as a function of their MITP. Careful analysis of the data distribution reveals a few important facts. It shows the distribution of individuals' cut-off point of perceived difficulty in swallowing if populations are divided into two MITP groups: low tongue pressure (≤ 45 kPa) and high tongue pressure (> 45 kPa) with an average MITP 38 kPa and 57 kPa, respectively. From our results, we can conclude that the cut-off point of perceived difficulty in swallowing for low MITP group scatters in various ranges when swallowing GS, COJXG, SCOJ and MP:XG with average of apparent viscosities 12, 12, 24 and 6.0 Pa.s respectively. Comparing with low MITP group, the high MITP group scatters in a narrow range for same samples but with different average of apparent viscosities 12, 24, 24 and 12 Pa.s

respectively. It is evidence that for very strong tongue pressure group, they have a great confidence and competence in dealing with various boluses. Ultimately the data indicates that the properties at the swallowing point can be compared for these samples against individual's swallowing capability (tongue pressure strength).
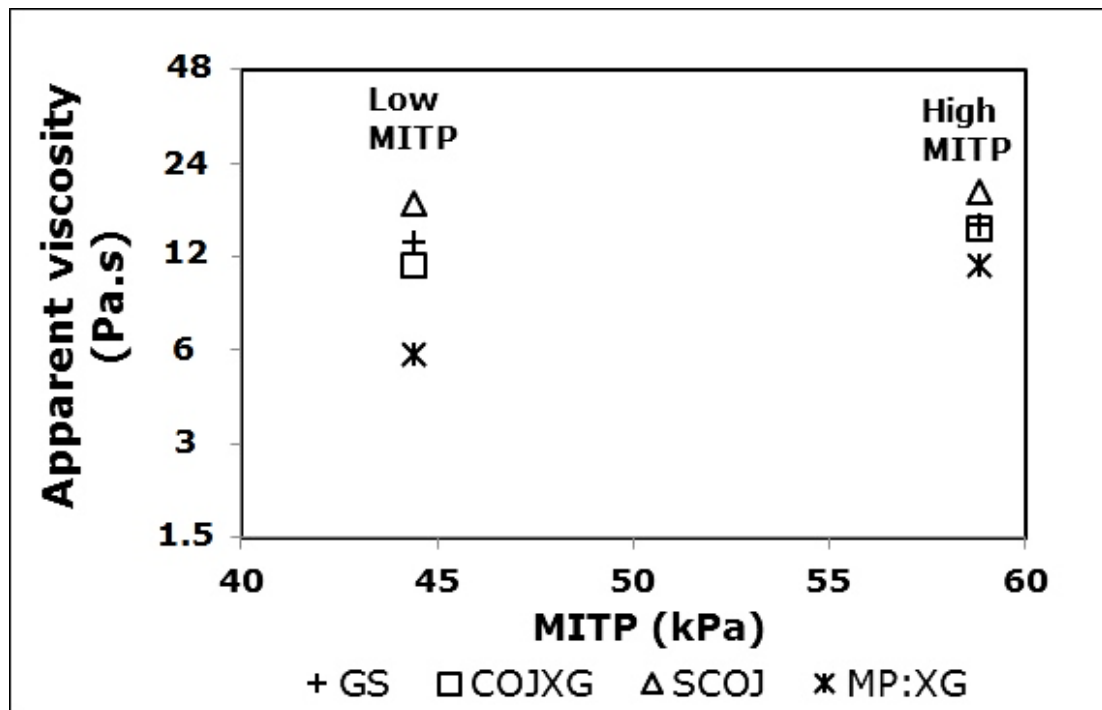
Figure 5.8 Individuals' maximum physiological capability in creating tongue pressure and their cut-off point of perceived difficulty in swallowing with increasing viscosity. Numerical numbers from 1 to 6 on y-axis refer to the apparent viscosity values from 1.5 Pa.s to 48 Pa.s of different food bolus: golden syrup (GS), mixture of concentrated orange juice xanthan gum (COJXG), super concentrated orange juice (SCOJ) and mashed potato xanthan gum (MP:XG)

On the other hand, the cut-off point of perceived difficulty in swallowing COJXG and MP:XG was found to be significantly different between the low tongue pressure and high tongue pressure groups, 12 and 6.0 Pa.s for low MITP group and 24 and 12 Pa.s for high MITP group, respectively. The difference was statistically significant for both groups with P value = 0.005. In particular high MITP group appears to be more capable to swallow high viscous food samples with ease for COJXG and

MP:XG samples of high xanthan gum concentrations (i.e. polysaccharide with a very high molecular weight) 2.77 % and 8.0 % respectively. In contrast, subjects with low MITP (≤ 45 kPa) struggle to different extent in dealing with different boluses, to some extent, they were able to swallow COJXG and MP:XG samples with ease but with lower concentrations (1.55 % and 5.0 % respectively). Based on previous experimental findings by Alsanei and Chen (2014), these results agree with the hypothesis that one's capability to generate tongue pressure could be related to the ease with which one can swallow. Pouderoux and Kahrilas (1995), Nicosia et al. (2000) and Miller and Watkin (1996) also reported that the force of tongue propulsion increases when a bolus of greater viscosity is introduced. On the other hand, both groups tend to have a close cut-off point of perceived difficulty in swallowing for GS and SCOJ samples with an average apparent viscosity of 12 and 24 Pa.s; respectively. Moreover, the difference between two groups was small and has no statistical significance with the *P* value of 0.005.

One can see that in the case of GS, it is not only recognised as a common food but also a familiar taste with high sugar content (around 65 %Brix) for consumers. Additionally, the viscosity of GS at room temperature is about 10^5 times when compared with water viscosity at same temperature. Therefore, GS is considered as a viscous fluid undergoing laminar flow (Figure 5.1A) (Muncaster 1993). Under shear rate, its flowability classifies as a typical fluid of a Newtonian fluid that which means that viscosity does not change when subjected to change in shear rates (e.g. 10 and 50 s^{-1}) as shown in Figure 5.9. These facts can explain the reason for the reported ease of swallowing GS at high viscosity levels even when there is a difference in both the tongue propulsion force and tongue shear rate applied by the two MITP groups during swallowing. GS viscosity remains constant as increasing or decreasing the shear rate. Based on an assumed oral shear rate, it was reported in previous literature studies the shear rate used by healthy individuals can be approximately 50 s^{-1} and the lowest shear rate can

reach 10 s^{-1} (as discussed in Chapter 2; section 2.8.1.2). Thus individuals' with low tongue pressure used the later shear rate for swallowing the maximum Newtonian viscosity with ease as much as the high tongue pressure group if they used shear rate of 50 s^{-1}.
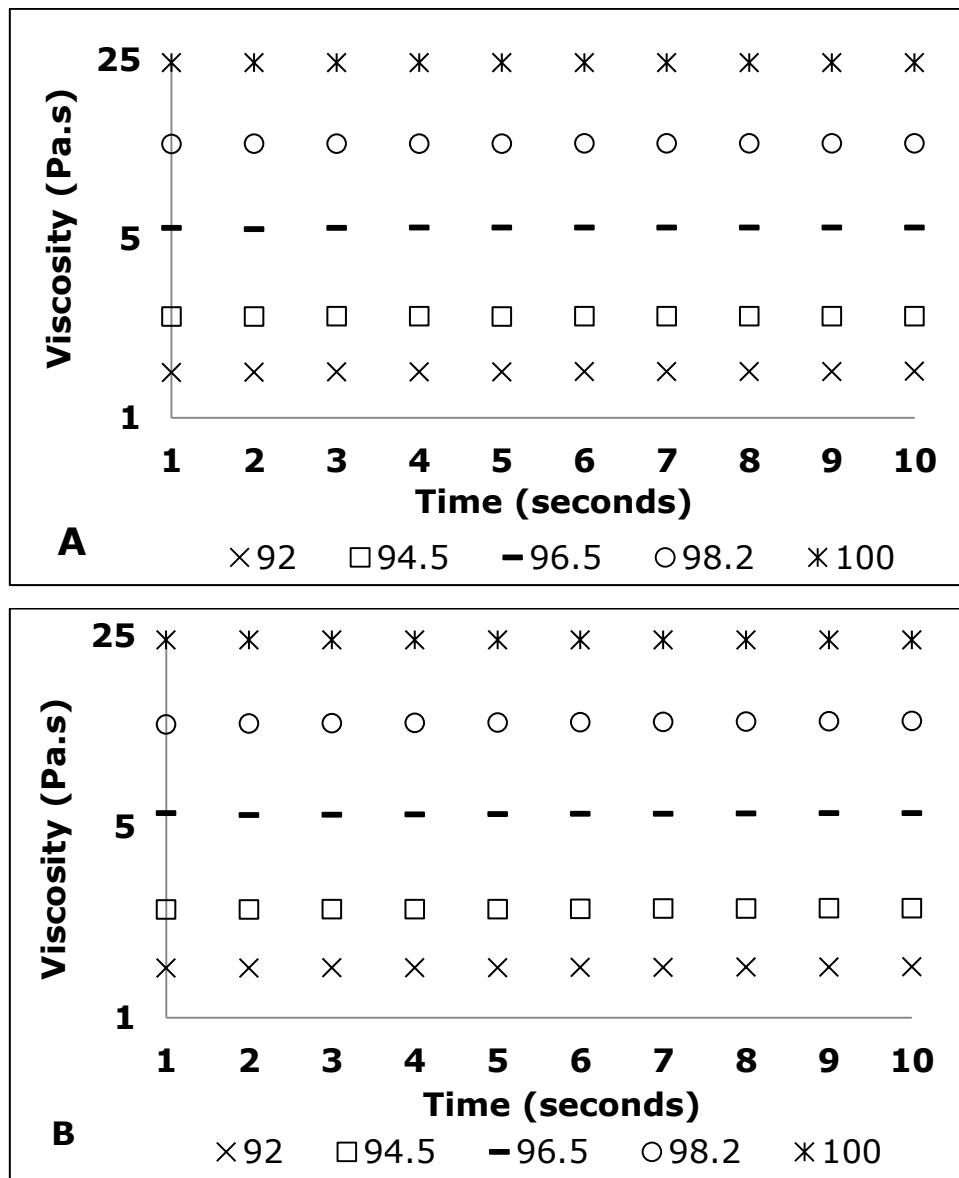
Figure 5.9 Viscosity measurement of Newtonian GS samples (%wt/wt) as a function of time at 25 °C and a consistent shear rate (A) 10 s^{-1} and (B) 50 s^{-1}

This work also explored the influence of viscosity on the easiness of swallowing SCOJ. We assume that it has different explanation for the bolus of high viscosity level (($\geq$ 12 Pa.s) and also high sugar content (>

80 %Brix). By studying the flow of non-Newtonian SCOJ, it exhibits a shear thinning (Pseudoplastic) behaviour. This behaviour means that once the minimum shear stress has been reached, the fluid thins which thus leads to a decreased viscosity with increasing shear rate (Figure 5.10). We proposed, for simplicity, a reason for a relatively close level in swallowing capability of such bolus by the two MITP groups. It can be explained by the creation of thin boundary layers around the bolus (that have lower levels of viscosity or fluidity than the intra-bolus viscosity). These boundary layers could lead to a substantial change in the bolus velocity.

Figure 5.10 Viscosity measurements of non-Newtonian SCOJ samples as a function of increasing shear rates from 0.01 to 100 s^{-1} at 25 °C. Minutes here indicate sample name used as shown in Table 5.1

First to illustrate the viscosity change in basic terms of food oral processing, ready-to-swallow SCOJ bolus on the top surface of the tongue (served at room temperature) has an initial temperature before swallowing starts. Based on this fact, the assumption is that during swallowing a friction relates to the force between surfaces of the bolus

and tongue-palate resulting in a thin layer near by the oropharyngeal walls being sheared. This contact leads to bolus temperature gradually change either increase or decrease. Therefore, the thermal diffusivity of the oral temperature into the bolus occurs (known as a heat transfer). Hence, bolus faces almost instantaneous alteration of its temperature caused by the influence of swallowing pathway temperature (Tripathi 2011) and the shear acting by the oropharyngeal walls during the bolus movement. This justification relies on the assumption that this change in temperature is initiating a gradual viscosity change as suggested by Stanley and Taylor (1993). Consequently, the bolus surface viscosity (bolus boundary layer) decreases (thins) when compared to the intra-bolus viscosity of the bolus. This phenomenon indicates that the viscosity change on the bolus surface affects the bolus velocity and bolus flow behaviour. Noteworthy, high MITP group sensed directly that SCOJ boluses of highly viscous levels ($\geq$ 12 Pa.s) display a change in the bolus flow behavioure from stretch bolus flow to sliding bolus flow in the form of apparent slip flow during swallowing. The creation of low viscosity levels on the bolus surface may be variable between MITP groups.

After extended discussion with subjects with high MITP participated in this task, the bolus with apparent slip flow pattern defines as a sensory attribute describing the ease of bolus movement along contact surfaces (i.e. tongue and oropharynx) while maintaining a constant level of its original viscosity and smooth surface. Meaning that, such bolus flows rapidly through the oropharynx with less likely to sense the post-swallow residue (bolus accumulation in the pharynx with thicker consistencies and/or remains on tongue base) or frictional resistance of the bolus movement into the rest of the swallowing apparatus. Further exploratory discussion will be to investigate SCOJ bolus flow pattern and establish firmer relationships between the individual's capability of swallowing SCOJ samples, their tongue strength and SCOJ rheological properties (i.e. viscosity and viscoelasticity).

5.3.3 Factors that Influence Perceived Bolus Flow Behaviour for SCOJ

5.3.3.1 Tongue Strength

From Figure 5.11, positive correlations were observed between individuals' scored easy-difficult-easy switching points of swallowing SCOJ bolus of thicker apparent viscosities and their MITP (individuals who were able to score easy-difficult-easy switching of points for swallowing SCOJ; Appendix 3). Where the values of y-axis from 1 to 5 refers to the labels used in the associated questionnaire form during the swallowing test: 1 *easy to swallow*, 2 *moderate to swallow*, 3 *difficult to swallow*, 4 *very difficult to swallow* and 5 *cannot swallow*. When the apparent viscosity of SCOJ bolus is higher than 12 Pa.s, a sudden pattern change is observed in the behaviour of scoring easy-difficult-easy switching points of swallowing across tongue pressure groups. One can see that subjects whose MITP falls below 45 kPa (low MITP), they show a gradual increase in the sensitivity of having swallowing difficulty with bolus of increased consistency. While those, whose MITP exceeds 45 kPa (high MITP), show a favourable change in the easiness of swallowing SCOJ. Thus, a positive correlation is clearly evident between one's capability to generate high tongue pressure and maximum bolus consistency swallowed with ease.
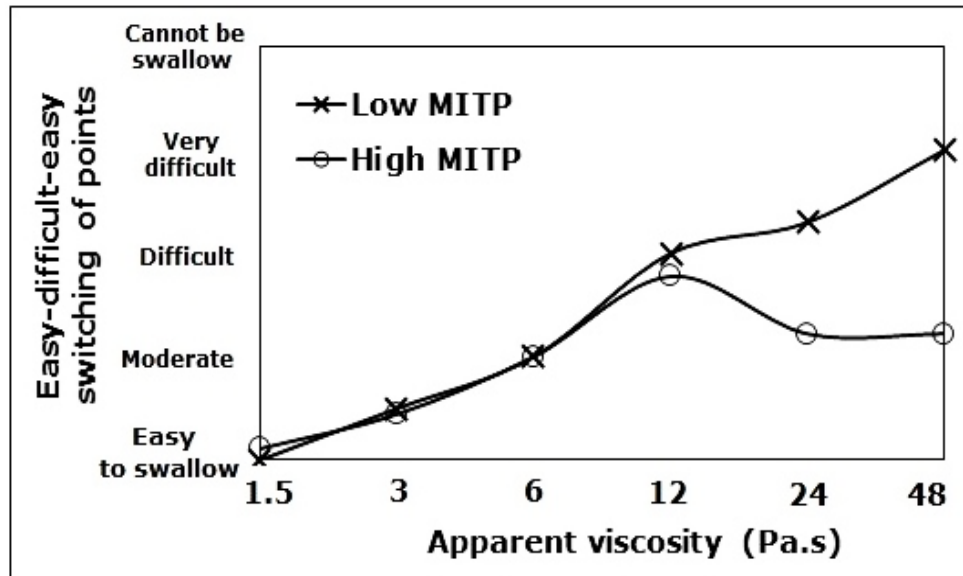
Figure 5.11 Correlations between individuals with low and high MITP groups and their scored easy-difficult-easy switching of points for swallowing as a function of apparent viscosity of super concentrated orange juice (SCOJ)

5.3.3.2 Bolus Formation and Boundary Layer Creation

A firmer evidence of high tongue pressure application may lead to exploration of a broader range of bolus flow characterisations during swallowing (perceived bolus flow behaviour) than those with low tongue pressure capabilities. Due to the higher viscosity of the SCOJ boluses, the creation of low viscosity boundary layers around the bolus surface occurs near to the oropharyngeal wall being sheared (Figure 5.12A). These layers define as the inside layers are formed around the bolus surfaces in close contact of the inside surface of the oropharyngeal walls. These layers prevent the bolus during flowing to be disturbed by sticking to the surface of oropharynx.
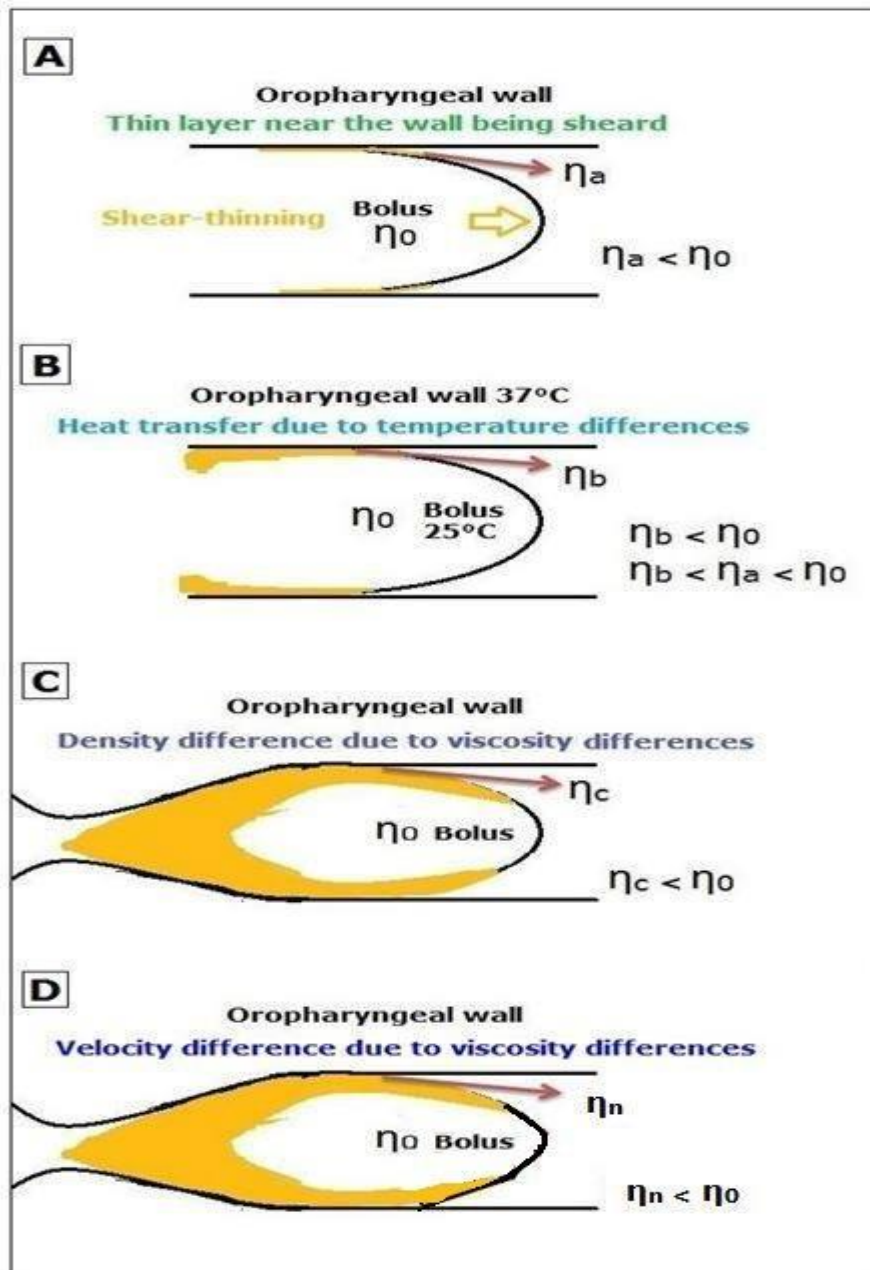
Figure 5.12 Simple schematic illustration of the factors that influence the SCOJ bolus flow behaviour: (A) the creation of a thin layer of high shear rate upon the surface near the wall being sheared, (B) heat transfer mechanism, (C) bolus viscosity differences (where η_0 means the original apparent viscosity of the SCOJ bolus; η_a means lower viscosity than η_0; η_b means lower viscosity than η_a and η_0; η_c means lower viscosity than η_b, η_a and η_0; η_n means the lowest viscosities than η_0) and (D) apparent slip occurs under above conditions in a very inhomogeneous thin layer of high shear rate upon the surface near the wall being sheared with different rheological properties than the essential homogeneous intra-bolus viscosity. It means that a low viscosity phase around the bolus creates a large velocity gradient near the wall to facilitate bolus movement and the intra-bolus velocity increases toward the centre of the cavity (Figure 5.2B)

As Hutchings and Lillford (1988) suggested that the degree of bolus surface lubrication during bolus breakdown reflects, to some extent, the changes in bolus rheology and bolus surface property that allow for swallowing and almost certainly relate to sensation of slip, rather than deformation (Stokes et al. 2013). Generally, individual's perceived ease with which a bolus flows is an indication of its viscosity (Chen and Lolivret 2011, Dingle and Tooley 2013, Ishihara et al. 2011). As a result, the high tongue pressure group was able to pass the lump of viscous bolus backward through the posterior oral cavity into the vallecular region of the tongue (or the piriform fossa of the pharynx) once its viscosity gradually changes (Pouderoux and Kahrilas 1995). For simplicity, we assumed that the relevance of bolus rheology and slippage of bolus boundary layers influence both the easiness of sensory perception and more critically aids the transport of the bolus from the oropharyngeal cavity into the rest of swallowing pathway. We predict that the sensory decision of individuals' with high MITP to pass bolus posteriorly with both sensation of ease and slippage flow influenced by the creation of thin boundary layers upon the bolus surface when flows. Beside the shearing effect between the surfaces, another possible factor of bolus boundary layer creation is caused by a thermos-physical (heat transfer) parameter between the surface of the bolus and swallowing contact areas (Figure 5.12B). Under these conditions, bolus rheological property is likely to change due to the operational of high bolus propulsion that individuals with high tongue strength produce by applying high shear stress and shear rate against the hard palate during swallowing.

5.3.3.3 Steady Shear Measurements

Instrumentally the SCOJ bolus viscosities displayed temperature dependence when compared the viscosity measurements at room and body temperatures as a function of increasing shear rates from 0.0 to 200 per second (Figure 5.13). It shows clearly a shear thinning flow behaviour that the viscosity decreases sharply with increasing shear rate and attains

a constant decrease after a certain shear rate for all SCOJ samples. In literature, the flow behaviour of the supersaturated sugar solutions can be explained on the basis of mobility (movement) of molecules under both temperature and shear rate effects. At room temperature (25 °C) and under low shear rates, the ability of the molecules to move around is small due to their low kinetic energy within a rubbery amorphous system of supersaturated sugar solutions, as evidence by the high viscosity samples. On the other hand, when the temperature increased up to body temperature (37 °C), this results in an increase kinetic energy of the sugar molecules. Spontaneously, this increase leads to a randomly distribution and mobility nature of the molecular organisation (a rubbery amorphous structure) meaning that: (1) there are spaces between the molecules of the sugar (the free volume) available for the motion of the molecules to move around quite easily (Doolittle 1951, Hartel et al. 2008), (2) the free volume leads to a significant increase in the mobility of molecules within such system (Abbas et al. 2010), (3) and resulting in an increase in the interaction between the molecules (through intermolecular forces) into which smaller molecules like water can diffuse (Husband 2014, Spencer et al. 2010), (4) thereby reducing the viscosity of the system (as illustrated in Figures 5.12C and 5.13) (Abbas et al. 2010, Labuza et al. 2004, Palzer 2010, Patidar et al. 2011). As a function of increasing shear rates (i.e. pharyngeal wall and peristaltic wave forces), it causes formation of distinct low viscosity layers around the bolus, which slowly penetrates into the intra-bolus viscosity that of higher viscosity, leaving behind large volume of thin viscosity layers during swallowing (as simply illustrated by η_n means lower viscosity than η_0 in Figure 5.12D). The slip occurs at the fluid-fluid interface instead of the fluid-solid interface, although it seems that the fluid slips at the wall (Peters 2008).

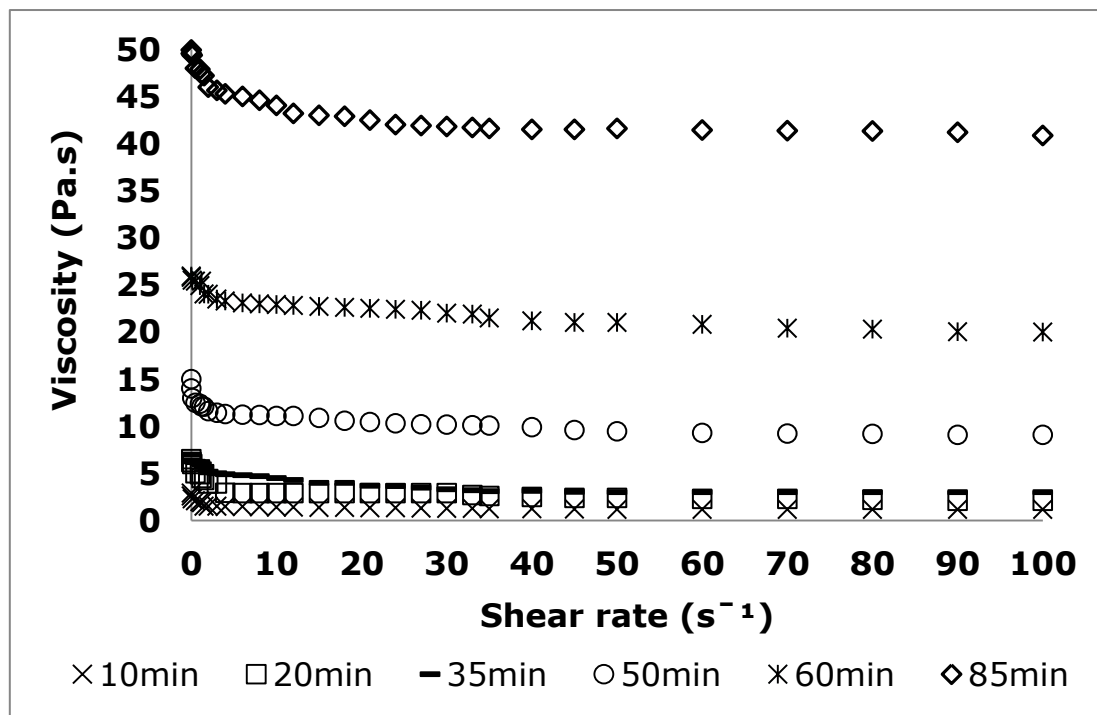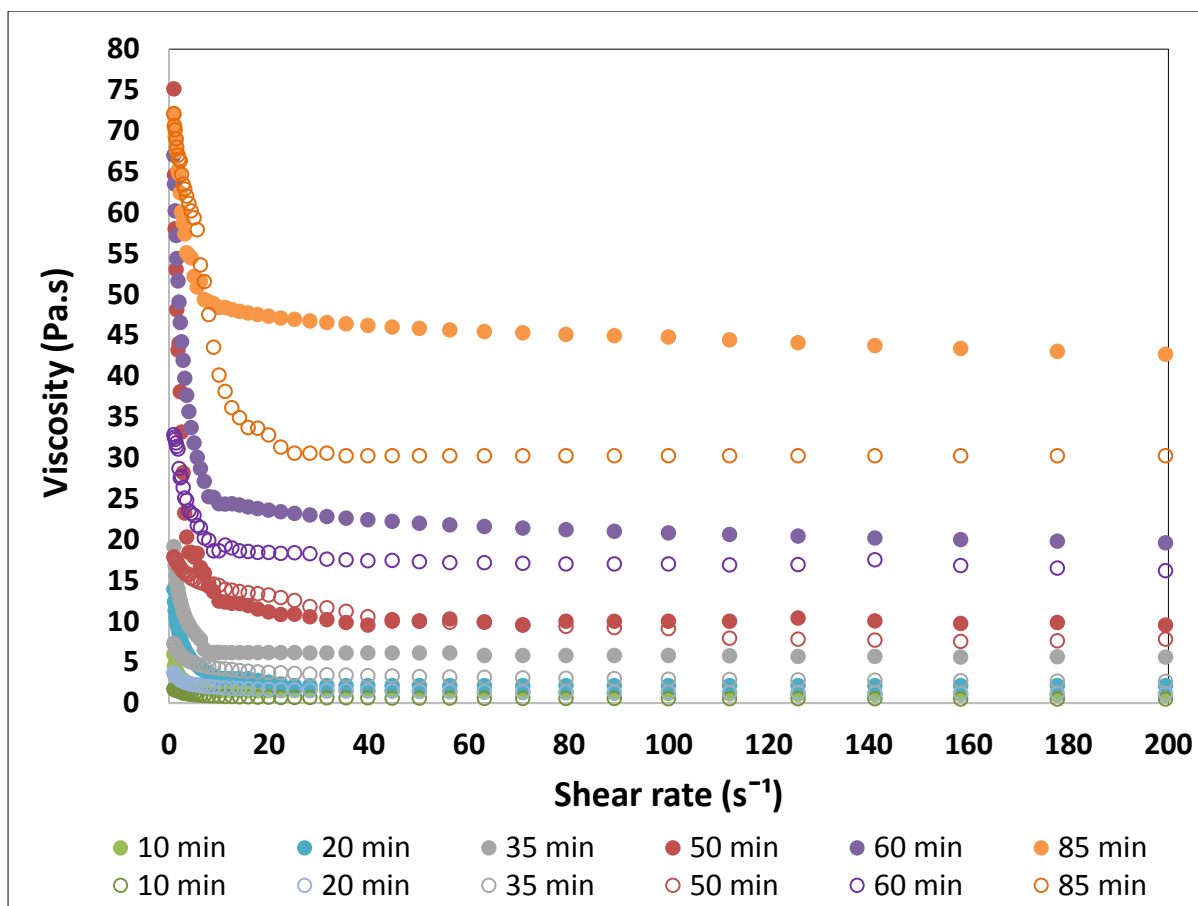**Figure 5.13** Viscosity measurements of SCOJ samples as a function of increasing shear rates from 0.01 to 200 s⁻¹ at both 25 °C (●) and 37 °C (o). Minutes here indicate sample name used as shown in Table 5.1

5.3.3.4 Sensory Evaluation

From the analysis of the instrumental and sensory panel data, we attempt to an interpretive approach for understanding the sliding SCOJ bolus flow behaviour with apparent slip flow for higher apparent viscosities (≥ 12 Pa.s) when the strong bolus propulsion force was applied by individuals with high MITP. This in turn resulted in forming a gradual change of the bolus viscosity surface that of high temperature than the intra-bolus viscosity. This change has a profound impact on its rheological properties by decreasing the viscosity of the bolus surface during the course of flow within an enclosed channel (Figure 5.14A and 5.14B). Though these boluses are classified to be supersaturated sugar solutions with rubbery amorphous state (Table 5.2), the formation of the thin

boundary layers occurs as following: (1) the SCOJ molecular layer in the contact with oropharyngeal surfaces tends to adhere and friction to the surfaces. (2) The next molecular layer of the SCOJ binds to the first layer by molecular attraction but tends to shear slightly. Therefore, it creates a movement with respect to the first static layer. (3) This process continues as successive layers shear slightly, relative to the under layers. (4) Spontaneously this process gradually increases in the velocity of the successive layer of the SCOJ. These thin layers act directly as lubricated layers around the bolus to limit both the frictional resistance and the frictional drag along the path direction of the bolus motion. Therefore, the bolus can be easily separated from the contact areas of the oropharyngeal walls (Figure 5.14C). In other words, the diluted boundary layers intend to facilitate bolus flow with the sensation of slipperiness by decreasing the negative effect (i.e. stickiness) of the bolus surface on the entire length walls of the swallowing channel in which is the case of low tongue pressure group. Due to insufficient creating low thin layers around the bolus surface by their tongue pushing force, their scored easy-difficult-easy switching of points for swallowing had shown an increased difficulty in swallow bolus of increased consistency (Figure 5.11).
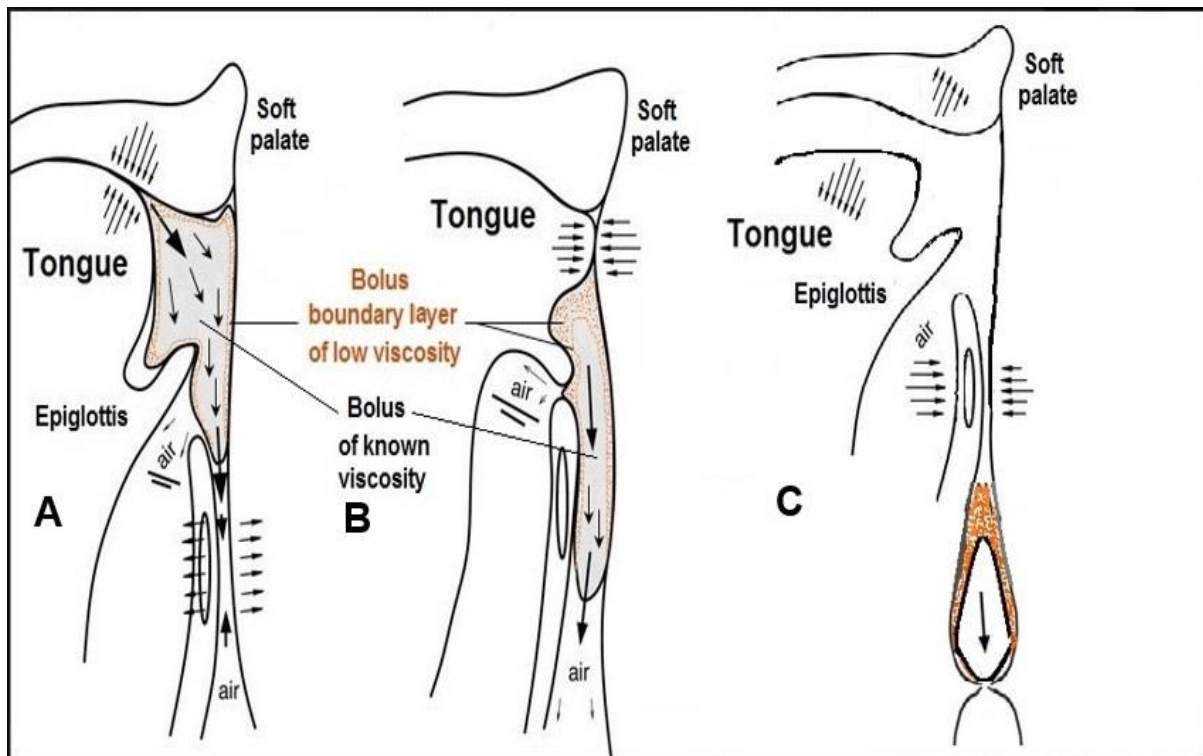
Figure 5.14 Schematic cross-sectional illustration of the SCOJ bolus motion with slip apparent flow and the thin boundary layers creation in the normal swallow. (A) Sliding bolus flow induces from both the tongue-palate acceleration and the creation of the bolus boundary layers by lowering the bolus surface viscosity. (B) The intra- bolus of higher viscosity moves from oropharynx into the oesophagus as a fast laminar flow. (C) As the intra-bolus moves faster than the boundary layers, the boundary layer flow separation is more likely to occur from the contact areas of the oropharyngeal walls causing bolus slipperiness through the mucosal surface of the oropharynx into the rest of swallowing apparatus; modified from Pal et al. (2003)

In this stage, it is important to illustrate the bolus slipperiness and the flow of the intra-bolus of higher viscosity (η_0) than the viscosity of the bolus boundary layers ($\eta_a < \eta_b < \eta_c < \eta_n << \eta_0$) which can be key factors that determine the bolus slipperiness on the surface with a maximum laminar flow velocity at the central line. To understand the laminar flow characteristic concept that influenced by bolus viscosity, under great stress and shear, each layer within the viscous bolus, which is far distance from the top of the bolus boundary layer, flow aligns vertically and slides over each other as in straight and order lines parallel to the cavity (Bangyeekhan et al. 2013, Barnes 1995, Johnson and Byrne 2003,

Magnin and Piau 1990, Meeten 2004, Nayak and Bhuvana 2012, Nguyen and Boger 1992, O'Leary et al. 2011, Olsson et al. 1994, Steffe 1996). This allows the layers to flow faster than the layer close to the oropharyngeal surface. We suspect that it is viscous forces which hold the intra-bolus together (Lucas et al. 2002, Prinz and Lucas 1997) and also prevents the intra-bolus to fall apart and dilute compared to the thin boundary layers around the bolus surface. These layers increase the slipperiness and the separation from the oropharyngeal walls. This explanation agrees well with the proposed of Peters (2008) that slip occurs at the fluid-fluid interface of lower viscosity layers rather than at the fluid-solid interface. More importantly, the greater the viscous bolus distance from the oropharyngeal walls exhibits the greater (maximum) the velocity of the bolus flow at the axial centre (Nave 2005) that tends to glide smoothly and greatly drag the flow from the surface of the oropharynx (no oropharyngeal residue and/or stickiness reported after the swallow). Along with increased pharyngeal pressure and relaxation of the upper oesophageal sphincter after immediate swallowing, the separated layers (with low viscosities than η_0) from the surface of the oropharynx flows behind the intra-bolus along the path direction of the motion. The separated layers may accumulate and increase both the bolus pushing force and speed (Figure 5.14C). Eventually, the bolus reaches terminal velocity which causes its weight force to be supported purely by drag force.

For low tongue strength capability and high viscosity samples, we expect that more potential problems with choking may arise from early swallowing when the bolus viscosity thins around the bolus surface as a result of increasing their salivary secretion causing further bolus dilution (slipperiness). It would be ideal for future studies to explore a narrow range of apparent viscosities than those tested in our experiment in particular the bolus of a rubbery amorphous state and also to determine the influence of saliva on slipperiness and flow of such bolus.

5.3.3.5 Dynamic Shear Measurements

In order to quantify the efficiency of swallowing function, the bolus rheological properties should to be studied not only in terms of apparent viscosity but also from different angles (i.e. bolus viscoelasticity) (Steele and Cichero 2008). Therefore, six representative oscillatory frequency sweep of SCOJ samples were studied for both the storage modulus (G') and loss modulus (G'') against the phase angle (δ) which appears as a red diamond shape in Figure 5.15. These figures show how SCOJ samples appear to be significantly viscous by having a large phase angle (> 45º) as a function of an increasing frequency from 0.0 to 10 Hz. Figures (5.15A, B and C) have the same characteristic features, namely, G' and G'' partially overlapping behaviour upon startup shear ranging from 0.01 to 1.0 Hz and G'' dominances over the rest of frequency range tested (> 1.0 Hz). However, G′ and G′′ exhibit strain hardening behaviour regardless of the imposed frequency for SCOJ samples evaporated for 60 and 85 minutes as shown in Figures 5.15E and 5.15F. The strain hardening parameter implies that both the G′ and G′′ increases with increasing the strain amplitude and the response is viscous-like behaviour, with a loss modulus that is much larger than the storage modulus.
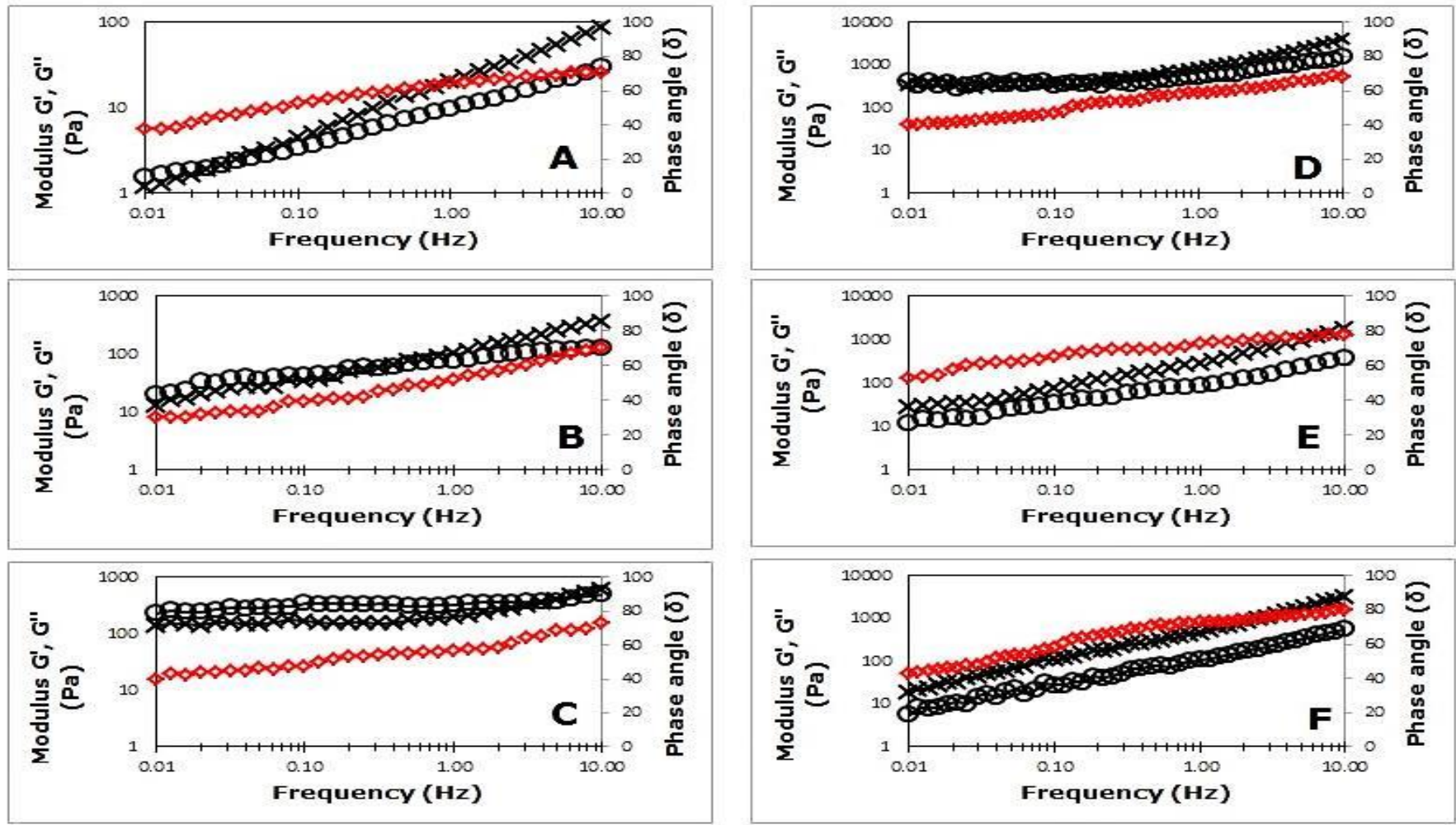
Figure 5.15 Dynamic storage (**O**) and loss (**X**) modulus against the phase angle (**δ**), as increasing function of frequency amplitude from 0.01 to 10 Hz at 25 °C for SCOJ samples evaporated for (A) 10 (B) 20 (C) 35 (D) 50 (E) 60 and (F) 85 minutes. Minutes here indicate sample name used as shown in Table 5.1)

From a closer examination of SCOJ sample evaporated for 50 minutes, interesting results are observed. An exceptional linear behaviour, where G' and G" are continuously equal, is known as a continuous crossover behaviour. This behaviour takes place at the lowest accessible frequencies ranging between 0.01 and 1.0 Hz. This characteristic feature could be a critical factor for this critical SCOJ sample to reveal the sudden change of scored easy-difficult-easy switching of points for swallowing in both MITP groups (Figure 5.11). It is also surprising that a marked higher values are given for G' and G'' modulus for the sample in Figure 5.15D (1615 Pa and 4015 Pa, respectively) than all samples. While SCOJ sample evaporated for 60 minutes showed lower values (368 Pa and 1729 Pa, respectively) which take place in the middle between SCOJ samples evaporated for 50 and 85 minutes. However, the loss modulus becomes superior to the storage modulus within a LVER; indicating that the rheological behaviour in this region is in nature dominated by a viscous property (loss energy) rather than an elastic property (storage energy) where high tongue pressure group sensed ease with swallowing such samples. Generally the dynamic G'' is often associated with internal friction (internal resistance) of food systems. Therefore, G'' is sensitive to different factors within the system such as food temperature, molecular or particle motions, molecular interactions, free volume within the food structur, transitions and other structural heterogeneities (Choi and Shah 2014, Kwan 1998, Rao and Quintero 2015, Stokes et al. 2013). Thus, the dynamic properties, which reflect the loss modulus, provide important information on how much portion of the energy investment for food bolus deformation in order to understand the food bolus flow behaviour as discussed previously in this chapter, section 5.3.3.5.

5.3.4 Factors that Influence Perceived Bolus Flow Behaviour for MP:XG

5.3.4.1 Tongue Strength

Figure 5.16 shows also a positive correlation between individuals' MITP and their scored easy-difficult-easy switching of points for swallowing MP:XG samples (individuals who were able to score easy-difficult-easy switching of points for swallowing MP:XG; Appendix 4). Observing low and high tongue pressure groups, they reported ease of swallowing MP:XG samples around 6.0 Pa.s. Above this value of apparent viscosity, these groups express different behaviours in perceiving ease of swallowing. Low tongue pressure group falls below 45 kPa has increased difficult in swallow MP:XG bolus of increased consistency. While those, whose MITP exceeds 45 kPa, tend to swallow bolus of increased consistency with ease. However, MP:XG bolus with apparent viscosity above 24 Pa.s appears to be very difficult to swallow of this group. To understand this tendency of swallowing between MITP groups, the study of the MP:XG bolus flow behaviour is required in relation to bolus rheological measurements and sensory evaluation.
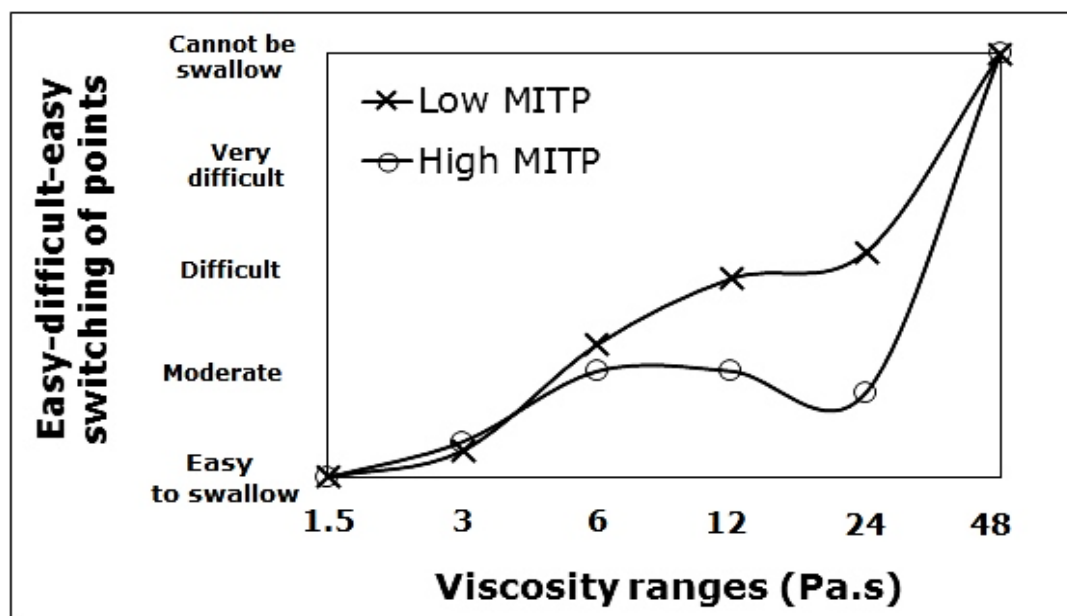
Figure 5.16 Correlations between low and high MITP groups and their scored easy-difficult-easy switching of points for swallowing MP:XG samples

5.3.4.2 Dynamic Shear Measurements

Xanthan gum-based thickener is a relatively recent introduction to the dysphagia as a thickener for various food products. Such thickener has unique rheological and gel-forming properties such as non-Newtonian shear-thinning flow properties that found to enhance the bolus properties during swallowing (García-Ochoa et al. 2000, Hanson et al. 2012a, Hanson et al. 2012b). In addition, xanthan gum is described to be a very slippery when it is thinning and has high cohesiveness property of high concentrations (Engmann and Burbidge 2014, He et al. 2014, Mackley et al. 2013). In this work, ready-to-swallow MP:XG bolus of high concentrations produces a high cohesive bolus. They were characterised during sensory evaluation of swallowing as boluses of high elasticity with limited deformability when exposures to the oral conditions such as oropharyngeal temperature and high shear rate and stress applied by individuals with high MITP.

As it is obvious from Figure 5.17, at relatively smaller frequency sweep (or strain sweep) range from 0.0 to 10 Hz, the elastic modulus (G') indicates a nearly independent of frequency over an entire range of frequency amplitude tested for the mixtures of mashed potato xanthan gum (MP:XG) with high concentrations (> 3.0 %). It clearly exhibits a linear behaviour region, resulting in a constant decline in the magnitude of storage modulus. As would be expected from a structured entanglement density with increasing polymer concentration, a balanced state is maintained between breaking down and rebuilding of the structure under small deformation (Isono and Ferry 1985, Song et al. 2006, Song 1996). Hence, there is no change can be observed in the elastic response of such sample below the critical deformation of xanthan gum. It is believed that with an increase in frequency amplitude range above the critical deformation level, a gradually change from linear to a non-linear behaviour occurs (> 10 Hz) resulting from the destruction and formation of internal structure (Isono and Ferry 1985, Santore and Prud'homme 1990, Song et al. 2006). However, the findings indicate that

the starch-gum mixtures had weak viscous-like property when compared to elastic-like property. Similar finding was reported by Choi and Chang (2012) for the mixture of starch and galactomannan (water-soluble polysaccharide).
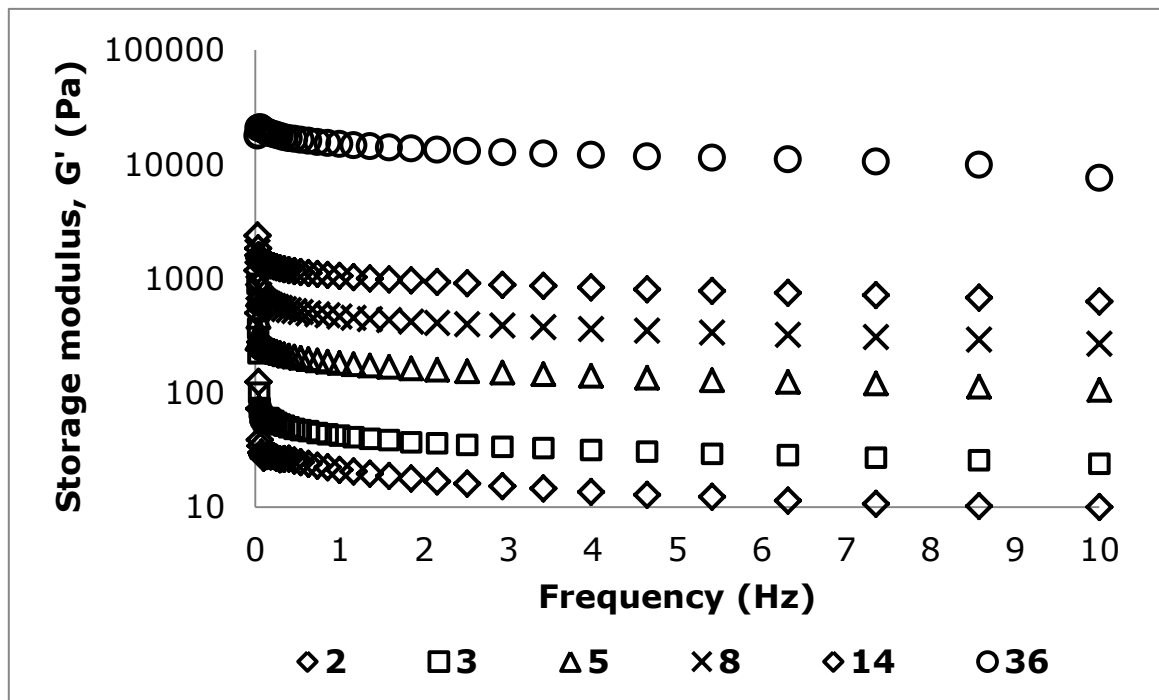
Figure 5.17 Storage modulus (G') as a function of an increasing frequency from 0.0 to 10 Hz for mashed potato xanthan gum mixtures with different concentrations from 2.0 % to 36 % at 25 °C

5.3.4.3 Sensory Evaluation

MP:XG boluses are rheologically classified as soft solid material. Such material exhibits solid property and thus shows a highly elastic response, when subjected to very small deformations (Figure 5.17). Additionally, xanthan gum exhibits viscosity dependence on temperature (Leonard et al. 2014, Ott and Day 2000). These factors seem to influence the flow pattern of bolus made with high xanthan gum concentration during swallowing process. They exhibit complex flow behaviour when compare the MITP groups (Figure 5.16).

For high elastic bolus, we assumed that if the strong force of tongue propulsion is applied, this leads to form plug flow behaviour (Figure 5.1C). The bolus flows uniformly as a plug flow. It is likely due to bolus property

of being high elastic and limited deformation (Figure 5.17). It is crucial to understand the characteristics of the plug flow mechanism. Figure 5.18 shows the schematic cross-sectional of MP:XG bolus flow of high viscosity within a pipe to illustrate the plug flow. The velocity of this flow is assumed to be constant, identical and direction of motion without any mixing. It means that each layer of the bolus travels as a single velocity within the oropharyngeal cavity for exactly the same length of time (Massey and Ward-Smith 1998). Under high shear rate upon the bolus surface, formation of a less viscous layer (xanthan gum under shear rate and high body temperature becomes thin) promotes around the bolus surface near the oropharyngeal walls being sheared causing slip surface as illustrated in Figure 5.1C (Song et al. 2006, Zhong et al. 2013). Thus the mechanisms of lubricated boundary layer are: (1) to reduce frictional force and stickiness between contact areas of the oropharyngeal walls and the bolus surface, and (2) to allow MP:XG bolus to flow easily along the path direction of the motion in this stage of swallowing. However, this flow behaviour of MP:XG boluses of thicker consistencies (> 6.0 Pa.s) influences by individuals' physiological capability (i.e. tongue pressure). For MP:XG apparent viscosities ≤ 24 Pa.s, high tongue pressure group reported that bolus flow through the oropharynx was rapidly with slip sensation during swallowing. While low tongue pressure group reported increasing difficulty in the forms of increasing swallow numbers of single bolus, reporting oropharyngeal residue, bolus breaking up into pieces and/or stickiness after the swallow. However, bolus of 48 Pa.s was very difficult to swallow by all MITP groups as the bolus becomes no-slip and very dry which requires mastication process. Primary data obtained in this work suggests a firmer evidence of the potential influence of tongue strength differences in relation to bolus flow behaviour from stretch bolus flow to sliding flow and the changes of bolus characterisation (i.e. viscoelasticity, viscosity, boundary layer creation, bolus velocity, saliva cooperation) which may require further studies to explore a narrow range of MP:XG apparent viscosities than those tested in our experiment.
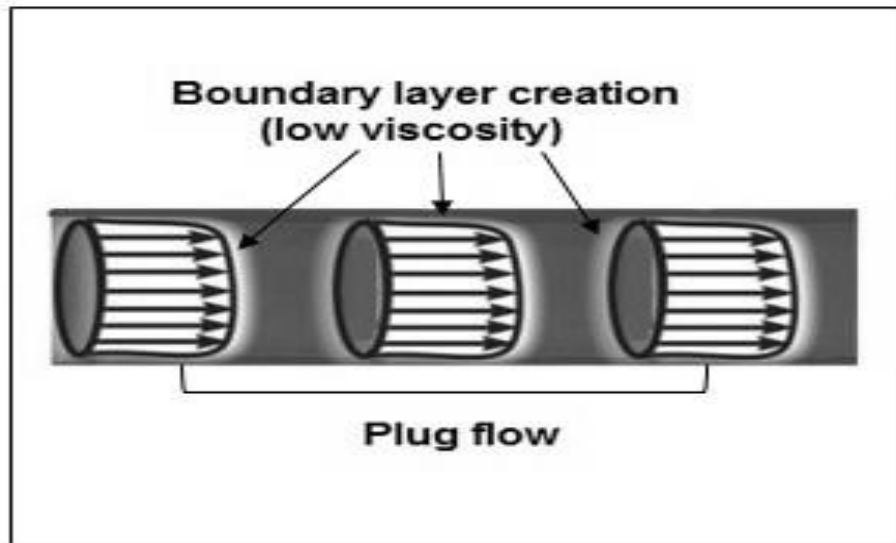
Figure 5.18 Schematic cross-sectional illustration of the MP:XG bolus slip motion as a plug flow and the creation of the bolus boundary layer by altering the bolus surface viscosity in the normal swallow (Bulwer et al. 2010)

5.3.5 Oral Residence Time

Figure 5.19 shows positive correlations between the average oral residence time (ORT) taken per swallow and increased bolus apparent viscosity. The average time of the lowest apparent viscosity tested (1.5 Pa.s) was the shorter time taken to complete a single swallow around 1.0 ± 0.5 seconds. However, the average duration time of swallowing viscous boluses of higher viscosities (12 and 24 Pa.s) was significantly longer (2.5 ± 1.3 and 2.6 ± 1.7 seconds, respectively) than the low viscous samples (1.5, 3.0 and 6.0 Pa.s) (1.0 ± 0.5, 1.3 ± 0.7 and 1.5 ± 0.7 seconds, respectively) with the P value <0.05. The ORT was not recorded for the highest apparent viscosity of MP:XG as subjects cannot swallow this very dry and no-slip sample. Thus the average duration time per swallow increased with increasing the bolus viscosity. However, a further link can be established between ORT and bolus flow behaviour. Carful observation of ORT showed that stretch bolus flow and apparent slip bolus flow have a

shorter ORT when compared with plug bolus flow and are easier to swallow than boluses that are less stretchy and slippery.
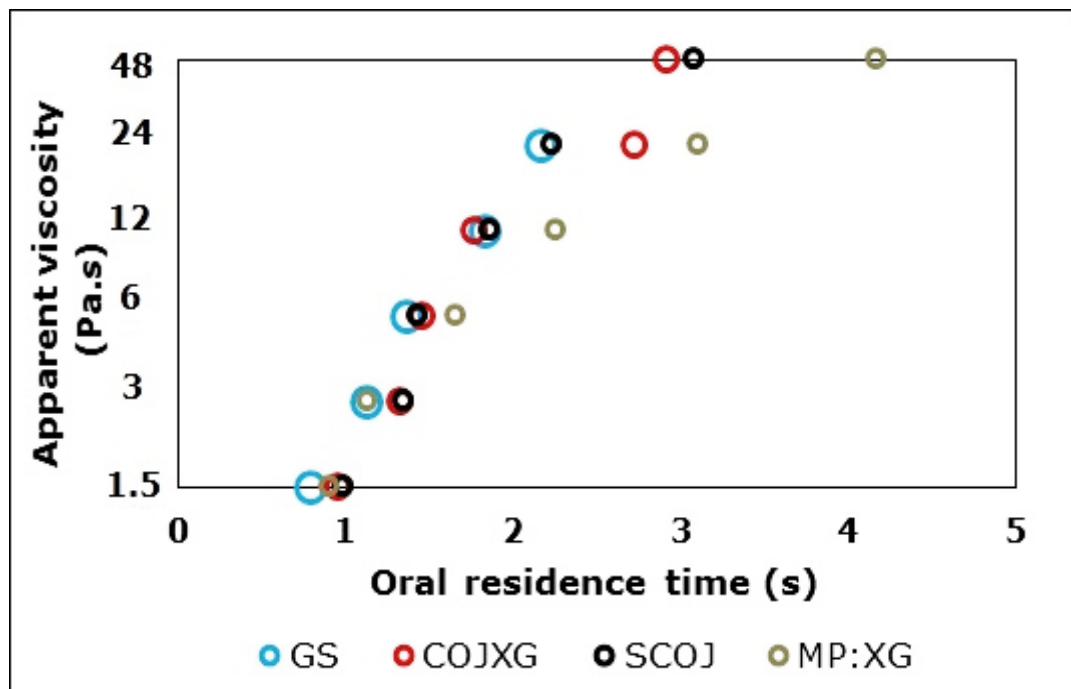
Figure 5.19 Average oral residence time of bolus swallowing (GS, COJXG, SCOJ and MP:XG) of increasing apparent viscosity (1.5, 3.0, 6.0, 12, 24 and 48 Pa.s). Numerical numbers from 1 to 6 present the apparent viscosity values of food bolus from 1.5 to 48 Pa.s

By individual observation of each sample for both groups, Figure 5.20 shows that low tongue pressure group spent longer ORT more than 2.0 ± 0.5 seconds for GS, COJXG and SCOJ boluses with apparent viscosities ≥ 12 Pa.s and 3.0 ± 0.8 seconds above 6.0 Pa.s for MP:XG sample when compared with high tongue pressure group with the P value <0.05. Additionally, low MITP group perceived a swallowing difficulty of such boluses by increasing the number of swallows per bolus due to increasing oropharyngeal clearance caused by the oropharyngeal residue and/or stickiness effect. However, high tongue pressure group was less likely with the P value <0.05 to report such difficulty with an exception of MP:XG sample with apparent viscosity value above 24 Pa.s. It can be concluded that the timing of bolus flow through the swallowing apparatus depends on both individual's physiological capability (tongue pressure) and bolus rheological properties.
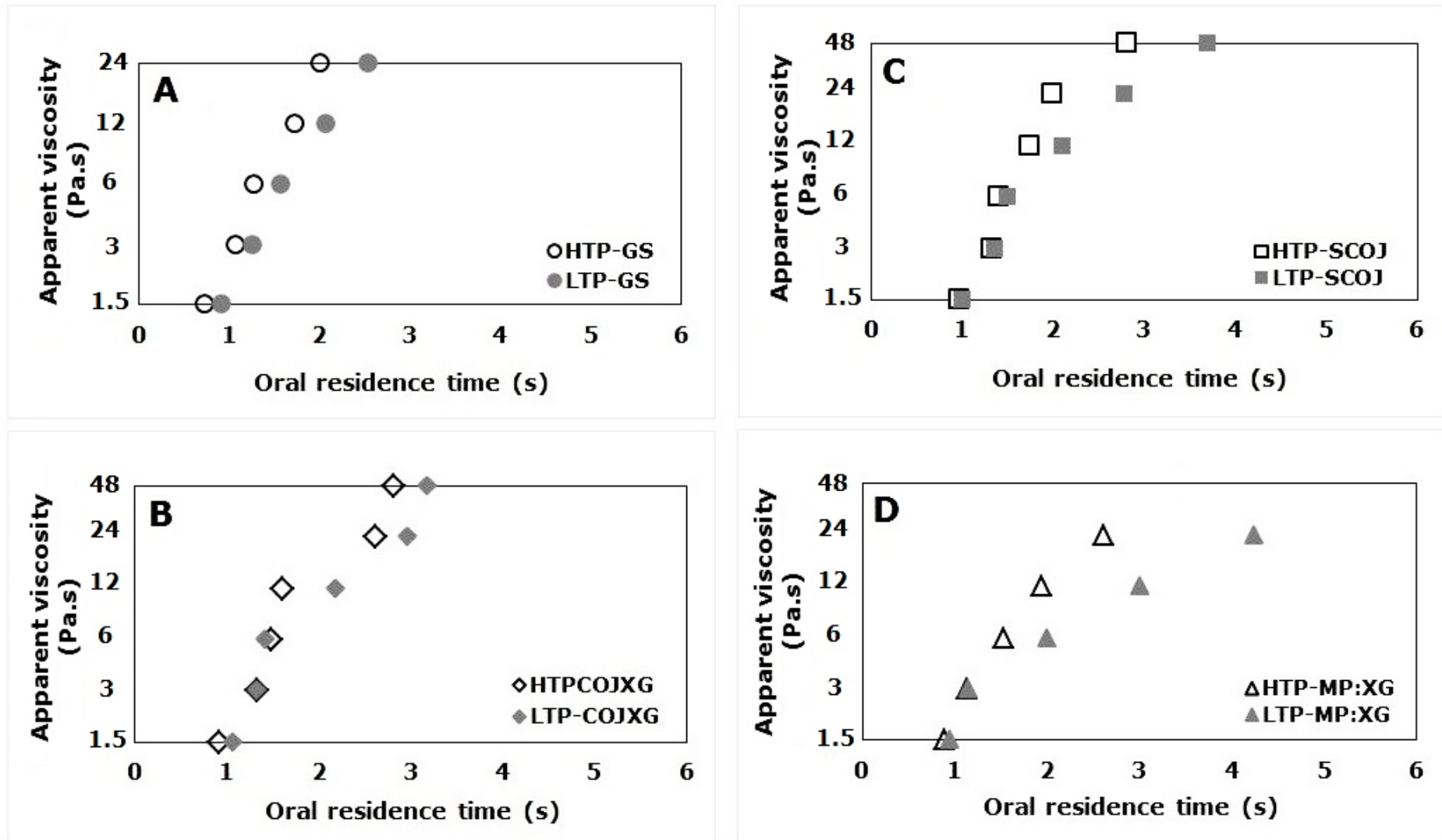
Figure 5.20 Average ORT for (A) GS, (B) COJXG, (C) SCOJ and (D) MP:XG of increasing apparent viscosity for high tongue pressure (HTP) and low tongue pressure (LTP) groups

5.4 Conclusions

The flow behaviour of the bolus is a complex phenomenon to which many factors contribute during swallowing. Possible factors can influence bolus flow behaviour the oral physiological conditions (i.e. tongue strength) and the changing of the bolus physical properties (i.e. rheology). Additionally, the bolus flow behaviours seem to have a potential impact on the perceived ease of swallowing for those who have high tongue pressure generation capacity ($\geq$ 45 kPa). There is no statistical significance in the capability of tongue pressure generating for both males and females aging between 21 and 60 years. The analysis of the rheometrical and sensory panel data against the generation of MITP suggested that an individual who has a higher MITP is expected to be able to perceived bolus flow behaviours and also perceived ease during swallowing boluses of higher consistencies compared to those with low tongue pressures. It is evidence that the cut-off point of perceived difficulty in swallowing for low MITP group scatters in various ranges when swallowing GS, COJXG, SCOJ and MP:XG of various apparent viscosities comparing to very strong MITP. The later has a great confidence and competence in dealing with various boluses. However, both groups tend to have a close cut-off point of perceived difficulty in swallowing for GS and SCOJ samples.

The assessment of each individual food bolus in relation to high tongue pressure reveals that the bolus flow behaviour divided into two scenarios: laminar flow and sliding bolus flows. The later occurs into two forms either apparent slip flow or plug flow. The apparent slip flow was nominated for SCOJ in this work. This flow occurs under high shear rate upon the bolus surface causing a heat transfer. Therefore, it would create thin boundary layers (low viscosity phases) than the viscosity of intra-bolus. As a result of these factors, the bolus flows with a large velocity gradient near the wall. While the plug bolus flow was nominated for the bolus flow of MP:XG of thicker consistency for the same MITP group.

Under high shear rate upon the bolus surface, the bolus flows uniformly, likely due to bolus property of being high elastic and limited deformation. The findings of this work support the premise that both the oral physiological condition (MITP) and the rheological properties of the food bolus are important factors influencing individual's perceived bolus flow behaviours and perceived ease of swallowing food boluses of thicker consistency as well as ORT. Important conclusions from this work can be a useful guidance to design ready-to-swallow foods for vulnerable population but there is still much speculation as to what extent the saliva cooperation and oral forces actually operate in the mouth. On the other hand, more researches are required to better understand the relevance of bolus rheology and slippage of bolus boundary layers in terms of their influences on both the sensory perception and more critically on how to aid the transport of the bolus through the oral cavity and the rest of swallowing stages.

Chapter 6 Conclusions and Prospect for Future Work

6.1 Thesis Summary

With a growing elderly population, dysphagia is becoming an increasingly common medical condition to investigate the relationship between the mechanical property aspects of bolus swallowing (e.g. rheology, bolus manipulations, perceived ease of initiation swallowing and perceived bolus flow behaviour) along with oral pressures (i.e. generated by the tongue) recorded in healthy subjects. This particular area has generated considerable interest from the food and clinical sectors as well as from pharmaceutical industries. Several studies were examined, all of which focused on bolus swallowing capabilities. Such capabilities are influenced by the rheological properties of the food (bolus) and the oral physiological conditions. This chapter summaries the key results and conclusions obtained from the detailed examination of earlier works and provide valid recommendations for future research.

Chapter 1 presented the aim, objectives and a brief background on dysphagia (swallowing impairment), causes, consequences and the prevalence of dysphagia. Food oral processing is researched mostly from a clinical point of view and thus knowledge in oral processing from sensory view point is currently limited. Therefore, the literature review included a detailed evaluation of some existing clinical researches which were then extended using relevant techniques (such as MITP, oral volume, oral residence time) presented Chapter 2. Additionally, bolus physical characterisations have been progressively under-researched, only having been studied by *in vitro* measurements (i.e. rheology and texture) and during *in vivo* measurements. Based on literature, this study approach can fall into two of the following three broad categories: "chew and spit bolus assessment", "oral processing and swallowing observation" or "tongue pressing and food breaking". In the last few decades model-

based approaches have been employed in characterisation of bolus breakdown for swallowing. The findings of existing bolus models emphasise that the capability of swallowing is thought to be related to the physical properties of the bolus. However, the key limitation of these models is that they involve saliva interaction, bolus breakdown, time-consuming and temperature effect during food oral processing. Hence there is a considerable need to design simple, repetitive, reliable and ready-to-swallow bolus. It will be easily adopted for primary sensory of perceived ease / difficulty of swallowing and perceived bolus flow behaviour.

Chapter 3 investigates a few interesting hypotheses on the biomechanics of food processing, especially tongue pressure for bolus management and transfer during oropharyngeal swallow. Additional oral physiological parameters including the maximum volume of the oral cavity and the optimum bolus size of water and custard were examined against ranging ages and both genders from the sample population. The results revealed little gender difference in terms of generated tongue pressure. Age was also found to have little influence under 64 years (the young adult group). However, an age-related change becomes evident for those over 65 years (the old group). Oral volume capacity was also significantly different between the two age related groups. Both tongue pressure and oral volume capacity exhibited an inverse relationship with tongue pressure decreasing as the age of the sample population increased. It was further observed that perceived ease in swallowing boluses of increased consistency correlated with an individual's ability to generate tongue pressure. The results show that both the oral physiological conditions and the rheological properties of food (bolus) are important factors influencing oral manipulation and swallowing of food boluses.

In a more precise manner, Chapter 4 has unified the instrumental and sensory panel experimental results and quantitative assessment to establish the correlations between an individual's tongue muscle strength

and oral capability of tongue-only food breaking. Three tasks were designed involving (1) measurement of an individual's tongue muscle strength, (2) assessment of an individual's capability of tongue-only food breaking and (3) measurement of tongue–palate pressure generation for food oral breaking. Findings showed that the breaking of the gel and mashed potato sample (within the mouth) occurs in very different manners as elastic and plastic materials, respectively. Positive correlations were established between tongue strength and the threshold gel/mashed potato strength for tongue-only oral breaking. Results showed that in order to deform and break food under the tongue stress, a proper matching of food mechanical strength by MITP is critically essential for tongue-only oral food processing as shown by the strong tongue muscle group. This group demonstrated a significant advantage for oral handling of viscoelastic and pastry foods without teeth involvement. Conclusions obtained from this work can benefit food manufacturer to design for older people.

A detailed investigation of perceived bolus flow behaviours in relation to bolus rheological measurements and tongue strength during normal swallowing is presented in Chapter 5. Data of three parameters including, perceived ease of bolus swallowing, perceived bolus flow behaviour and ORT were correlated with an individuals' physiological capability of tongue strength. Findings indicate that individual's capacity in tongue pressure generation needs to exceed a certain limit in order to perceive ease in swallowing bolus and also to perceive a bolus flow behaviour when compared to those with low tongue strength capability. Moreover, a positive correlation was also observed between the average duration time taken per swallow and increased bolus viscosity as a function of an individuals' tongue pressure. Carful observation of ORT showed that laminar bolus flow and apparent slip bolus flow have a shorter ORT when compared with plug bolus flow. In addition, laminar bolus flow and apparent slip bolus flow reported to be easier to swallow than boluses that are being high elastic and limited deformation.

6.2 Recommendation and Prospect for Future Work

The results obtained in this project demonstrate the positive correlations between bolus swallowing and tongue strength capabilities which could be a bridge between oral and food sciences. Nonetheless, it could be further developed in a number of ways:

6.2.1 Sensory Swallowing Tests

One of the highlights of the sensory swallowing test is that it can be coupled with a video camera to record and obtain real-time swallowing of ready-to-swallow food by identifying the swallow apnea that designates the oropharyngeal phase of swallowing during which respiration ceases. Another proposed approach is the involvement of the temporal dominance of sensations (TDS) technique to record the swallowing time while solid food structural properties change throughout oral processing by standardising the time-axis of the TDS curves from lip closure to swallow.

The impact of apparent viscosity on swallowing whilst designing a range of food sample tests, aids in the exploration of both the physiological (e.g. tongue pressure) and functional consequences of swallowing boluses of known apparent viscosity (i.e. bolus flow behaviour, perceived ease of swallowing and the time taken to swallow) in narrow and larger increments. However, apparent viscosity values lower ranges can be considered in future work when designing food samples for instrumental and sensory panel experiments. The challenge of matching rheological properties (or any assessment stimuli) of different food is definitely an area where additional research is needed. In this project apparent viscosity, for example, shows a positive correlation between individual's capability of swallowing different bolus types with matching apparent viscosities compared to tongue pressure strengths. Therefore, further research on oral perception of viscosity and the processes that

determine changes in swallow physiology resulting from changes in viscosity is required.

Perceived bolus flow behaviour can be further studied experimentally and numerically computational fluid dynamics (CFD).

Additional work, not limited to just, tongue shear stress, temperature of the bolus and the body's influence on the bolus flow behaviour, but also normal or artificial saliva cooperation on the bolus contact surface must be studied. During instrumental measurements, a number of considerations must be taken when involving saliva: whether to mix a sample with saliva or lubricate the geometry surface of a rheometer with a thin layer of saliva, saliva flow rate, the effect of time on the dilution of some food samples (highly concentrated sugar solution) or digestion of foods (starch) taking place in the mouth cavity in the presence of saliva, food rheology (i.e. viscosity) and the lubrication of food particles influenced by saliva etc.

For sensory panellists, the importance of training the panellists on the definitions of the sensory attributes, test steps, sample taste and texture and timing swallowing tests showed performance improvement. The involvement of healthy, elderly participants (over 65 years) in the study of Chapter 4 would draw a solid positive correlation between the mechanical properties of viscoelastic and paste foods and food oral breaking capability. Moreover, it is essential to increase the population size for future work to enable stronger conclusions regarding the correlations between oral physiological capabilities (tongue pressure) bolus rheological properties (i.e. viscosity, elasticity and flowability), perceived ease / difficulty of swallowing and swallowing time. A prospective study on the impact of tongue strength on swallowing capabilities for a larger population size will help us to better specify the potential relevance of bolus flow patterns and the perceived ease of swallowing, especially for disadvantaged populations.

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shear thinning fluid delivery for subsurface remediation. *Journal of Hazardous Materials, 244-245*, pp. 160-170.

Appendix 1
Ethical Approval

Performance, Governance and Operations
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UNIVERSITY OF LEEDS

Woroud Alsanei
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MEEC Faculty Research Ethics Committee
University of Leeds

10 September 2015

Dear Woroud

Research title **The determining roles of food rheology in triggering a swallow**

Ethics reference **MEEC 11-007**

I am pleased to inform you that the application listed above has been reviewed by the MaPS and Engineering joint Faculty Research Ethics Committee (MEEC FREC) and following receipt of your response to the Committee's initial comments, I can confirm a favourable ethical opinion as of the date of this letter. The following documentation was considered:

Document	Version	Date
MEEC 11-007 Committee Provisional.doc - response	1	28/11/11
MEEC 11-007 Information Sheet.docx	2	28/11/11
MEEC 11-007 Figure 1 - EMG - ElectroMayoGraphy1.JPG	1	28/11/11
MEEC 11-007 Figure 2 - IOPI - Tongue Bulb position in the mouth.jpg	1	28/11/11
MEEC 11-007 Figure 3 - The small blue bulb and IOPI device.jpg	1	28/11/11
MEEC 11-007 Woroud Alsanei - Ethical_Review_Form_V3.doc	1	25/10/11
MEEC 11-007 Participant Consent Form.doc	1	25/10/11

The Committee made the following comments:
- It is still not clear from your answer to question 10 that you are familiar with the University policy for raising the alarm please familiarise yourself with this and inform all the researchers involved.

Please notify the committee if you intend to make any amendments to the original research as submitted at date of this approval. This includes recruitment methodology. All changes must be ethically approved prior to implementation.

Please note: You are expected to keep a record of all your approved documentation, as well as documents such as sample consent forms, and other documents relating to the study. This should be kept in your study file, which should be readily available for audit purposes. There is a checklist listing examples of documents to be kept which is available at http://researchsupport.leeds.ac.uk/index.php/academic_staff/good_practice/other_information_nhs_sites in the '*Other useful documentation*' section.

Yours sincerely

Jennifer Blaikie
Senior Research Ethics Administrator, Research & Innovation Services
On behalf of Professor Gary Williamson, Chair, MEEC FREC
CC: Student's supervisor(s)

Appendix 2

Questionnaire for Swallowing Evaluation

Sensory Evaluation of Swallowing

❖ **Personal information:**

Name: **Age:**   **Gender:** ☐Female ☐Male
Email:

Weight (kg):   **Height (cm):**   **Date:** __ / __ /_____

❖ **Task (1) Instructions:**

The highest 5 peaks of maximum isometric tongue pressure will be recorded using the Iowa Oral Performance Instrument (IOPI).

Tongue Pressure (kPa)	1	2	3	4	5	Average	

❖ **Task (2) Instructions:**
- Please, take a sip of water to rinse your mouth before/between tasting the samples.
- In order, swallow all samples (**Golden syrup** (GS), mixture of **concentrated orange juice & xanthan gum** (COJXG), **super concentrated orange juice** (SCOJ), and mixture of **mashed potato & xanthan gum** (MP:XG).
- Place each sample toward the middle of the tongue to facilitate bolus swallowing.
- Place a (√) on the table to rate your perception of ease / difficulty swallowing according to the following scale that indicates your right description for each sample.
- Stop swallowing when you cannot swallow.
- During this test, the **duration** time of the **swallowing** will be recorded from the **start** to the **end** for each sample using digital timer.
- When you **start & finish** swallowing each sample use the bell to start/stop the timer.

Sample Code	Perceived Ease / Difficulty of Swallowing					Swallowing Time (s)
	Easy	Moderate	Difficult	Very Difficult	Cannot swallow	
	1	2	3	4	5	
Golden Syrup						
1						
2						
3						
4						
5						
Concentrated Orange Juice mixed with Xanthan Gum						
1						
2						
3						
4						
5						
6						
Super concentrated Orange Juice (SCOJ)						
1						
2						
3						
4						
5						
6						
Mashed Potato mixed with Xanthan Gum (MP:XG)						
1						
2						
3						
4						
5						
6						

❖ **Important:** Please, ask for more information, if you have any inquiries regarding this test **<u>BEFORE</u>** starting the evaluation.

Foods	Sample code	Swallowing time	Comments
GS	1		
	2		
	3		
	4		
	5		
COJXG	1		
	2		
	3		
	4		
	5		
	6		
ECOJ	1		
	2		
	3		
	4		
	5		
	6		
MP:XG	1		
	2		
	3		
	4		
	5		
	6		

Thank you! ☺

Appendix 3

Perceived Easy-Difficult-Easy Switching of Points for Swallowing SCOJ

			Easy-Difficult-Easy Switching of points Low MITP					
			SCOJ					
			Low MITP					
	Sample code	MITP	1.5	3	6	12	24	48
	1	49	1	1	1	2	3	3
	2	47	1	1	2	3	3	3
Code	3	45	1	1	1	3	3	4
Easy → 1	4	44	1	1	1	2	3	4
Moderate → 2	5	43	1	2	2	3	3	4
Difficult → 3	6	43	1	2	2	2	2	3
Very Difficult → 4	7	41	1	1	2	3	3	5
Cnnot swallow → 5	8	35	1	2	3	4	5	5
	9	29	1	2	3	3	3	4
	10	18	1	2	3	5	5	5
	Average	39	1.0	1.5	2.0	3.0	3.3	4.0

			Easy-Difficult-Easy Switching of points High MITP					
			SCOJ					
			High MITP					
	Sample code	MITP	1.5	3	6	12	24	48
	1	60	1	2	2	3	3	2
	2	59	1	1	2	3	1	1
Code	3	58	1	1	2	3	2	2
Easy → 1	4	56	1	1	1	2	3	2
Moderate → 2	5	55	1	2	2	3	2	4
Difficult → 3	6	54	1	2	2	3	2	3
Very Difficult → 4	7	54	2	2	2	3	3	1
Cnnot swallow → 5	8	51	1	1	3	2	1	3
	9	51	1	1	2	3	3	2
	Average	55	1.1	1.4	2.0	2.8	2.2	2.2

Appendix 4

Perceived Easy-Difficult-Easy Switching of Points for Swallowing MP:XG

			Easy Difficult Easy Switching points Low MITP					
		MP:XG					
		Low MITP					
	Sample code	MITP	1.5	3	6	12	24	48
	1	49	1	1	1	1	1	5
	2	45	1	1	2	4	4	5
Code	3	44	1	1	2	3	3	5
Easy → 1	4	43	1	2	4	5	5	5
Moderate → 2	5	43	1	1	2	2	1	5
Difficult → 3	6	33	1	2	4	3	3	5
Very Difficult → 4	7	29	1	1	2	3	5	5
Cnnot swallow → 5	8	18	1	2	3	4	4	5
	Average	**38**	**1.0**	**1.4**	**2.5**	**3.1**	**3.3**	**5.0**

Easy Difficult Easy Switching points
High MITP

Easy Difficult Easy Switching points High MITP			MP:XG					
			High MITP					
	Sample code	MITP	1.5	3	6	12	24	48
	1	75	1	1	1	3	2	5
	2	63	1	1	1	3	2	5
	3	60	1	2	3	2	2	5
	4	60	1	1	2	3	2	5
Code	5	60	1	2	3	2	2	5
Easy → 1	6	59	1	1	2	3	2	5
Moderate → 2	7	57	1	1	1	2	1	5
Difficult → 3	8	55	1	2	2	3	1	5
Very Difficult → 4	9	54	1	1	3	3	2	5
Cnnot swallow → 5	10	53	1	2	3	3	2	5
	11	52	1	2	3	2	2	5
	12	51	1	1	2	1	1	5
	13	51	1	1	2	1	1	5
	Average	**58**	**1.0**	**1.4**	**2.2**	**2.4**	**1.7**	**5.0**