A New Measurement of Maximum Comfortable Bite Force across Lifespan

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Live long and prosper.

"Star Trek"

Abstract

Mastication is an essential oral function that influences daily food intake, particularly for those who suffer from decreased, disordered or malfunctioning masticatory function. Various studies evaluate masticatory function according to its two fundamental aspects: masticatory performance and masticatory ability. However, a weak correlation exists between the masticatory performance and masticatory ability.

This study aims to establish a straightforward, objective measurement of (subjective) maximum comfortable bite force, which can be applied in a large population by evaluating the textural intensity of model gel foods. This new measurement attempts to find the potential relationship between masticatory performance and masticatory ability by linking texture perception to bite force, and assessing the effect of ageing on masticatory function across the lifespan.

A series of gel-based model foods with different mechanical properties was developed for this measurement technique by optimising the shape, size, gel type, and gelatine concentration of samples. The gel-based measurement proved useful for assessing masticatory function, successfully linking subjective and objective masticatory function by reasonable correlations between sensory *hardness* and mechanical hardness. It has been effectively applied to 317 participants at a low cost to investigate the influence of ageing on masticatory function and maximum comfortable bite force. The correlation between masticatory function and ageing was further investigated by information collected on oral health, the quality of masticatory function, biting difficulty and hardness sensitivity. The maximum comfortable bite force of different age groups assessed by the rate test strongly relates to the mechanical property of model and real foods (from candies to nuts), and suggests decline from the hardness of hazelnut at 20 years to that of milk candy at 70 years. We find that the turning point in

masticatory function appears to be at the age of 70yrs, after which there is a steep decline in maximum comfortable bite force. On the other hand, the starting point of reduced masticatory function is around 50yrs in the New Zealand population. A profile scale (0-10 pts) has been created to assess masticatory function based on the data collected by the new gel-based measurement technique, in which a higher score indicates poor masticatory function.

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Abbreviations

BCMI	**B**ody **C**ell **M**ass **I**ndex
BMI	**B**ody **M**ass **I**ndex
EMG	**E**lectro**M**yo**G**raphy
FC	**F**ast **C**lose
FTUs	**F**unctional **T**ooth **U**nit**s**
JND	**J**ust **N**oticeable **D**ifference
MBF	**M**aximum **B**ite **F**orce
OHIP	**O**ral **H**ealth **I**mpact **P**rofile
OHRQoL	**O**ral **H**ealth **R**elated **Q**uality **o**f **L**ife
QMFQ	**Q**uality of **M**asticatory **F**unction **Q**uestionnaire
QoL	**Q**uality **o**f **L**ife
RE	**R**ecoverable **E**nergy
SC	**S**low **C**lose
SDA	**S**horten **D**ental **A**rch
TDS	**T**emporal **D**ominance of **S**ensations
TI	**T**ime **I**ntensity
TPA	**T**exture **P**rofile **A**nalysis
VAS	**V**isual **A**nalogue **S**cale
VFG	**V**ideo**F**luoro**G**raphy

Chapter 1 Introduction

The oral system runs several complex processes, whose adequate function is ensured by the neural system, orofacial muscles and saliva-food interactions. According to the process of feeding behaviour, mastication is the first step for transforming the food before it proceeds to the stomach for digestion [1]. A brainstem situated central pattern generation controls the contraction of jaw muscles to complete a series of rhythmic jaw movements [2]. Due to the different bolus textures experienced during consumption, sensory feedback from oral receptors modulate this activity by adjusting the chewing pattern during eating.

Change in masticatory behaviour is one of the most common issues impacting individuals who suffer from reduced, disordered, or malfunctioning masticatory function. Mastication is an essential function for humans in daily intake of food, and is strongly correlated with nutritional ingestion and food selection [28, 29, 368, 369]. There are a large number of studies [3 - 5] evaluating masticatory function by two domains: masticatory performance and masticatory ability.

In general, masticatory performance is evaluated by various measurements as an objective function, including chewing efficiency, jaw muscle activity, bite force, particle size and saliva flowrate. Chewing efficiency is defined as the number of chewing cycles needed to prepare a swallowable bolus from the original piece of food [1]. Some studies found that between 10 to 40 chewing cycles are required to reduce the model foods (e.g. two-colour chewing gum) to a small particle size, forming a cohesive bolus for easy swallowing [6, 7]. Several parameters can serve as measures of masticatory efficiency: masticatory duration, the number of chewing cycles, frequency of chewing cycle and particle size [8, 9]. Jaw muscle activity relates to electrical activity, such that Electromyography (EMG) transforms synergistic muscle force into electrical signals; EMG has been widely applied in masticatory performance studies. Not only can muscle output force be collected from EMG, but differences in jaw movement patterns can also be detected as different EMG "bursts" in subjects with different types of chewing behaviours [10 - 12]. Bite force is a valuable indicator for assessing the efficacy and function of masticatory performance in dental occlusion [13]. A variety of techniques with various designs and working principles have been applied in recording bite force [14]. The bite force measurement can be electrical, mechanical or a combination of both.

In contrast, masticatory ability is a subjective measurement, related to oral status, dental health, general health, and other personal factors, including psychological, physiological, economic, social and cultural aspects. Although masticatory performance also relates to these physical factors, self-assessment really captures the influence of these factors that vary person-to-person. Masticatory ability may be self-assessed through questionnaires and interviews about an individual's health status, chewing habits and basic personal characters [15 – 21]. The subjective measurements, also called patient-based measurements, are widely applied in epidemiological research related to oral health, including tooth loss, periodontal disease, caries and temporomandibular disorders. Although some reports show that the self-assessed ability of mastication is weakly related to objective masticatory function, Feine & Lund (2006) [22] insisted that subjective assessment directly presents the perceptions of patients and reflects their objective masticatory performance. Such measurements can discriminate differences before and after clinical treatments.

To maintain a healthy life for the elderly, a good and balanced nutritional intake is one of the most critical components. Functional oral processing is the significant start of food digestion, leading to improved nutrient absorption. Ageing brings a reduction of other anatomical, physiological and psychological functions, including the number of missing teeth, periodontal disease, degenerated muscle strength and decreased motor skills, all of which lead to a decline of masticatory function in elderly individuals [1, 23 – 27]. Many studies support that masticatory deficiency is significantly related to malnutrition in older patients [28, 29]. The strong relationship results from mastication-related dietary changes with ageing [30]. In healthy elderly individuals, chewing behaviour changes to compensate for the reduction of masticatory function, leading to dietary changes. Due to the significantly reduced jaw muscle activity with ageing, certain foods (e.g. dry bread and meat) become difficult to chew [31, 32]. A slow loss of adaption of bite force to food texture was also found in older subjects compared to young adults [33]. Peyron *et al.* (2017) [30] proposed that the impact of advanced ageing on mastication-dependent digestion might cause a reduction of nutrient bioavailability. They reported that swallowing a poorly prepared food bolus causes digestive consequences, such as nutrient deficiencies and digestive diseases.

Food characteristics (hardness, size, moisture etc.) have a strong influence on masticatory behaviour. Adjustments to a characteristic such as hardness, for example, include extending the chewing time, increasing chewing cycles and vigorous jaw activity. However, once hardness reaches a certain level that exceeds an individual's masticatory ability, coarser particle sizes are observed in the bolus which is not safe for swallowing. Foegeding (2007) [34] found that the perception of food texture is a dynamic process during oral processing, meaning that the physical properties of food change continuously while eating. This means that studies of oral processing can investigate changes in masticatory performance for a variety of foods with different deformability and hardness.

The trend of a growing proportion of elderly in the population has been increasing since 1950, leading us into a 'super-aged society' in the near future. Consequently, it is necessary to understand the influence of ageing on oral processing to provide specific recommendations for the elderly to maintain a healthy life with adequate nutrition.

Aim

Due to the weak correlation between masticatory performance and masticatory ability, it is necessary to create a new measurement that can link objective and subjective masticatory function. The results from the new measurement can then be used to comprehensively understand how masticatory function changes in these two domains across the lifespan. This PhD project aims to create a new measurement of maximum comfortable bite force, by linking hardness perception to mechanical texture using a set of model foods. This measurement is applied in population study for residents of Auckland, investigating the relationship between maximum comfortable bite force and ageing across the lifespan. Based on the data collected from this project, a profile scale can be proposed as a preliminary estimate of masticatory function that also combines sensory tests and the questionnaires.

The specific goals of this research are:

1. Design a set of gel-based model foods, which discriminates perceived hardness by subjective measurements (sensory tests) and mechanical property by objective measures (compression test and recoverable energy tests).

2. Apply the set of model foods as a new measurement of maximum comfortable bite force, and compare findings against a conventional bite force test.

3. Apply the new measurement to a large population of varying age groups along with designed questionnaires, to determine how masticatory function changes with ageing.

4. Based on data collected from various measurements of the large panel study, establish a profile scale that can be used as a preliminary estimate of an individual's masticatory function.

Chapter 2 Measurements of Masticatory function

This chapter provides background for measuring masticatory function, including subjective measurements for assessing masticatory ability and objective measurements for evaluating masticatory performance. Section 2.1 introduces the background of masticatory function, including masticatory ability (objective) and masticatory performance (subjective). Section 2.2 describes masticatory ability measurements. Section 2.3 describes the devices for measuring masticatory performance. Section 2.4 focuses on model food as a tool for measuring masticatory performance. Section 2.5 introduces the combinations of foods and devices to measure masticatory function. Section 2.6 compares the objective and subjective approaches to measuring masticatory function.

2.1 Introduction

The oral system runs several complex processes, whose adequate function is ensured by the neural system, orofacial muscles and saliva-food interactions. Changes in masticatory behaviour is one of the most crucial oral processes influencing consumers who suffer from decreased, disordered or malfunctioning masticatory function. The reduction and dysfunction of the masticatory function can affect the choice of foods and the satisfaction derived from daily eating. As a consequence, consumers will lose their healthy nutrition status and self-esteem, which will cause social difficulties and eventually damage the quality of life. However, most declining oral health can be managed or prevented if the changes of the oral condition are detected in the early stages [35]. Mastication is an essential oral function in human daily intake of food and is highly correlated with nutritional ingestion and food selection, so there are a large number of evaluating the function of mastication by two aspects: masticatory performance and masticatory ability studies [3 - 5]. In general, masticatory performance is evaluated by various measurement in the objective function including chewing efficiency, jaw activity, bite force, particle size and saliva flow. Masticatory ability is self-assessed by questionnaires and interviews in the subjective aspect including chewing habits, oral status, chewing difficulties [17, 20, 36 - 39]. Compared to subjective evaluation, objective evaluation can be more direct, reliable and accurate through the use of instrumental techniques. However, the subjective assessment can analyse masticatory ability at the adaptational and psychological level, which the objective measurements cannot reach. The first aim of this review is to summarise objective measurements of masticatory function, especially a detailed evaluation of bite force. The conventional measurements of bite force can link to our project that a measurement assessing maximum comfortable bite force, which can relate to individual masticatory function. The second aim is to summarise subjective measurements of masticatory function, which are fundamental for establishing our questionnaire to investigate masticatory ability.

2.2 Masticatory ability measurements

The self-assessment masticatory ability is related to the oral status, dental health, general health, and other personal factors including psychological, physiological, economic, social and educational aspects. Although masticatory performance also relates to these physical factors, self-assessment really captures the personal factors. This ability may be self-assessed through questionnaires and interviews about individuals' health status, chewing habits and basic personal profiles [15 – 21]. The subjective measurements, called patient-based measurements, are widely applied in epidemiological research related to oral health, including tooth loss, periodontal disease, caries and temporomandibular disorders. Although some reports show that the self-assessed ability of mastication is weakly related to objective masticatory function, Feine & Lund (2006) [22] insisted that subjective assessment directly presents the perceptions of patients and reflects their masticatory performance. The measurements can discriminate differences before and after clinical treatments.

2.2.1 Oral health status

Since the oral disease (e.g. periodontal and caries) status have been changed from acute to chronic, improvement of quality of life becomes the primary aim of the treatments [40]. The quality of life (QoL) is a subjective measurement for evaluating individual general health. It reflects oral health status, which can indicate the oral comfort and pain level of human perception. For a thorough assessment of oral health, clinicians collect and analyse the data not just from professional measurements but also subjective performance [40]. The oral health-related quality of life (OHRQoL) was introduced by Locker (1988) [41] and applied in oral therapy in self-assessment of oral health status [42 - 44]. OHRQoL measures: status of teeth; the presence of symptoms, impairment and disease related to oral health; the level of pain and discomfort related to masticatory functions; the level of controlling emotional function related to smiling; the level of controlling social function related to regular roles; the degree of perceptions and satisfaction of oral health and influence of oral status in culture or society [45]. Due to the psychometric tools that were developed and proven to have high reliability and validity [46 - 49]. OHRQoL has become a crucial indicator of oral health status, particular widely used in clinical treatments. The masticatory ability has been found to be related to the quality of life relating to oral health [50 - 52].

Category scales is one of the typical response measurements in questionnaires which aim to collect information from participants of the survey [53]. They suggested that answers may represent the strength of an experience using the words including: ‘not at all’, ‘somewhat’, ‘moderately’, ‘very’, “extremely’ and ‘impossible’. To reflect the frequency of an experience, answers use words including: ‘never’, ‘sometimes’, ‘often’ and ‘always’. It is crucial to use appropriate groups of response words in a particular questionnaire. These classified response measurements are readily accepted and widely used in different groups of people.

For developing a comprehensive measurement of self-assessed oral health, The Oral Health Impact Profile (OHIP) with a 5-point-scale is established based on OHRQoL to measure and the influence of oral health in physical, psychological and social domains. OHIP-49, as a full edition, has the seven aspects (each aspect includes seven items) of influence of oral health on human well-being, which consists of functional limitation, physical pain, psychological discomfort, physical disability, psychological pain, psychological disability, social disability and handicap. The five-point scale has five responses: including ‘never’, ‘hardly ever’, ‘occasionally’, ‘fairly often’ and ‘very often’. The scores of each question based on the five-point scale are from 0 (equal to ‘never’) to 4 (equal to “very often). The measurement is a universal and standardized measurement has been used in numerous countries with different languages to assess the impact of oral treatment on daily life [54 - 57]. However, category scales have become a limitation of OHRQoL tool because continuous variables are categorized leading to inconsistent and inadequate of results. Also the development of measurements maybe not a reliable and valid indicator of masticatory functions.

2.2.2 Self-assessed satisfaction and masticatory functions

In addition to OHRQoL, which can measure the oral health of individuals or patients, "self-assessed satisfaction" is another method which has been proved sensitive to collect clinical differences before and after various prosthodontic therapies [58, 59]. Self-assessed satisfaction is a useful measure as it can directly quantify different oral functions through individual's opinions or patients' perception of a given oral treatment. Self-assessed satisfaction and OHRQoL are usually used separately in clinical research to evaluate the effectiveness of treatments. However, OHRQoL cannot replace the self-reported satisfaction because the former is too broad to deeply study aspects of participants' satisfaction, particularly in the aspect of masticatory functions [60]. In some clinical studies, a relationship between OHRQoL and self-assessed satisfaction have been found in different treatments, for example, tooth-supported prostheses [61] and conventional complete dentures [62]. Therefore, self-assessed satisfaction, associated with OHRQoL measurement, maybe a more comprehensive method to evaluate masticatory functions.

Streiner & Norman (2006) [53] claimed that small statistical discriminations are essential in some studies and these cannot be detected by categorising tools described above. To acquire the subtle information from satisfaction questionnaires, a visual analogue scale (VAS) has been introduced into self-assessed satisfaction. VAS is a typical tool that measures the frequency or intensity of symptoms in clinical and epidemiologic studies [63]. The simplest VAS is a 100mm line, and the end-points are extreme conditions of the parameter [64].

The self-assessed satisfaction questionnaire can relate to general satisfaction, comfort, chewing ability, speaking ability, stability, aesthetics and ease of cleaning. For measuring the masticatory functions of individuals, chewing ability includes chewing difficulty and chewing efficiency, which is the ability to cleave food in small particles [65]. All of the factors are rated by subjects using the VAS, for which lower scores indicate worst satisfaction and masticatory functions. In a longitudinal research study, Johansson *et al*. (2007) [17] have shown that in a panel of 50-year-old participants, in 10 years, the masticatory ability reduced significantly while there were only minor changes to the participants' dental status including the number of teeth loss and conditions of wearing dentures.

2.2.3 Other aspects self-assessment

The number of teeth as significant indicators that influence chewing ability is well documented [16, 38, 66]. A reduced masticatory ability has been found to be correlated with the number of missing teeth in the elderly [52, 67, 68]. The self-rated chewing function survey explained that increased age is a reason causing the number of missing teeth, but ageing had an only marginal effect on chewing ability [69]. The compensation of this chewing dysfunction is to change diet and nutrition patterns to foods with smaller particles or softer texture. A correlation between diet/nutritional state and masticatory function is expected, which can predict the improvement of masticatory function will be associated with oral treatment and dietary intervention [53]. In addition, other personal factors also introduced into subjective masticatory measurements including economic, social, educational and cognitive questionnaires. Tonetti *et al*. (2017) [35] showed that lack of economic resources may cause less access to professional dental service, and lack of knowledge of dental care may lead to less personal effort in dental care. Furthermore, the individual with severe mental illness related to less dental care leading to a prevalence of the dental disease [70] and the number of tooth loss [71].

2.3 Device for measuring masticatory performance

Many studies have claimed that assessment of masticatory ability is overly optimistic and there is a weak relationship between masticatory ability with the masticatory performance [4, 72, 73]. As such, different types of objective masticatory measurements have been developed to evaluate different factors of masticatory performance, including mastication time, masticatory efficiency, particle size, bite force, jaw muscle activity, salivary flow and neuromuscular activity.

2.3.1 Mechanical measurements

In 1681, Borelli built the first device called the gnathodynamometer [74] and similar mechanical devices have been applied in measuring bite force in the decades, and centuries, since. The original mechanical device used a cord to attach the molar teeth of the mandible to different weights in the open-mouth position. The individuals were required to close their jaws. The maximum weight that individuals were able to raise was about 200 kg [75]. In 1893, a scientific force instrument was designed by Black, in which the bite force measurement relates to the stiffness of deforming a spring [74]. Based on the mechanical principle of this early device; several other techniques have been developed, modified and altered by researchers; like the manometer spring and lever device, micrometered devices and lever-spring devices [74]. Manometers and pneumatics, which are also mechanical instruments, have been applied in measuring bite force [76]. Although electronic devices have been widely used in quantifying bite force, mechanical devices still have been validly used due to the mechanical principle provides accurate results [74].

2.3.2 Electrical measurements

2.3.2.1 Jaw activity and movement in Electromyograph determination

Jaw activity is one of the most important requirements for chewing. Many have shown that the activity of jaw muscles increase as harder texture of test foods becomes harder

[77, 78]. This means that the degree of muscle activity can quantify the level of chewing force that an individual can use to clench or grind the teeth together. Mastication muscles are critical to moving the jaw and include the masseter, temporalis and pterygoid muscles (external and internal parts), all of which are controlled by the trigeminal nerve [79]. These muscles work as a group rather than separately which means single jaw muscles should not be measured directly. Researchers have attempted to define an indirect relationship between jaw muscle activity and electrical activity, which transforms synergistic muscle force into electrical signals. After several studies discovered the classic linear relationship between the output force and activity of contraction of human limb muscle at constant length by Electromyography (EMG) measurement, the technology has been widely applied in masticatory performance studies [80 - 82]. Not only can muscle output force be collected from EMG, but differences in jaw movement patterns can also be detected as different EMG rhythms in subjects with different types of chewing behaviours [10 - 12].

The normal EMG instrument relates to insertion of electrodes to the inter- or surface muscles and amplification and detection of the electrical signals generated during muscle movement. Since the late 1940s, EMG has been used in dental studies, which focus on studying asymptomatic and dysfunctional muscles in both dynamic and static functions [83, 84]. The most frequent of muscle parameters obtained by EMG research have involved postural or rest-activity and maximum muscle activity during chewing. It has been used in evaluating the influence of occlusal masticatory muscle function, either with an interocclusal appliance or not.

Many researchers have confirmed that the surface EMG of the masticatory muscles is positively and linearly related to a stable level of bite force during isometric contractions [85, 86]. Furthermore, the correlation of EMG and bite force during chewing tests (static condition) can estimate bite force from the dynamic conditional recording of EMG during chewing function. The reliability and validity of using EMG measurement for bite force to evaluate the masticatory performance in both non-pathological and pathological areas have been investigated by researchers who adopted different experimental condition to estimate the bite force including different testing positions and types of sensors [87]. However, EMG is limited because the measurement may not evaluate the dynamic bite force. The correlation between EMG and bite force under dynamic conditions is different from that under isometric conditions because of the force-shortening and force-length velocity connections of muscles dynamical movements. [88. 89]. Using isometric data, it was found that the dynamic bite force was overestimated when the force is predicted from chewing data [89].

2.3.2.2 Bite force measurement using Strain-gauges determinations

With the development of electronic instruments, came the invention of more sensitive electronic devices for measuring bite force from 50 - 800 N (± 10N) with 80% precision [90]. Based on the principle of electrical strain gages, most this type of instruments can provide adequate precision and accuracy for the common evaluating purposes [91]. The working principle of electronic devices is using transducers to convert bite force into electrical energy. The early stain-gauge transducers consisted of a metal fork or plate. Upon loading, the resistance of metal plates changes because of the deformation of these plates, resulting in a change of electric voltage or potential. The loading force can be calibrated by a calibration curve of voltage-weight. Although the measurements of maximum bite force by strain-gauge transducers have been validated as accurate, they are still unable to collect a true *maximum* bite force. This is because subjects have reported feeling uncomfortable, and fear breaking their teeth [90, 92]. As a result, more comfortable materials (gutta-percha, polyvinyl chloride, acrylic resin and gauze) have been used to the surface of the metal transducers, which can make subjects less uncomfortable [27, 93]. However, subjects still fear to bite on a hard surface with protective covers [90]. The shapes and dimensions of transducers limited recording data in the frontal regions of the oral cavity have been found [94 - 98]. Moreover, the thickness of the metal plate or fork is a disadvantage of strain gauge transducers because subjects have to open mouth over 15 mm. Many studies found that mouth opening above 15 mm change the correlation between bite force and closing jaw muscles [99 - 101].

With the improvement of technology, smaller, more sensitive electronic devices have been created which enable the application of strain-gauge measurements to restored previous teeth [102, 103] or implanted complete dentures [104]. Arrays of small strain-gauges cells have been used to simultaneously determine the global, and per tooth, bite force such as the T-scan device (Tekscan Inc., Boston, USA). A horseshoe shape sensor embedded into pressure sensors means this device can rapidly measure the contact area of teeth and dental force data [103]. Since the development of this device, various research has scrutinized this system. There are results provided both in the agreement with [105, 106] and against the system [107 - 109] with most claiming that the requirement and cost of specialist training were the limiting factors for its use. With reduced size and raised commercial availability, strain-gauge transducers are still widely used to measure bite force. Based on advantages in reducing size and increasing sensitivity of strain-gauges, several commercial systems have been developed for determining bite force, such as GM 10 Occlusal Force Meter (Nadno Keiki Co., Japan), I-SCAN 50 (Nitta Corp., Japan) and the Krato digital dynamometer (Equioamentos Industriais Ltd., Brazil).

The small and thinner structure of new gauges provides more opportunity to evaluate bite force closer to the intercuspal position [27]. However, there is a controversy of reliability and accuracy of the new gauges performances. The transducers collected incomplete data from several contact areas, which compared with the results by occlusal foils [108, 110]. However, 95% of reproducibility using the transducers have been proven in two studies [106, 111]. The controversy and high cost of these commercial instruments suggest that the technology can still improve.

2.3.2.3 Bite force measurement using Piezoelectrics

Piezoelectric (piezoresistive) transducers are a device for measuring occlusal load (bite force). The raw materials of piezoelectrics allow the development of relatively thinner sensors, which can be about 0.25 mm [90]. Due to the small size of piezoelectric sensors, they can be directly placed in previously restored teeth to measure bite force in three dimensions [112]. Except for the size, other benefits of this transducer are low-cost and flexible which can be widely applied in commercial devices [113, 114]. In addition, customized development of piezoresistive transduces covered rubber bite pads in the sensor to make subjects comfortable from bite force experiments [115]. However, some studies showed that the narrow range of bite force evaluated by piezoelectrics sensors could not be sufficient for particular measuring purposes [106].

2.3.2.4 Bite force measurement using Pressure sensors

Pressure force transducers can be divided into pneumatic and hydraulic types depending on two different mediums filling the chamber of the device. The pneumatic type is filled with air and the hydraulic one filled with liquid. The compression of the fluid is transformed via pressure to an electrical signal, which can be used to quantify strain. Braun *et al*., (1995) [116] claimed that pressure sensors of this type can collect the real maximum bite force, as the material and design makes subjects feel that the sensor is safe to bite. Pressure force transducers are still in development, with new advancements such as more comfortable materials, like rubber [117], and the magnetic system [118], helping to improve validity and reliability. However, the use of these devices is still limited in the clinical field due to expertise requirements and expensive costs.

2.3.2 Bite force measurements using multiple instruments

Except for using single bite force measurements in bite force study, multiple instruments have been developed and applied in measuring. The benefits of multiple instruments can provide the study different aspects, which can better understanding mechanism and changes of bite force.

2.3.3.1 Multiple transducers applied to 3D bite force measurement

The majority of bite force devices only capture vertical masticatory force. Although vertical force is a dominant force under most occlusal conditions, the lateral and anterior forces also play important roles [119, 120]. Van Eijden (1991) [121] used force transducers that can measure three-dimensional (3D) bite force to evaluate the effect of 3D direction of maximum force. It has been shown that the bite forces generated from posterior and medial directions are larger than from the anterior and lateral directions. Osborn & Mao (1993) [122] developed an H shape of force transducer with two different types of sensors (strain-gauge and piezoelectric sensors) (Figure 2.1), which have capability to detect six orientations. The study showed that the maximal incisal force is 17 - 26% of bite force magnitude where arises from 10 - 15° anterior to the frontal plane.

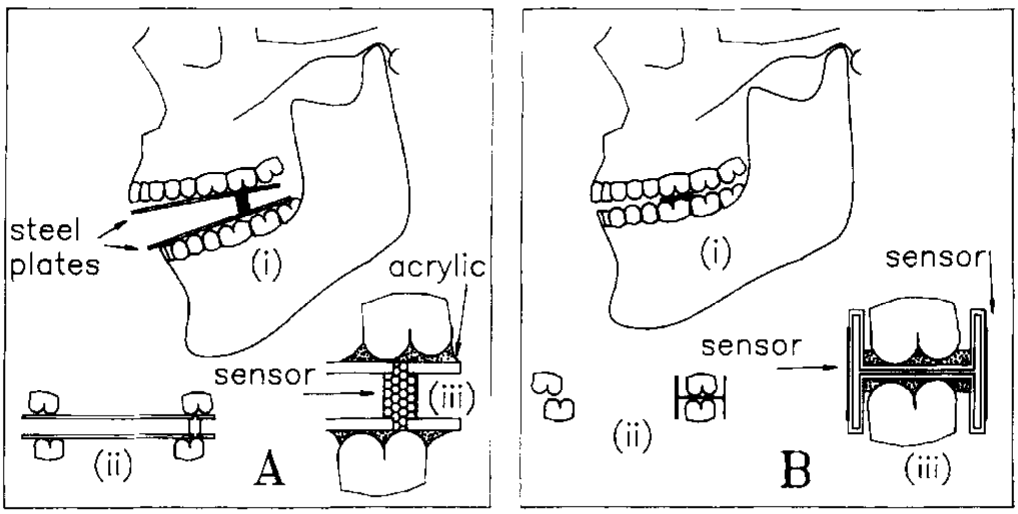


Figure 2.1 A is the Amsterdam transducer and B is the developed strain-gauge transducer. (i) Side view; (ii) Front view; (iii) Zoomed view.

2.3.3.2 EMG and force transducers apply in steadiness of bite force measurement

Force steadiness can predict the occurrence of neuromuscular disorders with ageing [123 - 126]. Bite force and other features of an EMG can distinguish between differences in the physiological factors of muscle control [127, 128]. Moreira *et al.*

(2020) [129] customized an instrument with piezoelectric sensors and EMG to establish a measurement of the incisal bite force (Figure 2.2) and designed a protocol to evaluate the steadiness of the measurement. A linear correlation between incisal bite force and EMG was found in both masseter and temporalis muscles. It may prove that the activity of these muscles, captured using EMG, can define the total muscle electrical activity around the jaw. If this incisal bite force measurement is stable and reliable, it may predict that jaw muscles are optimized in terms of neuromuscular control.

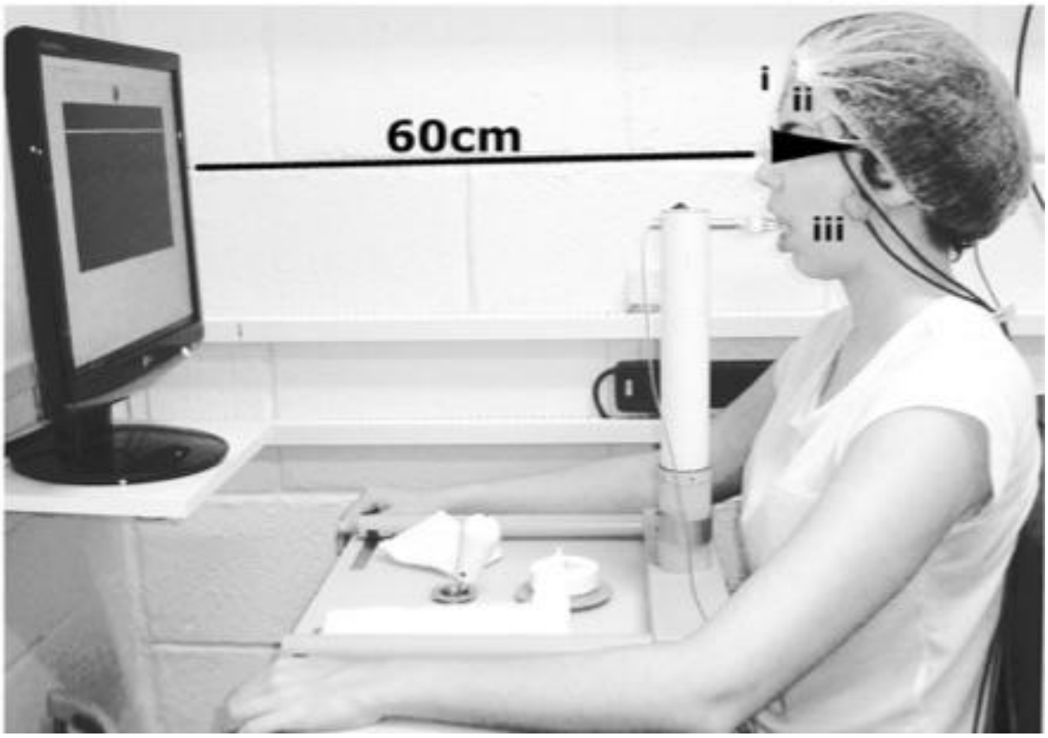


Figure 2.2 The incisal bite force measurement setup. A customised instrument with piezoelectric transducer fixed on an adjustable desk. The sensors of EMG located in (ii) temporalis muscle and (iii) masseter of both sides.

2.3.3.3 Bite force determinations apply in Maximum bite force measurement

The maximum bite force (MBF) of the chewing sequence has been studied to assess the levels of masticatory function. Fontijn-Tekamp *et al.* (2000) [16] and Hatch *et al.* (2000) [130] claimed that correlation coefficients of MBF and masticatory function up to 0.8. It means that the MBF can explain more than 60% the variance in masticatory performance. Table 2.1 is a review of the maximum bite force of full natural teeth and healthy physical subjects in different age range, sex, test region of teeth and instruments.

From Table 2.1, the peak value of MBF found in two studies was 870 N (subjects' right side of molars) [99] and 878 N (male subjects' bilateral molars) [131], which are more than 50% greater than some of these studies. In these studies, strain gauge transducers used in were covered with rubber layers, and this may indicate that the rubber is a comfortable material making the participants willing to exert their MBF without fear of impairment of teeth. Apart from age (discussed later), other reasons for difference between these studies may be the bilateral or unilateral measurements, which can be proved in van der Bilt *et al*. (2008) [132] and Tortopidis *et al*. (1998) [87]. The two studies compared both bilateral and unilateral measurements, the results have shown that the bilateral MBF was significantly larger than the unilateral one. The lowest value of MBF was 234 N for female subjects [85]. Sex appears to be a key factor that influences lower MBF except in the case of unilateral measurements, and measurements with uncomfortable transducers. MBF of males is much greater than of females in all of the research that compares these factors. This finding can be explained due to the strength of muscles being influenced by sex.

Table 2.1 A review of MBF of full natural teeth and physical healthy subjects in different age range, sex, test region of teeth and instruments.

	Number Of Subjects (Male/Female, *n*)	Age Range (yr)	Region Of Teeth	Instrument measured	Maximum Bite Force (Male/Female, N)	References
1	196/188	21-23	Bilateral molars	Strain gauge (rubber)	878/690	Ahlberg *et al*., 2003 [131]
2	20/20	33-52	Unilateral First molar	Strain gauge	652/539	Al-Omiri *et al*., 2014 [61]
3	35/45	21-30	Unilateral molars	Unilateral Dynamometer (Fork shape)	R: 643/427 L: 627/420	Apostolov *et al*.,2014 [131]
4	8/11	20-60	First molar	Strain gauge	480	Bakke *et al*., 1989 [134]
5	59/63	8-68	First molar	Strain gauge	522/441	Bakke *et al*., 1990 [135]
6	10/10	50-65	Bilateral First molar	Strain gauge	339	Pal, 2013 [136]
7	20/20	19-27	Full teeth	Strain gauge	722/520	Bonakdarchian *et al*., 2009 [137]
8	10	19-30	Second premolar to	Strain gauge	354	Clark & Carter, 1985 [138]

9	2/0	-	First molar Unilateral Second molar	Strain gauge	550	Fasiter-Woller, *et al.*, 2016 [139]
10	36/16	19-29	Full teeth	Strain gauge	306 /234	Ferrario *et al.*, (2004)
11	32	21-62	Full teeth	Strain gauge	398	Fontiji-Tekamp *et al.*, (2000) [85]
12	7/13	17-55	Full teeth	Piezoelectric	725	Gibbs *et al.*, 1981 [140]
13	11/33	28-76	Left and right side molars	Strain gauge	720	Gibbs *et al.*, 2002 [141]
14	0/9	20-26	Full teeth	Strain Gauge (York shape)	395	Hagberg, 1986 [91]
15	283/348	37-80	Full teeth	Strain Gauge	583	Hatch *et al.*, 2001 [130]
16	57/68	15-65	First molar	Strain Gauge (York shape)	444/357	Helkimo *et al.*, 1977 [142]
17	444/376	Over 60	Full teeth	Press Sensitive sheet	511/442	Ikebe *et al.*, 2005 [23]
18	4/0	20-30	Bilateral Second molar	Strain Gauge	567	Howell & Manly, 1948 [143]
19	3/2	18-32	Full teeth	Miniature Strain gauge	296	Koc *et al.*, 2012 [144]
20	13/0	20-30	Bilateral First molar	Press Sensitive sheet	359	Kumagai *et al.*, 1999 [145]
21	15/15	22-32	Right side: First premolar and molar	Strain Gauge (Customised)	Premolar: 373/314 Molar: 384/339	Lepley *et al.*, 2011 [146]
22	13/68	18-25	Bilateral First molar	Strain Gauge	481/422	Linderholm & Wennström, 1970 [147]
23	88/91	7-80	Left and right molars	Strain Gauge	Right: 339/273 Left: 348/287	Marcelo & Mariangela, 2010 [148]
24	301	32(13)	Full teeth	Press Sensitive sheet	511/442	Miyaura *et al.*, 2000 [149]
25	177	7-80	Bilateral First molar	Strain gauge	342	Palinkas et al., 2010 [150]
26	27/28	18-40	Left and right molars	Strain Gauge (York shape)	Right: 632/427 Left: 627/420	de Abreu *et al.*, 2014 [151]
27	10	35-70	Left and right molars	Strain Gauge	Right: 350 Left: 388	Rosa *et al.*, 2012 [152]
28	14/14	22-35	First Molar	Strain Gauge	520	Thompson *et al.*, 2001 [153]
29	8 (Male)	25-32	Unilateral and	Strain Gauge	Unilateral:428 Bilateral: 579	Tortopidis *et al.*, 1998 [87]

			Bilateral			
30	20/16	24-35	Bilateral First molar	Optical	635/525	Umesh *et al.*, 2016 [154]
31	13/68	19-69	Unilateral and Bilateral	Strain Gauge	Unilateral: 490/418 Bilateral: 652/553	Van der Bilt *et al.*, 2008 [132]
32	30/30	15-18	Bilateral First molar	Strain Gauge	778/482	Varga *et al.*, 2011 [155]
33	15/15	20-35	molars	Strain Gauge (rubber)	Right: 870/598 Left: 818/595	Waltmo & Konone, 1993 [99]

2.4 Measuring masticatory performance with model foods

Food characteristics (hardness, size, moisture etc.) have a strong influence on masticatory behaviour. Adjustments to a characteristic such as hardness, for example, include extending the chewing time, increasing chewing cycles and vigorous jaw activity. However, once hardness reaches a certain level that exceeds an individual's masticatory ability, coarser particle sizes are observed in the bolus which is not safe for swallowing. Foegeding (2007) [34] found that the perception of food texture is a dynamic process during oral processing, meaning that the physical properties of food change continuously while eating. This means that studies of oral processing can investigate changes in masticatory performance for a variety of foods with different deformability and hardness.

Foegeding (2007) [34] found that changes in the perception of food texture are a dynamic process in oral processing that arise from mastication, meaning that the physical properties of food change continuously. This means that studies of oral processing can be investigated through the changes in masticatory performance for a variety of foods with different deformability and hardness. Two main types of food models have been used in the evaluation of masticatory function: natural food models and artificial food models. Natural test foods have been widely used in evaluating both pathological and nonpathological masticatory functions, as test subjects more easily accept the use of conventional and natural foods in such tests. Natural foods typically used for these studies include: carrot, apple, cheese, meat and nuts. However, the physical properties of the same natural food are not wholly consistent because of variations in season, ripeness, sub-species, etc. Due to complex components and structures of natural foods, it is difficult to isolate one specific textural property which may influence oral processing. Foster *et al*. (2006) [156] explained that artificial model foods can be pure and valuable stimuli for chewing studies. Artificial food models can be designed to fit particular textural requirements and controlled mechanical properties, thus ensuring consistency. Moreover, characteristic foods have been used as examples of preferred texture in the JBMB Mouth Behaviour tool [441- 443] to explore preferences for an individual's mouth behaviours (e.g. cruncher, chewer and sucker). The different preferences for mouth behavior may influence measured bite force, particularly if biting as hard as possible is not commonly used by the individual when masticating food.

2.4.1 Masticatory efficiency

Chewing efficiency is defined as the number of chewing cycles needed to prepare a swallowable bolus from the original piece of food [1]. Some studies found that between 10 to 40 chewing cycles are required to reduce the model foods (e.g. two-colour chewing gum) to a small particle size, forming a cohesive bolus for easy swallowing [6, 7]. Several parameters can serve as measures of masticatory efficiency: masticatory duration, the number of chewing cycles, frequency of chewing cycle and particle size [8, 9].

2.4.1.1 Masticatory duration time and number of chewing cycles

The main goal of mastication is to reduce the particle size of food to form a bolus suitable to be swallowed. Some clinical studies reported that dental patients significantly reduced mastication time after treatments [11, 157, 158]. Therefore, masticatory time and the number of chewing cycles are the most straightforward measurements evaluating masticatory efficiency. Natural foods with differing hardness have been used as a scale of hardness to study the number of chewing cycles [159], masticatory duration [160] with increasing with harder foods. The use of artificial model foods also shows this relationship in more detail. An upward trend of both chewing duration and number of chewing cycles with increasing hardness were found in many studies using different types of artificial food models, including gelatin-based models [78, 156, 161], gullan gum [162], tablets with $CaCO_3$ and cellulose [163], and hydrocolloid gels [164]. In addition, Foster *et al*. (2006) [156] found that the difference between elastic (jellied products) and plastic (caramel products) food models with similar hardness was the frequency of vertical and lateral movements, the elastic food needed higher frequency chewing. Peyron *et al*. (2002) [78] found a positive correlation between the hardness of gelatin-based test foods and masticatory performance (chewing time, jaw muscle activity etc.).

2.4.1.2 Particle size

Some studies equate masticatory efficiency with the ability to masticate food by measuring the size of the food particles after a certain number of chewing cycles [165 - 167]. Among the measurements of particle size, a sieve system is one of the most frequently used measurements. The first sieve measurements were introduced by Gaudenz in 1901, where a natural test food (almond) was used [151]. Literature reports that different types of natural foods influence results of masticatory efficiency [168, 169]. Kapur (1964) [168] concluded that fibrous natural foods (celery and lettuce) are more difficult to chew than test foods containing lower fibres (chestnuts, sardines and sausages). Additionally, they suggested that raw carrots may be an appropriate food model for sieve tests because carrots presented a high level of precision in reliability tests one day and a week apart.

Median particle size is an important feature used to evaluate the bolus before swallowing [170, 171], and can be used to assess masticatory performance after chewing for a fixed of masticatory strokes in natural or artificial foods [5, 172, 173]. Normally, larger median particle sizes can indicate a reduction of masticatory performance. Compared to the significant variability of physiological factors including duration of mastication, the number of chewing cycles and activity of jaw muscles [5, 174 - 177], the variability of median particle size is narrower in different types of test foods [33, 176]. Some studies [178, 179] explained that the reason for the lower variance is that a prepared bolus can avoid the risk of choking, aspiration and overload of the digesting. And another reason for the narrower distribution in particle size may depend on food fracture properties, which affect selection and breakage function. However, the measurement of the median particle size is a demanding laboratory task that cannot be applied to a large panel for a mastication study.

2.4.1.3 Formation of food bolus

Masticatory performance is often evaluated by the capability of individuals to form a bolus. Two-colour test foods (moulded rice and rice cake) as natural model foods applied to assess masticatory function during a fixed number of chewing cycles (10, 15, 20 and 30 cycles) by image analysis. The degree of mixing test foods significantly increased with the increased number of chewing cycles [438]. Two-colour chewing gum has been used as an artificial food model to evaluate masticatory function [180 – 182]. The mixing degree of the two colours can be assessed by visual examination [183], image analysis [184, 185] or a combination of both methods [182]. The mean of the Pearson correlation coefficient between results of mastication and two-colour mixing test was 0.58, while the highest one was 0.86 after 15-20 chewing cycles. The higher correlation coefficient indicate that two-colour chewing gum determination may be more appropriate and has better discrimination in assessing the masticatory performance during bolus formation than comminution test (coefficient = 0.52) [185].

2.5 Combination of food and device to measure masticatory performance

Kohyama *et al*. (2004) [186] established an artificial model food made of silicone rubber with three hardness and a sheet sensor with 269 pressure cells. The advantages of this method are that both bite force and occlusal contact area measurements can be obtained and the hardness can be varied in different degrees. However, the maximum load force of this method is up to 150 N which may not measure the strongest bite force. However, artificial model food measurements mandatory require the subjects chew foods, which cannot reflect the real and comfortable masticatory function. And the hardness of artificial models in many rent studies are too soft to reflect the real capability of individuals' maximum bite force.

A manipulation-and-split device [17, 187. 188] has been introduced into the study of the regulation of masticatory functions and behaviour of periodontal mechanoreceptors. The device consists of two parts: hold-and-split equipment (Figure 2.3) and custom-built EMG. Subjects were required to bite different natural test foods (e.g. biscuit, candy and peanut) before and after anesthesia of teeth. The bite force was detected by two strain-gauge transducers and jaw muscle activity was recorded by EMG during the biting period time that from holding time (4 seconds: hold the food between teeth) to food completely split. The result [187] showed that participants with healthy teeth had nearly one third lower holding bite force compared with participants without periodontal support. And in normal conditions, the holding bite force was half of that on anaesthesia conditions [17, 188]. Compared to the holding bite force, the splitting bite force and jaw muscle activity have no significant difference between anaesthethetized and not. Therefore, these studies demonstrated that periodontal mechanoreceptors have a significant influence on controlling low bite force levels [189].

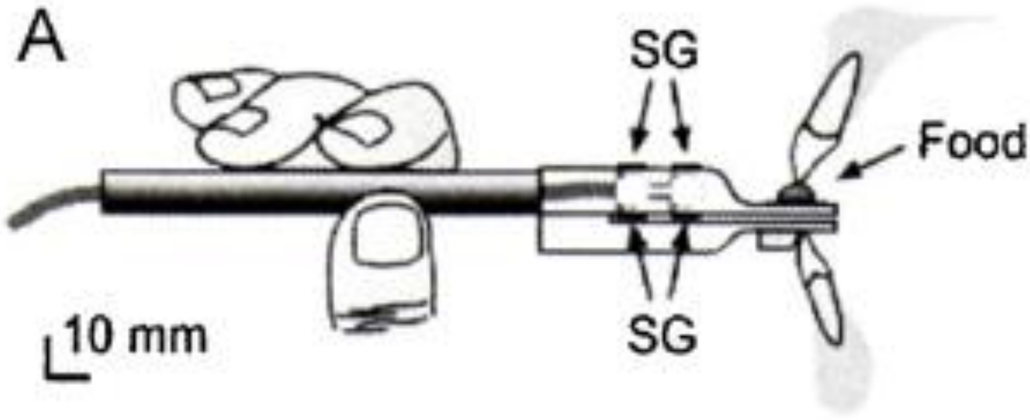


Figure 2.3 The hold-and-split device for recording bite force exerted on food morsel.

2.6 Comparison of objective vs subjective approach to measuring masticatory function

Questionnaires and interviews as subjective measurements of masticatory functions can be easily understood and accepted because of focusing on the perceptions of subjects. The benefit of subjective measurement is it can capture the effect of personal factors. The high acceptance and low technical requirements mean these self-assessed measurements can be widely used across different types of subjects and studies without limitations of gender, age, ethnicity, culture. Self-reported questionnaire can be applied to large numbers of participants and longitudinal studies, due to the low cost and consistency patterns/questions. Another limitation of questionnaires is that subjects may not be able to rate their masticatory ability on test foods they have little experience with. For example, the rating for "difficulty level of chewing" from a subject who has never eaten dried sausage is then unreliable for dried sausage.

Objective measurements can effectively evaluate different factors of masticatory function including jaw movement, jaw muscle activity, chewing efficiency, median particle size and bite force. In addition, skeletal craniocervical and craniofacial morphology directly impact masticatory function [439]. Compared with the other two ethnic groups, the Amazon Indian ethnic population has a wider dental arch and higher bizygomatic width, which significantly correlates to stronger bite force [440]. However, these laboratory measurements of chewing require professional experts, expensive instruments and high standard testing locations. These requirements will limit the number of test subjects, which may increase the impact of variability on the experimental design. Besides this, a potential lack of proficiency may impact the consistency of experiments and influence the reproducibility of data. Although some commercial devices exist without tester proficiency, some studies are against the reliability of these measurements of masticatory functions [107, 190]. Some techniques are intrusive and use metallic materials, which can make subjects feel uncomfortable [90, 92].

The correlation between the results of objective masticatory performance and self-assessment masticatory ability is analysed in several studies [3, 5]. One study [4] reported that the range of this correlation coefficient is between 0.12 and 0.34 when the subjects wear complete dentures, and another study [3] showed that the correlation coefficients are between 0.11 and 0.36 when the subjects have been treated with implant and wear fixed dentures. Data from self-assessment is often overestimated can arise from a poor correlation between subjective and objective masticatory function [72, 73]. Fenie & Lund (2006) [22] complained that the results of objective masticatory functions do not always reflect individual performance in the mastication field. Since the ultimate aim of studying masticatory functions is to ensure the ability of intake foods, measurements based on model foods may be a practical alternative pathway. Artificial food models have controllable consistency of mechanical properties, such as hardness, crispness and rubberiness. Furthermore, artificial food as the test "transducer" may make subjects feel more comfortable and therefore have greater acceptance for undergoing tests measuring mastication factors.

Chapter 3 Oral Processing related to Ageing

This chapter summarised the crucial factors influencing age-related masticatory function during oral processing, as a consequence, leading to mastication-related malnutrition with ageing. Section 3.1 introduced the background of age-related oral processing. Section 3.2 describes each stage of oral processing. Section 3.3 detailed summarized different factors that impact masticatory function with ageing, including oral health, jaw muscle activity, tongues, saliva and swallowing. Section 3.4 introduced mastication-related malnutrition with ageing.

3.1 Introduction

Due to the advances and developments in nutrition, lifestyle, medical science and technology, the elderly population continually increases worldwide. World Population Review 2021 reported that the fertility rate of New Zealand is Rank 111/200 in the world with 2.0 children per woman, which is below the population level of 2.1 birth per woman. According to the New Zealand 2018 Census estimation, the national older adult population (aged 65^+) will be one person out of every five New Zealanders by the early 2030s, which is approximate 1.1 million elderly. The trend of a growing proportion of elderly in the population has been increasing since 1950, leading us into a 'super-aged society' in the near future. Consequently, it is necessary to understand the influence of ageing on oral processing to provide specific recommendations for the elderly to maintain a healthy life with adequate nutrition.

To maintain a healthy life for the elderly, a good and balanced nutritional intake is one of the most critical components. Functional oral processing is the significant start of food digestion, leading to improved nutrient absorption. Mioche *et al*. (2004) [1] explained that chewing behaviour could influence the condition of nutrition in two different pathways. The first way is the pleasure of intake of foods elicited from the perception of food sensory properties, which is significantly determined by oral processing (chewing and swallowing). The levels of pleasure influence food choice and intake, directly leading to a variety of nutritional statuses. In addition, the oral condition can impact the properties of the bolus during swallowing with a consequence on the nutrients released during the digestion phase. Ageing is described as a critical factor in oral processing, which influences oral physiology to different degrees. With the increased aged population, it is necessary to clarify the ageing's influence on ageing's oral processing to provide specific recommendations for the elderly to maintain a healthy life with adequate nutrition. This chapter will analyse the effects of physiological ageing and age-related diseases that frequently impact on masticatory function status in older age, eventually leading to poor oral health and deficient nutrition.

3.2 Oral processing-Feeding behaviour

Since videofluorography (VFG) have been used in human subjects [191, 192], feeding behaviour has been confirmed as a sequence that starts from food intake and ends as food enters the stomach. For solid food, feeding behaviour includes the processes of ingestion, stage I transport and processing and, stage II transport and swallowing [194, 201]. Figure 3.1 presents the detailed flowchart of the process of feeding behaviour, including two sensory judgements. The tongue manipulates the food into the mouth, sending it to the teeth for chewing before compressing it against the hard palate and transporting it to the occlusal surface. With decreasing particle size due to processing, a bolus forms and is swallowed.

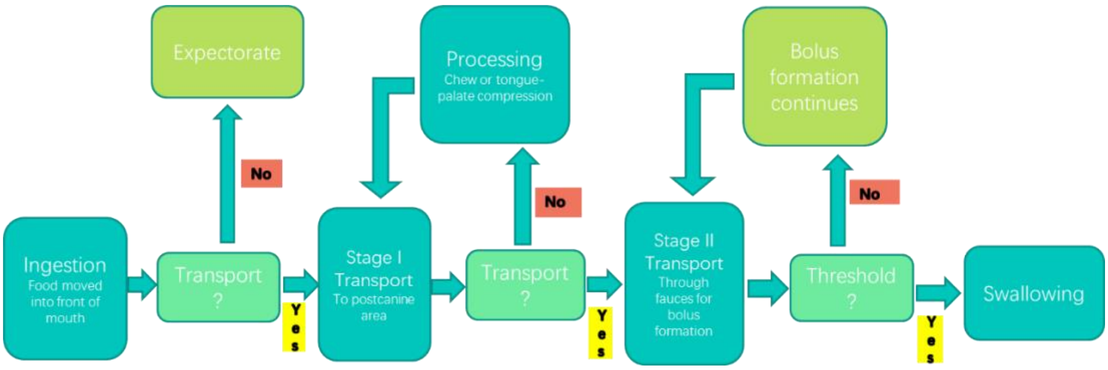


Figure 3.1 the process of feeding behaviour in solid food.

3.2.1 Ingestion and Stage I Transport

Ingestion is the first step of feeding behaviour. To start, the tongue tip and lower lip touches the food, which involves the opening of the lips and jaw and lowing of the tongue. The length of the tongue retraction has a correlation with the size of ingestion in one bite [193]. After the mouth bites the food, the lips and jaw close, and the tongue moves upward and downward to move the one-bite size food from the oral cavity to the occlusal surface of the premolars and molars, this process is called Stage I Transport.

Before Stage I Transport, Hiiemae (2004) [194] found that there is a short period (two seconds) where the judgment of the possibility of human consumption of the bite of food is made. He also called Stage I transport as the "pull-back" stage because the retraction of the tongue pulls the food forward and positioned in the molars. The function of the tongue to position food was also investigated by Prinz & Lucas (2001) [195]. A slight compression between the tongue and hard palate in Stage I Transport was noticed by Arai & Yamda (1993) [196], who claimed this function of compressing has a significant influence on the recognition of food texture. The activity of tongue muscles and hard palate has been strongly related to the intra-oral sensory input [197 - 200]. The duration of Stage I Transport varies from 191 ms to 300 ms [193, 194, 201] due to different food samples texture and the sensory test patterns.

3.2.2 Processing - Masticatory cycle

In the processing stage, the food is triturated by a series of jaw movements which are also known as "masticatory cycles". The number of cycles has a significant correlation with food texture and individual oral status and chewing patterns. A masticatory cycle is divided into three phases which are the closing, intercuspal and opening phrase. The closing phase can contain two different types of movement: Fast Close (FC) and Slow Close (SC). FC occurs until tooth-food-tooth contact occurs, after which the speed of lower jaw movement is lower, and the facial muscles are active by the resistance of the food. SC occurs when the food reduces by triturating [194]. The intercuspal phase occurs between closing and opening phases when the teeth move medially until they start to part. At this point, the tongue moves forward to touch the incisive papilla, extending the distal contact area with the hard palate which makes the food squeezable by the post-molars in the late closing phase [193]. The opening phase occurs when the tongue moves backwards and a masticatory cycle is completed.

3.2.3 Stage II Transport

The masticated food is transported through the palatoglossal isthmus from the oral cavity to the oropharynx by a drop and push of the tongue with simultaneous rising of the palate. This occurs over a series of chewing cycles along with continuous mastication. Intra-oral sensory inputs tell the brain when mastication is complete/adequate and the requirement of Stage II Transport starts when the food reaches the particle size suited to bolus formation. Stage II Transport occurs in multiple events because the food is different particle sizes and only those suitable for bolus formation will be transported by the movement of the tongue. The transport processing is repeated until a bolus is formed in the oropharynx and a swallow occurs.

3.2.4 Swallow

A large number of studies focus on the trigger of swallow; for example, the threshold of particle size is a key requirement for swallow trigger. Other papers claim that the viscous force produced from food particles bonding to form the bolus initiates the swallow. However, it is agreed that swallowing can occur unconsciously without being intentionally controlled [202, 203] and is highly correlated with food characteristics [204]. Although the swallow trigger is still veiled, the pattern of swallows occurring in a complete feeding sequence was consistently interposed with swallow and terminal swallow [193, 194]. Hiiemae (2004) [194] suggested that with a series of feeding sequences, a part of the food may become earlier suitable to swallow than others. Those particles are accumulated and transported to the oropharynx. Furthermore, other "swallowable" particles may be passed to the same position and merge with the ones earlier placed there. The first interposed swallow starts and ends. Any residual particles in the oral cavity may repeat the process above to swallow multiple times. There is always a clearance period called terminal swallow to collect and form the residual particles in every corner of the cavity and pharynx to a terminal bolus to end of the closing phase to the intercuspal phase, which has been found to occur in humans [191, 192, 205] and animals researched [206 - 208]. The processing period of terminal swallows is unstable, some claimed [209, 210] in that it occurs during feature mandibular movements (pre-swallowing cycles), but others demonstrated [194] that it happens in the clearance period. However, Okada *et al.* (2007) [193] shown that humans often need more than one swallow in the natural feeding sequence regardless of the size of food suggesting it a healthy, normal feeding pattern. Once the bolus reaches the pharynx, the pharyngeal constrictors push the tail of the bolus through the upper oesophageal sphincter, which relaxes and is supported to open by the hyolaryngeal complex. A peristaltic wave transits the bolus through the oesophagus to the stomach. Bolus properties including volume and viscosity lead to modulation of this process and affect timing and displacement of the physiological structures [211].

3.3 Masticatory function related to ageing

According to the processing of feeding behaviour, mastication is the first step for transforming the food to the stomach [1]. A brainstem situated central pattern generation controls the contraction of jaw muscles to complete a series of rhythmic activities [212]. Due to different bolus textures, sensory inputs modulate the activity by adjusting the chewing process during the masticatory sequence. Orchardson & Cadden (1998) [213] found that the mastication process is a highly complex sensory-motor activity, including teeth, dental arch, jaw muscles, tongue, and saliva. Ageing with other reduction of anatomical, physiological and psychological functions, including the number of missing teeth, periodontal disease, degenerated muscle strength and decreased motor skills lead to a downtrend of masticatory function in elderly individuals [1, 23 - 27].

3.3.1 Dentition

Oral health is one of the most important factors that influence masticatory function because it is involved in every stage of the feeding sequence. The teeth chop the food, ten dental arch compress and grind food and the tongue transports foods. Absence in one or more of the parts of dentition causes masticatory function decrease, disorder and even dysfunction. Therefore, tooth loss, malocclusion and periodontal disease are the main causes of deficiencies in masticatory function [214]. Although most people who suffer from these dentition problems claim that they are able to compensate with these levels of difficulty, this compromised dentition is responsible for extending the chewing time before swallowing [69, 215]. Furthermore, decreased masticatory performance causes individuals to consume mainly soft and easy-to-chew food. This particular diet tendency may induce marginal nutrition intakes and poor dietary [216 - 220]. Compromised dentition can therefore lead to food avoidance, food refusal, malnutrition and potentially choking and death particularly in the elderly with compromised cognition. In fact, choking is the second common cause of death in aged care after falls (www.iddsi.org).

Through the advanced phylogenetic reason, the shape and position of teeth is the key mechanical factor to break down food in the mouth [221]. To examine the ancient human skulls, the ratio between the teeth's crown and root is unbalanced with ageing [1]. This unbalance status was caused by the occlusal abrasion by repeatedly chewing activity of hard food. In the modern society with ageing, intake amount of processed and soft foods lead to the lack of occlusal abrasion. As a consequence, the persistence of occlusal tooth relief cause oro-facial disorders [222]. The changes of dental arch related to primary ageing were found in the anatomy. The dental arch is one of the critical parameters that affect the chewing platform area. A strong linear correlation between chewing performance and the platform area has been established, showing that the masticatory function reduces when the platform area decreases [19, 193, 194, 223 - 225]. A person whose posterior set of premolars and molars start to decrease or are absent is defined as having a shortened dental arch (SDA) [19, 226]. The asymmetric SDA patient (3-4 pairs of premolars) with a long side cause impairment of masticatory ability to intake hard food. The masticatory ability of extremely SDA patients (0-2 premolars) are impaired severely [19].

3.3.2 Tooth loss

3.3.2.1 Number of teeth

A normal adult has 32 permanent teeth which are classified as four types of function teeth including incisors, canines, premolars and molars (Figure 3.2). Most research found that masticatory ability is highly related to the number of teeth. An individual with less than 20 natural teeth begins to have chewing difficulties [227, 228]. Some studies reported [36, 39] that with individuals missing more than 7 teeth, the chewing ability was impaired significantly. Others have shown that individuals who have more than 20 teeth are satisfied with their chewing ability [28, 229 - 231]. Furthermore, some studies suggested that 21 teeth were the lowest requirement for sufficient masticatory ability [228, 232]. However, Andersson *et al*. (2004) [233] claimed that the patients who have more than 16 teeth feel satisfaction in a small panel. The lowest number of teeth allowing for satisfactory ability may vary because of the variety of individual status, geographic distribution and dietary patterns.

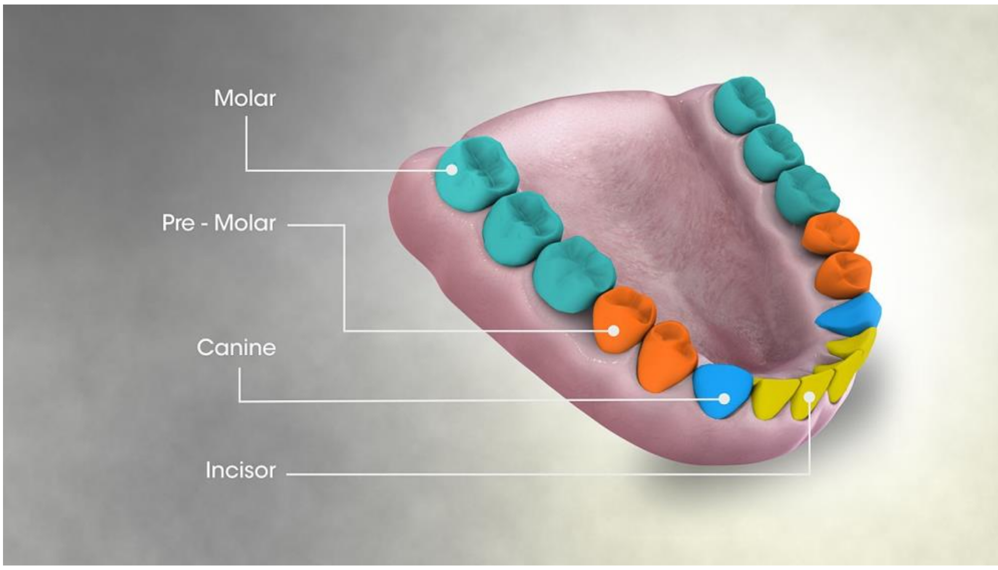


Figure 3.2 Molar teeth and their arrangement in the amount of an adult human being.

(https://upload.wikimedia.org/wikipedia/commons/thumb/f/f4/3D_Medical_Animation_Still_Showing_Types_of_Teeth.jpg/522px-3D_Medical_Animation_Still_Showing_Types_of_Teeth.jpg).

3.3.2.2 Functional tooth units

To assess the masticatory function, dietary intake and oral condition, pairs of opposing teeth have been called functional tooth units (FTUs) [16, 21, 36, 234, 235]. An individual normally has 12 natural FTUs: 4 FTUs being 4 pairs of premolars and the remaining 8 FTUs are the 8 molars (third molars excluded). The number of FTUs is an effective indicator of masticatory performance [5, 130, 215, 236]. The number of FTU can cause about 50% of the variance in masticatory performance [237]. Increasing chewing difficulties are correlated with decreasing FTUs [20, 221, 232, 238 - 243]. Some studies have proven that individuals with more than 5 natural FTUs are satisfied with their chewing ability [228, 239]. The masticatory performance of individuals with less than 3 posterior FTUs is reduced, and partial dentures can only compensate part of the decreased chewing function [244].

3.3.2.3 Teeth related to ageing

Steele *et al*. (1997) [232] claim that maintaining at least 21 teeth with good distribution is necessary to continue a moderate masticatory function. The number of remaining teeth is inter-individual and varies among the elderly in primary ageing [105]. However, there is a gradual upward trend of the average number of teeth loss with ageing [1]. A survey reported that the elderly whose age is between 65 and 69 years remain 18 natural teeth in average level [245]. In most countries, individuals aged over 75 were found to be very likely to retain less than 20 of their natural teeth [246]. The types of teeth have a different average life span, which is a trend from posterior to anterior teeth [247]. Nagao (1992) [247] found that the average life span of the second molars is 42 years and the incisors is approximately 60 years. Osterberg *et al*. (1996) [248] divided the elderly group into three subgroups that are young-old subgroup (60-65 years old), middle-older elderly have significant impairment of chewing ability. Compared to natural teeth, wearing prostheses that aim to rehabite chewing ability is a less efficient treatment of masticatory function [249 - 251]. Partial denture wearers cannot completely recover to the level of the masticatory function of those whose number of natural teeth are more than 20 [244]. Mishcellaby-Dutour *et al*. (2008) [252] found that the denture wearers chewed more cycles and made larger median particle size for swallowing than fully dentate individuals in the elderly group.

Tooth loss is considered an unhealthy oral status for the elderly. Oral diseases including periodontal and caries significantly cause tooth loss by tooth extraction. Caries commonly occurs in the first part of life, but periodontal diseases are one major reason tooth loss occurs after 50 years old [253, 254]. Periodontitis is characterised by connective tissue attachment and alveolar bone loss and implies a loss of collagen fibres in the periodontal ligament subjacent to the pocket epithelium [226]. The ligament linking to the root of the teeth and alveolar bone has mechanoreceptors that launch the brain signal about masticatory actions (food biting, chewing and holding) by teeth [193, 224, 225]. So, periodontitis can cause chewing impairment, tooth loss and unilateral mastication. The reduced tissue of periodontitis has been studied to affect the adjustment of bite force [17]. Swallowing problems impact the reduction of the ability to eat sufficient quantities of foods [233, 255]. Osteoporosis can be another reason for influencing oral bone, which leads to dental status [256]. Krall *et al*. (2001) [257] studied that a special diet with a high concentration of calcium and vitamin D has a positive effect on retaining teeth.

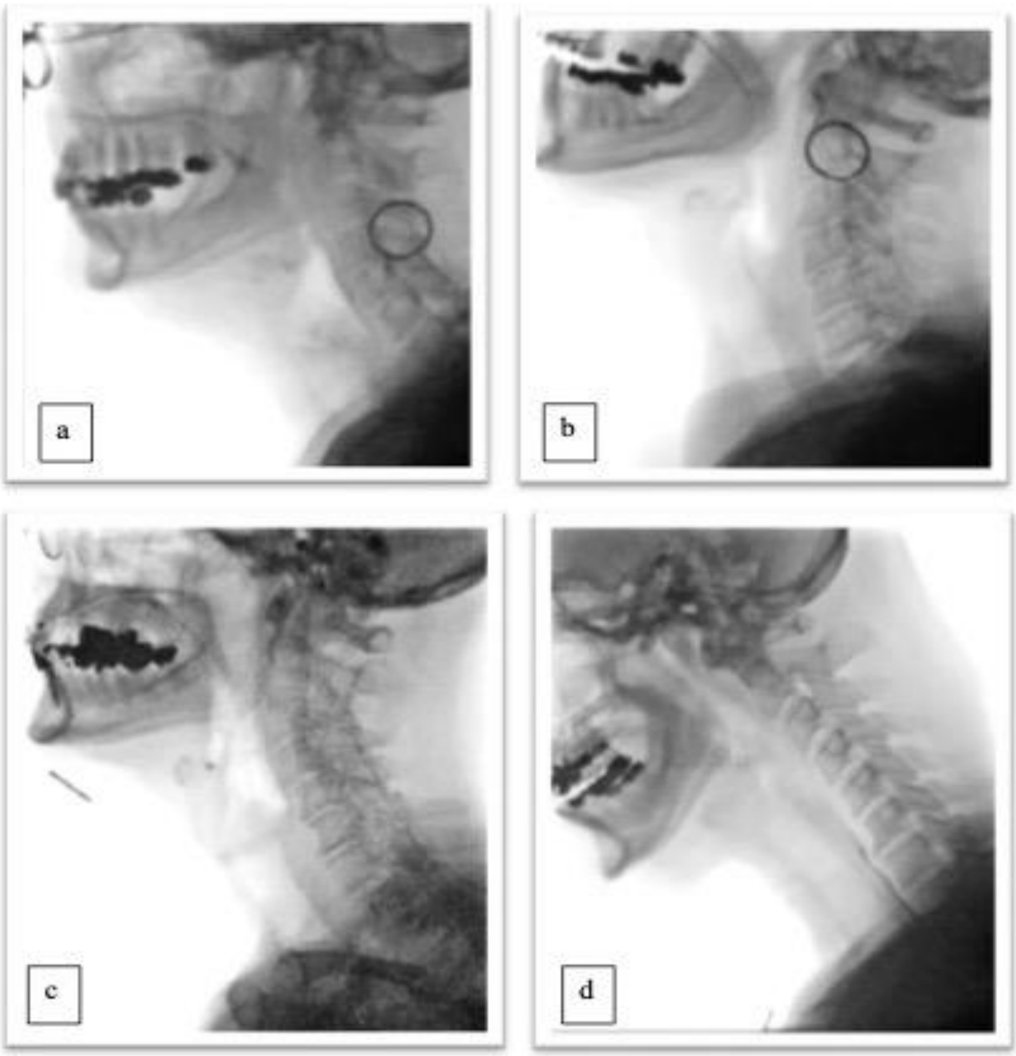


Figure 3.3 Typical deterioration in dentition in older age: a) 78yr old male multiple fillings with lower removal plate; b) 69yr old female multiple fillings with upper & lower removal plate; c) 89yr old female multiple filling with upper & lower removal plate; d) 81yr old female multiple fillings with upper & lower removal plate. Acknowledgement University of Auckland Swallowing Research Laboratory Database.

The edentulous population is the last stage of tooth loss, consisting of 40% of those between 65 and 74 years old and 64% of those above 75 years old [258, 259]. While 92% of the edentulous population wear dentures [260], 13% sporadically or never wear dental prostheses [261]. Maintaining the good condition of natural teeth is costly and complex, so the variety of socio-economic status leads to the significantly different prevalence of edentulism [1]. Māori is the indigenous and a large population (15%) in Aotearoa, New Zealand [262]. 2009 New Zealand Oral Health Survey (2009 NZOHS) shows that Maori adults have a more significant oral problem (e.g. untreated decay and tooth loss) than non- Māori. There was a controlled trial that comparison Māori and non- Māori women (40-74 yrs) after screening for education, age, diabetes, cardiovascular disease history, BMI and smoking. Māori ethnicity strongly relates to tooth loss and edentulism was found, which shows that Māori females had a five-time possibility to be edentulous than non-Maori [263]. Fontijn-Tekamp *et al*. (2000) [16] found that the osteo-integrated implant improves patients' objective masticatory function, but the treatment may be expensive. Van der Bilt (2011) [237] shown that edentulous individuals' masticatory function is handicapped, and the complete denture is a poor replacement of natural teeth. Although the objective masticatory function of complete wearers is low, 80% of them self-report their chewing ability are good [17, 264]. The elderly being still satisfied with their masticatory function can be explained by adaption and enhancing chewing ability in good health. Some researchers [5, 265 - 267] have claimed that older adults who have healthy oral status can extend the duration time of chewing sequence and increase the number of chewing cycles to get the required particle size of food to form a bolus, which is well preparation for swallowing. Moreover, the finer and smaller particle size of some types of food were found to be favoured with the ageing individual [252, 265, 268].

3.3.3 Jaw muscles

3.3.3.1 Mastication muscles

Mastication muscles are critical to moving the jaw and includes the masseter, temporalis and pterygoid muscles (external and internal parts) (Figure 3.4), all of which are controlled by the trigeminal nerve [79]. These muscles work as a group rather than separately. The muscles use the temporomandibular joint as a fulcrum to move the mandible in multiple directions.

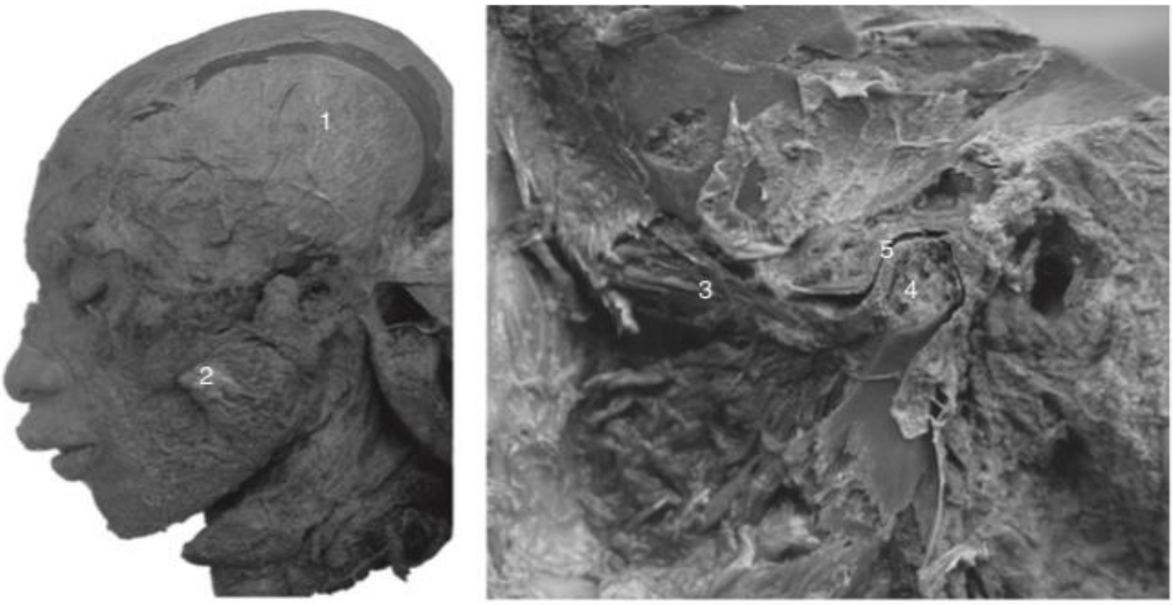


Figure 3.4 Mastication muscles (1. Temporalis; 2. Masseter; 3. External pterygoid; 4. Condyle; 5. Articular disc) [269].

The most significant muscle for elevating the jaw is the masseter, which is divided into the superficial and deep parts. The fibres of the superficial part are backward and downward, while the deep ones are forward and downward [270]. The deep part is smaller and its fibres are more vertical than the superficial one. The temporalis muscles are segmented into 3 parts depending on the locations of the fibre: anterior, mid and posterior. This change is the reason that the anterior part is more dynamic when the jaw is closing. The posterior part is more active when the jaw is retracting. The external pterygoid cover the area between the infratemporal fossa and the condyle of the mandible in the nearly horizontal orientation. Both sides of the external pterygoid contract simultaneously leading to the forward movement of the jaw. The contraction also involves rotation and downward movements of the mandible. Horizontal movements of the jaw involve only one side of the external pterygoid muscle, in other words, contraction of the right side causes the jaw moving to the left, vice versa [79]. The internal pterygoid muscle has three different directions of fibres, including downward, backward and laterally [270]. The contraction of both sides of muscle involves the jaw moving downward and forward, while unilateral contraction causes contralateral excursion.

The direction of jaw movement is determined by coordinating between the different masticatory muscles, and the occlusal force is also controlled by them [271]. Pereira *et al*. (2006) [272] found that the thickness of masticatory muscles on the bite force and facial dimensions. The physiological properties (fatigability, contraction speed and force output) of the jaw muscles motor units significantly affect their function [273]. The muscles controlling the jaw opening are adept in generating phasic and faster movement, while the muscles controlling the jaw-closing are producing vigour, slower movement [274].

3.3.3.2 Jaw muscle activity related to aged

Decreased muscle mass and impaired muscle tissue related to ageing are observed [275]. A similar result is a gradual downward trend in the maximal voluntary contraction and thickness of masseters from the subjects aged up to 60-year-old [150]. Although masticatory performance (objective masticatory function) has no significant relationship with muscle effort, it is related to maximal voluntary contraction [276]. Observation of the single bite and the chewing cycle showed that the maximal voluntary contraction decreased with advanced age [277]. They suggest that the deteriorated masticatory performance with ageing in older women with or without natural dentition. Bakke *et al*. (1990) [135] found that the age-related changes of voluntary muscle relate to the decreased bite force. The microscopic and macroscopic alterations of masticatory muscles related to ageing in the anatomy were found [278]. Similar results showed that ageing causes a downward trend of bite force [135]. With increased age, impairment of muscle mechanical performance and muscle mass has been reported [279], as well as reduction of density and cross-sectional area of masseter and pterygoids that severely impact particularly in edentulous subjects [278]. A gradual diminishing of masseter muscle thickness is associated with decreasing maximal voluntary contraction related to ageing [277]. Additionally, the reduction of the cross-sectional area of the masseters correlates to the decreasing of maximum bite force [130]. Jaw muscle activity assessed by EMG showed that there was no significant difference between the older and young individuals with full dental in brittle food [268, 280]. In contrast, the maximum bite force [5, 266, 281] and jaw muscles (masseter and pterygoid muscles) [236] are decreasing along with tongue activity (Hayakawa *et al*., 1998). However, Prinz (1999) [282] found that the elderly have some difficulty chewing tough food (e.g. meat). And the reduction of EMG activity with the extension of chewing time results in inefficient mastication and a coarser bolus.

3.3.3.3 Jaw muscle activity related to elderly nutritional status

Body mass index (BMI) is a crude but common measure of nutritional status calculating weight versus health [283]. The relationship between masticatory muscle activity and nutritional status was reported in elderly female subjects [277]. They found that the elderly females whose BMI was in the standard range would exhibit a higher jaw muscle activity during mastication. Compared with BMI, body cell mass index (BCMI) calculates the fat-free mass (metabolical active component) and is thought to be a more precise method for evaluating the nutritional status of elderly individuals because older subjects have more intensive fat mass in the body composition. BCMI has been applied to evaluate skeletal muscle function. A reduction of BCMI in the older subjects is more significant than appendicular skeletal muscle mass and fat-free mass [284]. The reduction of BCMI is related to the low nutritional condition, weak muscle strength and decreased functional performance [285]. To maintain musculoskeletal function, the correlation between masticatory function, nutritional intake and dietary selection is the essential factor [286].

3.3.4 Tongue

3.3.4.1 Tongue and masticatory function

The tongue is an essential and fundamental part of the feed sequence, including ingestion, transportation, mastication and swallowing. The movements of the tongue introduce the food from the lip to the oral cavity for ingestion, transport the food from the anterior oral cavity to the posterior area from mastication, and provide the driving force for the food to transport from the posterior oral cavity to the oropharynx for bolus formation and swallowing [201]. Okada *et al.* (2007) [193] found that the tongue also holds a critical sensory role and is involved in recognition of food texture and evaluation of the size of the bite taken. Food texture is strongly related to masticatory function, so the tongue may indirectly influence the masticatory function.

The capacity of the tongue pressure should be sufficient to transport and compress the food. Arai & Yamada (1993) [196] shown that the compression generated from the tongue compressed against the hard palate can shear the soft texture foods during the masticatory processing. The duration of the shearing force from the compression has been proven to extend with the increasing hardness of food texture in mastication [194, 287]. The maximum tongue pressure positively and directly correlated with masticatory performance occurs in childhood (6-12 yrs) [288, 289] and early adulthood (20-25 yrs) [288, 290]. The tongue pressure manometer has been applied in measuring the maximum tongue pressure in many research studies to compare the relationship between the force and age/gender/dental in the oral function [291 – 294]. The studies have shown that women reach their maximum tongue pressure earlier than men and in both genders, early adulthood is the peak of tongue pressure.

3.3.4.2 Tongue related to ageing

Although the range of tongue strength values is varied in the healthy population, age can be considered a significant factor is influencing tongue strength. Many studies report that the maximum tongue strength decreases with ageing among the healthy population [295 – 303]. Comparing the results of different age groups, the average of younger subjects' maximum tongue strength was 10-15 kPa greater than that of elderly healthy individuals. Assessing the tongue strength of Portuguese speakers in a small number of participants showed a downward trend with ageing [298]. Compared with the tongue strength from three positions (tip, dorsum and blade), a similar decreasing trend was reported with elderly subjects demonstrating lower maximum tongue strength than younger subjects [301]. A meta-analysis reported significantly lower tongue strength in individuals ⩾60 years compared to adults <60 years [304]. However, the tongue strength of edentulous older subjects was greater than that of young dentate adults perhaps due to the enforced tongue need for assisting masticatory function, leading to tongue strength increased [305]. The maximum tongue strength of males has been reported as 49-73 kPa and for females as 37-67 kPa [295 – 303]. A meta-analysis indicated that the average tongue strength of elderly males (⩾60 years) was 8 kPa lower than that of young subjects (<60 years) [304]. Compared to the female subjects' results, the older females whose age was above 60 years was 9 kPa lower than younger females.

Tongue endurance has been examined to evaluate the tongue strength, which isometrically measured at half of the maximum tongue strength in the anterior position. Many studies reported that no significant differences in tongue endurance with ageing [298, 302, 303]. However, Neel & Palmer (2011) [299] reported a trend that the tongue endurance of elderly subjects (42-78 years) was higher than that of younger subjects (20-40 years).

3.3.5 Saliva

3.3.5.1 Salivary secretions

Saliva significantly influences tasting, masticating, swallowing, digesting, maintaining the oral tissues and dentition, controlling the oral microbial environment, and speak [1]. A healthy individual normally secret a volume of saliva between 0.5 and 1.5 litres per day. Saliva, a heterogeneous fluid, composes of water and solids. 99.5% of saliva is water, and 0.5 % is solid including 0.3% proteins and 0.2% trace and inorganic substance [306 – 308]. The protein in saliva includes enzymes, glycoproteins, mucins, immunoglobulins, and various peptides with antimicrobial activities [306, 308 - 310]. Mucins create the scaffold-like network because of the high molecular weight and long molecules, which eventually lead to highly viscoelastic saliva [311, 312]. The viscosity of saliva depends on the shear rate and pH value [313]. Schipper *et al*. (2007) [313] reported that an increasing shear rate relates to the reduction of viscosity of saliva. The inorganic substances in saliva include potassium, chloride, sodium and bicarbonate, which are normal electrolytes with lower concentrations leading to saliva become a hypertonic fluid [313].

Three major glands (paired) produce 90% of the whole saliva: Sublingual glands, submandibular glands and Parotid glands. 10% of saliva is produced by the minor glands in the oral mucosa. Parotid glands are found beneath both ears, which secrete up to 50% of the mouth volume of saliva (watery, low viscosity and amylase-rich). Submandibular glands are found at the lower jaw, which predominately secretes the rest of saliva (high viscosity and mucin-rich). Sublingual glands positioned under the tongue produce 1-2% of the mouth volume of saliva (unstimulated, high viscosity and mucin-rich). The minor glands significantly contribute to lubricating the epithelial surface, which distributes among the oral mucosa.

3.3.5.2 Saliva and ageing

Some studies found that the proportional volume of acini decreased with fibrovascular tissue and fat increased [314, 315], which led to increasing functional parenchyma being replaced by fat and connective tissue with ageing. Although fatty generation has not been observed, the reduction of functional parenchyma with ageing was found in the minor salivary gland [315 - 319]. With advanced age, the reduction of the synthesis of proteins leads to the loss of functional parenchyma have been found [320]. The study reported that older rats' have 60% of the regular rate of protein synthesis in the parotid acinar cells. Although there is no clear result in humans age-related reduction of the rate of protein synthesis, the concentration of organic substance decreased with ageing can relate to a similar phenomenon [321].

The typical salivary flow rate at rest or in an unstimulated state is between 0.3 mL/min and 0.5 mL/min, and the limitation of normal rate is 0.1 mL/min [308, 322,323]. The salivary flow rate increases with different stimuli (e.g. chewing action and citric acid), which leads to the range of accepted stimulated flow rate in the saliva is from 0.2 mL/min to 7 mL/min[308, 322]. Salivary flow rate as an essential factor related to salivary glands function with ageing has been studied. Osterberg *et al*. (1992) [324] reported that 25% of institutionalised elderly subjects self-reported suffering from oral dryness. Some literature showed that unstimulated and stimulated salivary flow rates do not significantly correlate to increased age [325 - 329]. A study collected saliva flow from 50 participants between 29 and 72 years and repeated assessment 10 years later. The twice evaluations showed that no change of saliva flow with ageing [330]. However, other studies reported that the salivary flow rate decreased with ageing [301, 331]. Additionally, age reduces the salivary flow rate was observed from the healthy and unmedicated subjects [219, 326, 332]. Smith *et al*. (2013) [333] hypothesised that the reduction of salivary flow rate with ageing attribute to the age-related alteration of motor and sensory [301, 331, 334]. The different measurements of collecting the saliva and varied stimulus used may cause the converse results of the relationship between ageing and salivary flow. A study that used 10% citric acid as an intense stimulation observed the reduction of sublingual/submandibular salivary flow rate with ageing [335].

3.3.5.3 Disease elderly subjects

Osterberg *et al*. (1992) [324] reported that 25% of institutionalised elderly subjects self-reported suffering from oral dryness. Xerostomia, described as dry mouth, is a common side-effect of medication including antipsychotics, antihypertensives and antidepressants that are more frequently applied in elderly treatments [336]. A greater number of regular medications was associated with decreased stimulated/unstimulated salivary flow rates was found in elderly patients [337]. The radiotherapy of head or neck and autoimmune diseases (e.g. Sjogren's syndrome) cause severe xerostomia [1]. The report of conditions and diseases associated with ageing found that the saliva rate and components of elderly peoples' saliva substantially changed [338]. The degeneration of chewing function with salivary flow rate may cause dietary changes due to tougher foods becoming more difficult to chew [219, 228, 238, 338, 339]. The decreased chemical senses with ageing caused the reduction of sensory acuity, which led to more easily loss of the senses of taste than smell [340]. Such losses unavoidably result in less satisfaction derived from eating [341], change the perception and preference of sensor and eventually a detrimental effect on food intake and appetite [340].

3.3.6 Swallowing related to ageing

In the deglutition literature, the age-related swallowing changes have been termed senescent swallowing, presbyphagia and sarcopenic dysphagia. The upward dysphagia-related diagnosis, medications, and comorbidities lead to the increased elderly prevalence of dysphagia [342]. Swallowing involves more than 25 muscle contractions in a series of closely coordinated events, which transport a bolus from the oropharynx to the oesophagus [1, 343, 344]. Mioche *et al*. (2004) [1] claim that elderly adults may not have sufficient capability to compensate for the alterations of sensory functions and muscular tissue in swallowing. The age-related changes in tongue pressure during swallowing may be attributed to age-related oropharynx's morphological changes and muscle impairment [345]. Videofluoroscopic has been applied in age-related swallowing studies. The results show that older individuals took longer for swallowing reaction, pharyngeal delay, and modulation of upper oesophagal sphincter opening. While the shorter transport time was observed that bolus transport from pharynx to epiglottic deflection [346]. There is a significant and positive correlation between oesophageal transit time for a liquid bolus (20 mL) and ageing [347]. Another videofluoroscopic swallowing study suggests that cricopharyngeal bars and cervical vertebral osteophytes should be considered essential symptoms for assessing dysphagia. [348]. They found that increased these symptoms were significantly related to advanced age. Siebens *et al*. (1986) [349] estimated that 30%-40% of the institutionalised elderly suffer from swallowing disorders. Moreover, dysphagia was a higher frequency of incidence in the older individuals than in young individuals had been observed [350, 351]. Although the mild changes in swallowing function cannot cause elderly adults' deglutition risks, the deterioration or underlying pathology in general health relate to swallowing disorder with ageing [352].

3.4 Mastication-related deficient nutrition relate to ageing

Malnutrition is underestimated in the elderly [353], many studies reported that 30% to 50% of the elderly population in the institutions is inadequate nutrition [354 – 357]. In New Zealand, a High prevalence of malnutrition (93 %) and frailty (76 %) in the elderly who live in residential care was observed [358]. A similar result was found that the older adults who are living in residential care (47 %) had a higher prevalence of malnourishment than those admitted to the hospital (23 %) [359]. Guigoz (2006) [360] reported that the elderly who live independently have a 24% mean prevalence of malnutrition and 45% malnutrition risk. The malnutrition in older individuals consequently leads to increased infection risk, lengthened hospital stays, mental issues and higher mortality risk [361 - 364]. Although the factors causing malnutrition are complex, ageing is a significant factor [356]. Mental health problems, physical deterioration, particular medication (e.g. opioid and treatments (e.g. radiotherapy and chemotherapy)) [356, 361] leads to loss of appetite which would eventually cause the decreased dietary intake [365]. Dietary changes and digestive disease are two crucial factors that could cause deficient nutrition with ageing [217]. Figure 3.5 summarises the main factors causing malnutrition related to the age-related reduction of masticatory function.

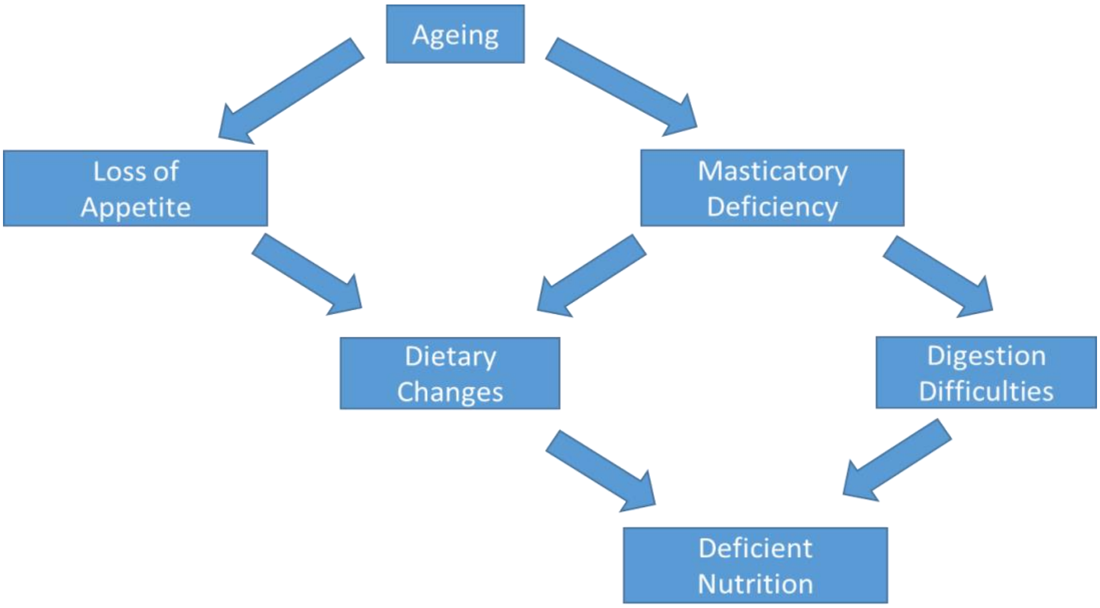


Figure 3.5 the flow chart summarised the main ageing changes (loss of appetite and masticatory deficiency) cause malnutrition.

Department of Health (1994) defines adequate oral health as

> "*A standard of health of the oral and related tissues which enables an individual to eat, speak and socialise without active disease, discomfort or embarrassment and which contributes to general well-being*."

Due to the accumulation of diseases with time, poor oral health is more prevalent in the elderly [365]. Oral health assessment associated with the evaluation of nutrition (e.g. mini nutritional assessment) is a reliable and easy measurement in estimating the high risk of malnutrition in the elderly population [360, 366]. Van Lancker *et al*. (2012) [365] found tentative results from the elderly subjects in a long-term care facility, which demonstrated the independent relationship between oral health status and age-related malnutrition.

Many studies support that masticatory deficiency is significantly related to malnutrition in older patients [28, 29]. The strong relationship results show mastication-related dietary changes with ageing [30]. In healthy elderly individuals, chewing behaviour changes to compensate for the reduction of masticatory function, leading to dietary changes. Due to the significantly reduced jaw muscle activity with ageing, certain foods (e.g. dry bread and meat) become difficult to chew [31, 32]. A slow loss of adaption of bite force to food texture was also found in older subjects compared to young adults [33]. Karlsson & Carlsson (1990) [367] observed that vertical mandibular displacement and velocity reduction in older age might result from muscular impairment. The chewing sequence lengthens as an alteration of chewing behaviour to compensate for jaw muscle activity's minor but consistent weakness. With the muscular impairment processed, a study showed that the lengthening of chewing meat boli is unable to compensate for the commuted in the elderly before swallowing [32]. A study of texture perception assessment in elderly groups hypothesised that denture wearers had higher acceptability of juiciness than tenderness due to severe masticatory deficiency. The number of teeth loss associated with reduction of chewing efficiency contributed to inappropriate intake choices in the elderly groups [368, 369]. Hence, the masticatory deficiency that causes alteration of chewing behaviour may consequently lead to diet-related malnutrition in the elderly population.

Peyron *et al*. (2017) [30] proposed that the impact of advanced ageing on mastication-dependent digestion might cause a reduction of nutrient bioavailability. They reported that swallowing a poorly prepared food bolus causes digestive consequences, such as nutrient deficiencies and digestive diseases. A relationship between masticatory function and digestion was found in some studies, which showed that poor chewing efficiency might lead to various gastrointestinal disorders [370, 371]. In addition, Chewing efficiency has a significant impact on gastric emptying has been observed [372]. The definition of chewing efficiency is the capability of preparing a swallowable bolus during mastication sequences. The number of teeth associated with other factors strongly impact chewing efficiency [373, 374]. Compared with the young participants with natural dentition, the older adults wearing dentures had approximately one-sixth of the youngers' chewing efficiency with a cost of twice the chewing duration of younger subjects [374]. Mioche *et al*. (2004) [1] observed jaw muscle activity with tough meat by EMG. They showed that the alteration of chewing behaviour including increased chewing duration and total EMG activity was insufficiently compensated for the reduction of EMG activity per chewing cycle. Consequently, the decreased chewing efficiency in the elderly subjects led to a less prepared food bolus than in younger adults. Chewed food has been proven more easily cleared from the oesophagus [375], whilst the stomach emptying is modulated by the consistency of an intake meal [376]. In addition, some studies showed that insufficiently chewed food related to the reduction of oesophagus clearing and stomach emptying [22, 33, 237, 377].

In conclusion, ageing itself maybe not be an isolated factor for reducing masticatory function and eventually leading to malnutrition. However, ageing associated with oral health, jaw muscle activity, saliva and swallowing can significantly influence masticatory function and mastication-related malnutrition. Based on the various measurements of masticatory function, the relationship between ageing and masticatory function is still poorly understood. This research aims to link objective masticatory function by maximum comfortable bite force with subjective masticatory function by questionnaire, so that a new method can be established to measure maximum comfortable bite force associated with varied oral conditions across the lifespan. The results can shed insight into how ageing influences masticatory function with differences in maximum comfortable bite force. The secondary aim of this research is to explore the relationship between masticatory function and ageing by linking maximum comfortable bite force to hardness perception. The results will be useful for developing the texture of food products, especially for elderly consumers who may have a relatively weaker maximum comfortable bite force. Moreover, the particular functional food products focused on the elderly with masticatory dysfunction can rationally design food hardness based on the set model foods developed in this research. The optimised products can provide the elderly with a comfortable and enjoyable chewing experience.

Chapter 4 Materials and Methods

This chapter describes the process taken to establish a masticatory method for evaluating comfortable maximum bite force by texture perception. This method develops a set of model food to apply in a series of sensory tests to investigate the trend bite force across the lifespan in a large population in Auckland city. The chapter details the development of model foods, methodology used and the design of additional, supplementary self-report questionnaires describes:

Phase 1. Model foods development and preparation

Phase 2. The masticatory method establishment and development: mechanical properties tests, sensory tests and oral tests.

Phase 3. Development of supplementary subjective masticatory measurements: self-assessed dental condition, masticatory ability and performance questionnaires.

4.1 Development of model foods with different levels of hardness

Use of model foods as a method for investigating objective masticatory function has been previously reported in research (refer to Chapter 2). To explore the possibility of using model foods as a new masticatory function method, this study links food physics (mechanical properties) to sensory psychology (sensory evaluation) to assess an individual's maximum bite force using a set of gel-based model foods of increasing hardness. A number of factors need to be considered when developing model foods: artificial vs. natural foods, particle size and shape, flavor, visual properties and hardness range.

Natural food, including carrots, nuts and biscuits because of particular texture perception (e.g. crispness and hardness), is widely used in masticatory efficiency. Due to the significant variation in natural foods' physical properties batch to batch, artificial model foods including Optosil®, alginate, and other hydrocolloid have been developed to diminish the natural interference (e.g. season, ripeness and sub-species. The artificial model foods are commonly applied in the assessment of bolus formation. For example, the mixing degree of two-colour chewing gum can be measured by the visual [183] and optical [184, 185] methods.

Artificial gels have several advantages. The texture perception of artificial gel foods can be easily modified to suit experimental requirements (e.g. hardness and shape). Hardness has been known as one attribute of texture perception that can link to the first dominating sensation when human consume foods [183]. Many studies proved that the hardness of the foods had been an essential factor related to masticatory function in the first bite or first five chewing cycles [2-6]. In addition, a thicker food with similar mechanical property significantly related to a higher bite force has been found [378]. Because the mechanical properties of artificial gels respond to the individual's masticatory function including bite force and masticatory efficiency by subjective and objective measurements of masticatory function. It is necessary to explore different physical properties of model foods to create a set of model foods with a wide range of *texture* perception by changing the mechanical properties. We expect that the set of model foods' hardness levels is from medium to hard texture can be discriminated through selecting the dimension, food ingredients and concentration. Considering that individual differences in physiology (e.g. volume and size of mouth cavity) will impact measured bite force, some model food makes biting difficult and uncomfortable due to the carefully selected dimension of the sample, more plastic deformation behaviour, and harder texture. Figure 4.1 showed the steps of designing a set of model foods with different goals.

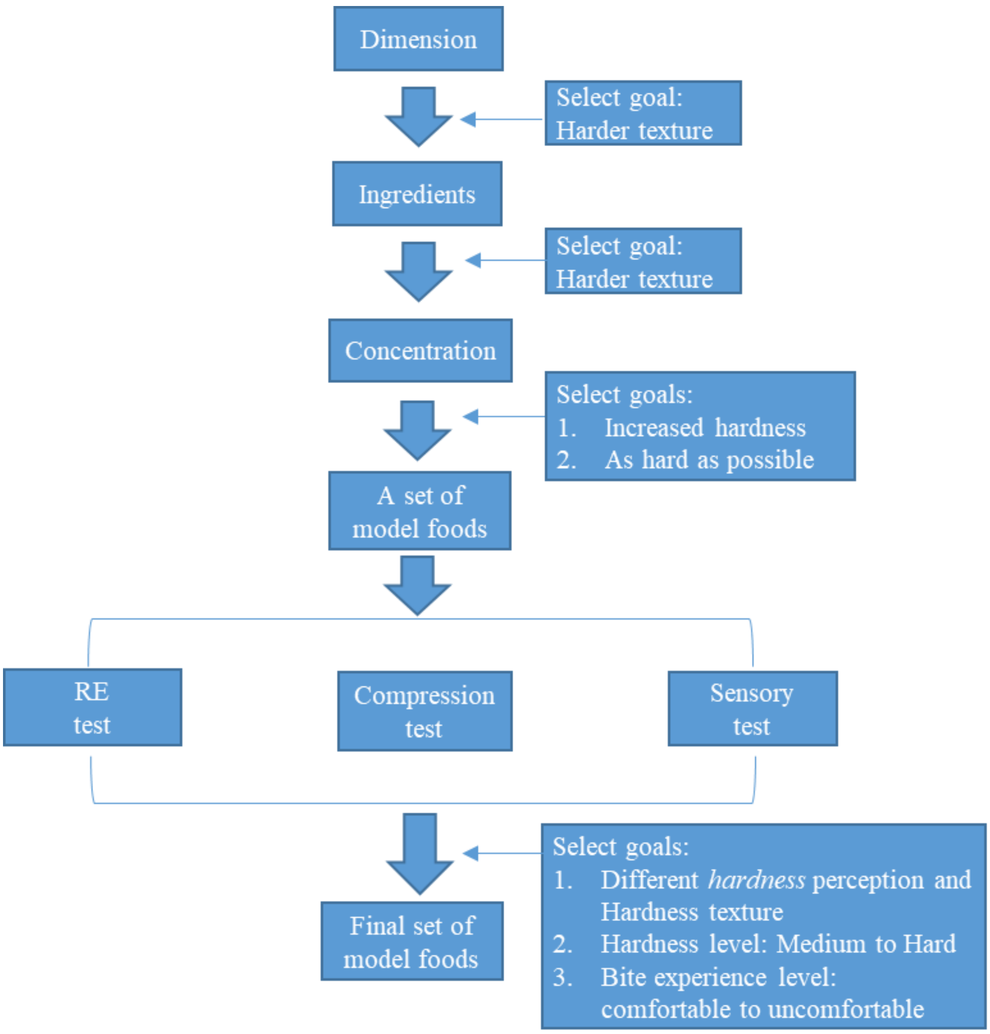


Figure 4.1 details steps of designing a set of model foods can be applied in a large panel.

The preliminary design of gel-based model foods was trialled in different shapes and sizes as shown in Figure 4.2. The muffin and cube shapes were selected because they simulate the regular and common shape of real processed foods. Figure 4.3 demonstrates the main set of gel-based model foods with increasing hardness levels, named M1 (softest) to M6 (hardest). In addition, two different intermediate sub-levels of hardness were created between every two of the main samples. For example, the subset of model foods between M1 and M2 were named M13 (softer) and M16 (harder).

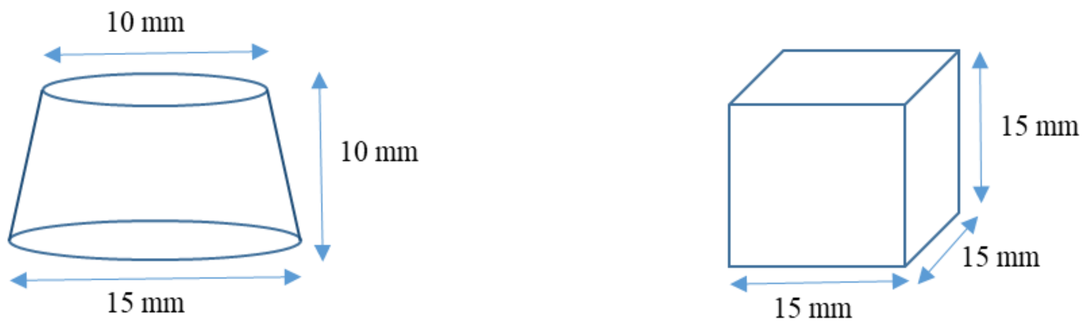


Figure 4.2 The shape and size of gel-based model foods created for this study.

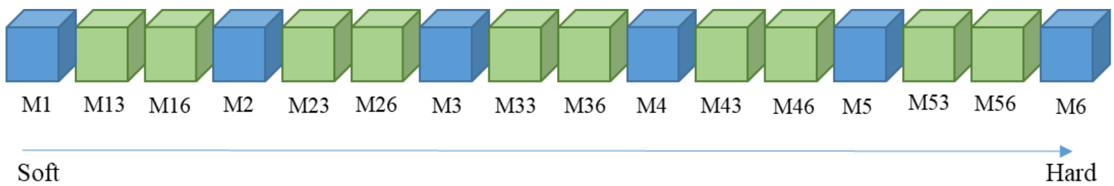


Figure 4.3 illustrates the different hardness of gel-based model foods created for this study.

Model foods were designed to link the mechanical properties evaluated by instrument tests, including the compression test and the recoverable energy test, to the perceived hardness assessed by sensory tests. The set of model foods must meet two critical requirements. Firstly, the range of hardness texture perception span from confidently/comfortably bite to challengeable/uncomfortably bite. It is necessary to build up several model foods that have a harder mechanical property. Secondly, the series of food models should be an appropriate substitute for real foods in terms of texture.

4.2 Model food preparation

The study aims to establish a new method that can quantify bite force by linking the texture perception of “hardness” to the mechanical properties of the model food materials in a large panel of participants. The foods preparation was to create a set of samples with different hardness texture by changing ingredients, shape, size and concentration of gels.

4.2.1 Ingredients and Equipment

The following ingredients were used: Gelatin powder (250 Bloom, 40 mesh, Davis Food Ingredients Ltd, Auckland, New Zealand); Agar-agar powder (PandaMART Telephone Ltd, Thailand); Distilled water (Pure Dew Ultra-distilled water Ltd, Auckland, New Zealand). Gelatin powder was purchased directly from Davis Food Ingredients Company (Auckland, New Zealand). Other ingredients were purchased from local markets.

The model gels have the original flavour/taste, without any additives to modify these qualities. No significant difference in flavour/taste among set of model gels has been reported by the participants.

Steel or Silicone moulds (food grade) were used to establish specific and consistent size and shape for the gel-based model foods (Figure 4.4).

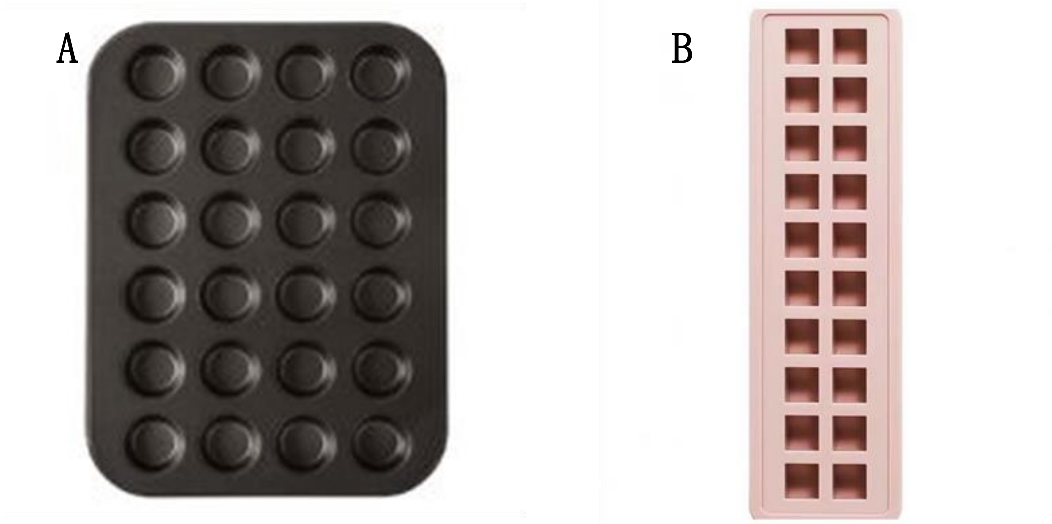


Figure 4.4 A. Muffin shape steel mould (size: 10 mm(D) ×15 mm (D)×10 mm (H)); B. Cube shape silicon mould (size: 15×15×15 mm).

4.2.2 Protocol for establishing a series of gel-model foods

4.2.2.1 Selection of model food shape

The gelatin powder (20%, w/w) was mixed in distilled water, stirred and stand still for 30 min at room temperature to ensure the samples absorbed water adequately. The mixture was heated in an 85 ℃ water bath to dissolved. After heating in 2-3 hours, the solution was poured into a cube (15×15×15 mm) or a muffin (10 mm (D) × 15 mm (D)×10 mm (H)) shaped moulds, and cooled down to the room temperature in 30 min as a pre-cooling step before transferring to the fridge. The gel-based model samples were appropriately sealed and stored in a 4 ℃ fridge overnight for the mechanical properties' tests.

4.2.2.2 Selection of gel-model foods ingredients

The agar agar powder (8%, w/w) and gelatin powder (40%, w/w) were mixed in distilled water respectively, stirred and stand still for 30 min at room temperature to ensure the samples absorbed water adequately. The agar-mixture and gelatin-mixture were heated in a 95 ℃ and 85 ℃ water bath respectively to dissolve and degas the solution. After heating for 2-3 hours, the solution was poured into cube (15×15×15 mm) shaped moulds, and cooled down to the room temperature in 30 min as a pre-cooling step before transferring to the fridge. The gel-model samples were appropriately sealed and stored in a 4 °C fridge overnight for the compression test.

4.2.2.3 Selection of gel concentration in model foods

The gelatin powder (45%, 50%, 60%, 65%, 70%, w/w) were mixed in distilled water, respectively, stirred and stand still for 30 min at room temperature to ensure the samples absorbed water adequately. The mixtures were heated in a 90 °C water bath to dissolved and degas. After heating in 4-5 hours, the solution was poured into the cube (15×15×15 mm) shaped moulds, and cooled down to the room temperature in 30 min as a pre-cooling step before transferring to the fridge. The gel-model samples were appropriated sealed and stored in a 4 °C fridge overnight for the mechanical properties' tests, including compression test, puncture test and recoverable energy test. The formulation of gel-model foods for just noticeable test (4.3.3.2) and Rank&Rate tests (4.3.3.1) demonstrated in Table 4.1. The steps for making gel are described as above.

Table 4.1 Formulation of gelatin gel-based model foods.

Sample name	Gelatin powder (g)	Water (g)	Concentration (w/w)
M1	90.0	110.0	45.0%
M13	93.4	106.6	46.7%
M16	96.8	103.2	48.4%
M2	100.0	100.0	50.0%
M23	103.6	96.4	51.8%
M26	106.4	93.6	53.2%
M3	110.0	90.0	55.0%
M33	113.4	86.6	56.7%
M36	116.8	83.2	58.4%
M4	120.0	80.0	60.0%
M43	123.4	76.6	61.7%
M46	124.4	75.6	62.2%
M5	130.0	70.0	65.0%

M53	136.8	63.2	68.4%
M56	138.0	62.0	69.0%
M6	140.0	60.0	70.0%

4.3 Establishment of a masticatory function measurement for evaluating comfortable maximum bite force with a series of gel-model food

A series of edible gel-model foods, consisting of small, bite-sized foods produced exclusively from food-grade ingredients, were produced as 4.2.2.3. The model foods linked the mechanical properties evaluated by instrument tests, including the compression test and the recoverable energy test, to the perceived hardness assessed by sensory tests.

4.3.1 The core of oral processing for establishing a new method to test bite force

The core principle of "food oral processing" is the intersection of three disciplines: food physics, sensory psychology and oral physiology [379]. The common methodologies of food physics are rheology, tribology and microstructure imaging, investigating the fracturing and deformation of food to link to sensory perception. Sensory psychology reveals psychophysical sensation and perception by the various method of sensory analysis and brain activities. The data collected and analysed from jaw muscles activity, chewing efficiency and saliva secretion can provide information about oral physiology during food oral processing. This study's edible model foods, with the use of an instrumental masticatory function test, aim to bridge food physics, sensory psychology, and oral physiology.

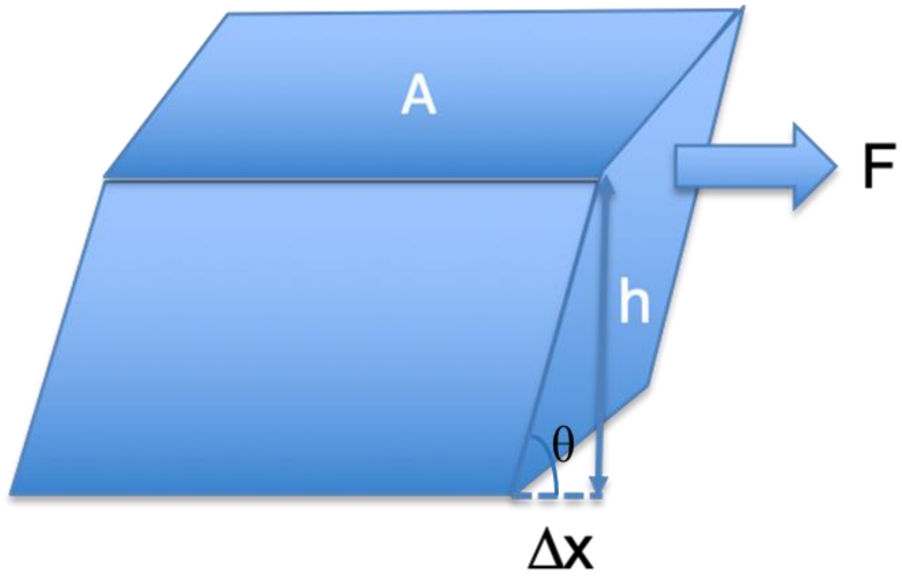
Maximum bite force, an indicator of oral physiology, can be evaluated by multiple instrumental measurements. However, the definition of "comfortable maximum bite force" is defined as the objective meaning of maximum bite force from oral physiology and the subjective meaning of comfort from sensory sensation and perception. This study aims to use a series of gel-model foods as a stimulus to assess the comfortable maximum bite force, which combines sensory perception and mechanical properties. The texture of model food can be directly investigated by objective mechanical properties measurements. Sensory perception can be assessed by subjective analysis, such as Time Intensity [380] and Temporal Dominance of Sensation analysis [381].

4.3.2 Food physics- Mechanical properties of model foods

4.3.2.1 Deformation

Rheology has two categories of study: Deformation and flow [269, 382]. Deformation focuses on the principle of solid matter relating to stress, while flows concern fluid-like behaviour. Two fundamental rheology theories analyse elastic deformation of solids as springs (by Robert Hooke) and the viscous flow of ideal, Newton liquids (Isaac Newton) [383].

The deformation refers to the size or shape of the original simple solid be changed, which is express by the relationship between stress and strain. Figure 4.5 shown that shear stress applies to the surfaces of the elastic solid matter. Shear stress (σ) is the applied force per contact area, which evaluates the force holding the material's inter-atomic bonds together (Equation 4.1a). Shear strain (γ) is defined as the displacement of the shear plane (Δx) divided by the thickness under deformed force (h), which evaluate the unit alteration in shape during deformation of materials (Equation 4.1b). The angle (θ) moved is the parameter reflecting the change of applied stress.



$$\sigma = \frac{F}{A}$$ Equation 4.1a

$$\gamma = \frac{\Delta x}{h} = \tan\theta$$ Equation 4.1b

Figure 4.5 The deformation process for a solid material subjected to a shear force.

The law follows the flow of a simple Newtonian fluid, in which shear stress (σ) is characterised by the relationship between the shear rate ($\dot{\gamma}$)and fluid viscosity(η) (Equation 4.2). Note that shear rate is the change of shear strain with time.

$$\sigma = \eta\dot{\gamma}$$ Equation 4.2

4.3.2.2 Material behavior and Mechanical properties

The mechanical properties of food material have been measured by various techniques, including compression test, puncture test, tensile test and 3-point bending test. All of these tests measure the correlation between stress (force) and strain (displacement). The curve of Stress vs Strain in Figure 4.6 illustrates five stages of material deformation.

Point A represents the unloaded ($\sigma = 0$) and undeformed condition ($\gamma = 0$) of a material. Starting from Point A, the material is loaded with stress, and strain increases proportionally until Point B, called the Yield Strength (σ_y), is reached. This initial deformation is 'Elastic (Stage 1)', and the area between Point A and Point B is the 'Elastic Region'. If the material is unloaded before Point B is reached, the deformation is reversible. Because the curve of stress and strain is linear between these two points, the slope of stress-strain is constant and is called the Young's or Elastic Modulus (i.e. measure of stiffness). The region beyond Point B is called the 'Plastic Region'. Stage 2 is from Point B to Point C where the material continues deforming under increasing stress. The line processing from Point C to Point D demonstrates what occurs when the material is unloaded after Point C (Stage 3). Although the slope (Young's Modulus) of the line between Point C and D is the same as the slope between Point A and B, the key difference is that the strain AD is irreversible, which means the material's deformation is permanent from Stage 2 onward. Stage 4 follows the line from Point D to Point C when the material is re-loaded. The yield strength increases due to the permanent strain add in Stage 3 by a mechanism known as *Strain Hardening*. Stage 5 is the process of non-uniform deformation as applied force continues to increase, which causes stress to decreasing after Point C due to the material's change in cross-sectional area. The material will fracture into two separate pieces when Point F is reached.

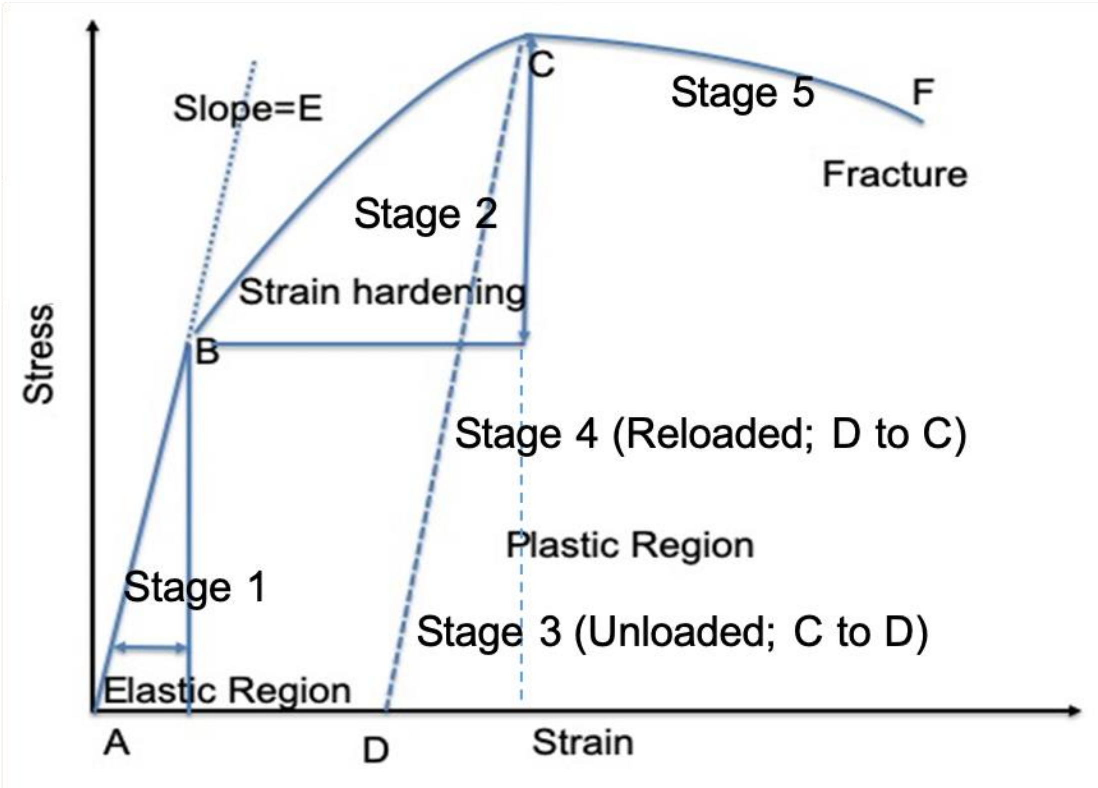


Figure 4.6 Typical stress vs strain diagram including five stages of deformation.

The mechanical properties are commonly measured in instrumental methods to describe the texture of the food material, such as hardness, toughness, rubberiness and brittleness [384]. Hardness is defined as the ability of material in resisting deformation, either via indentation, wear and/or abrasion. The Rockwell hardness scale and Brinell hardness scale can quantify this mechanical property. Toughness is defined as the ability of a material to absorb energy, which can be quantified by measuring the area under the Stress-Stain Curve. Rubberiness is defined as the ability of a material to deform before failure, which can be quantified by the final value of strain at the fracture point on the Stress-Stain Curve. In contrast to ductility, brittleness is defined as the inability of the material to deform before failure.

A study investigated the effect of strength (fracture stress) and deformability (fracture strain) of gel-based model foods (agar gels and mixture gels) on mastication processing while minimized the different other mechanical properties [385]. Figure 4.7 demonstrated the two-dimensional texture map of the mechanical properties when stress and strain at fracture. With increased fracture stress, no change in fracture strain was observed from agar gels with higher concentrations [386]. With the increasing value of the fracture stress, the hardness level of food increases. The more rubberiness relates to an increased fracture strain. The hardness (fracture stress) of age gels increased, which produced the constant low brittleness (low fracture strain). Compared with the mechanical properties of agar gels, the mixture gels (locust bean gum and κ-carrageenan) presented a relatively high rubberiness (high fracture strain) with a constant hardness (fracture stress). This increased rubberiness with a slight change of hardness has been related to the increased concentration of locust bean gum [387]. Some foods have one outstanding texture perception arising from their strain response to applied stress. For example, chips are described as brittle food because of the weaker fracture stress and strain. However, the food's mechanical properties must be paired with the psychophysical interpretation of the tactile and visual perceptions that occur when consuming foods to understand what causes differences in the texture completely.

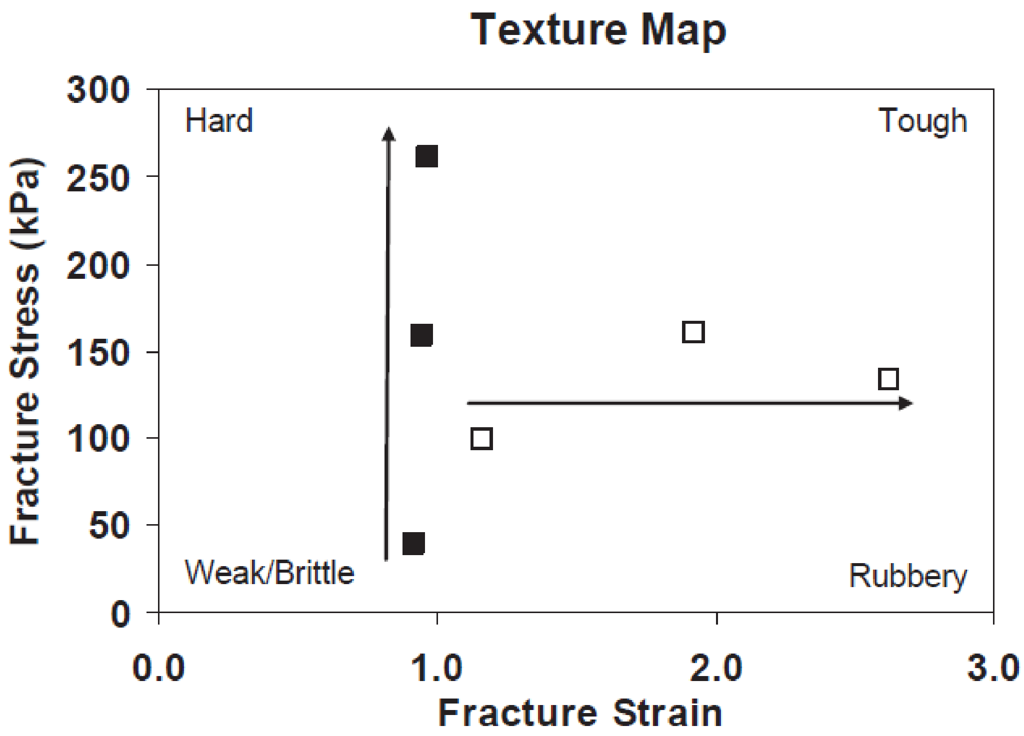


Figure 4.7 Texture map of the gel-based model foods: ■: Agar gels; □: Mixture gels (locust bean gum and κ-carrageenan) [385].

4.3.2.3 Hardness via TPA

Hardness is one of the most well studied sensory factors relating to oral processing. Increased chewing cycles, jaw muscle activity and chewing time have been strongly related to hardening texture of foods, including model foods [156, 388] and processed food [389]. Oral sensation is a dynamic process that can shift from time to time during mastication. Hardness has been known as one attribute of texture perception that can link to the first dominating sensation when human consume food [379]. Depending on this theory, Figure 4.8 [384] summarizes various studies investigating different dominating sensation during oral processing as a function of chewing time. Figure 4.8 shows that the hardness of the model foods is an essential factor related to masticatory function, perceived in the first bite or first one to five chewing cycles [390 - 394].

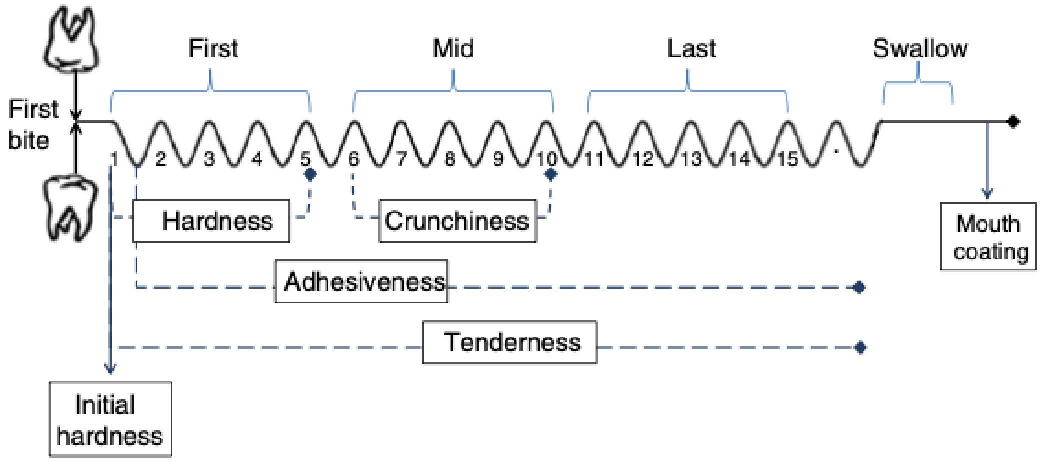


Figure 4.8 The dominating texture perception of semi-solid model food (whey protein/k-carrageenan mixed gels) during mastication [384].

Texture analysis is an instrumental texture test applied to determine the physical characteristics and behaviours of semi-solids and solids with being compressed, which aim to simulate the sensory perception during oral processing.

Texture profile analysis (TPA) has been widely used in determining the mechanical properties of food with reliable, quantifiable and repeatable data. During a TPA test, the sample is compressed twice by the analyser to mimic a similar chewing action. Duo to the double compression test, TPA is commonly called as "two bite test". The advantage of TPA is one experiment can quantify multiple texture properties, including hardness, cohesiveness, and springiness. Hardness is defined as the maximum force of the first compression in a given deformation parameter. The value of hardness is collected from the highest peak (Gram, g/Newton, N) during the first TPA cycle (Figure 4.9).

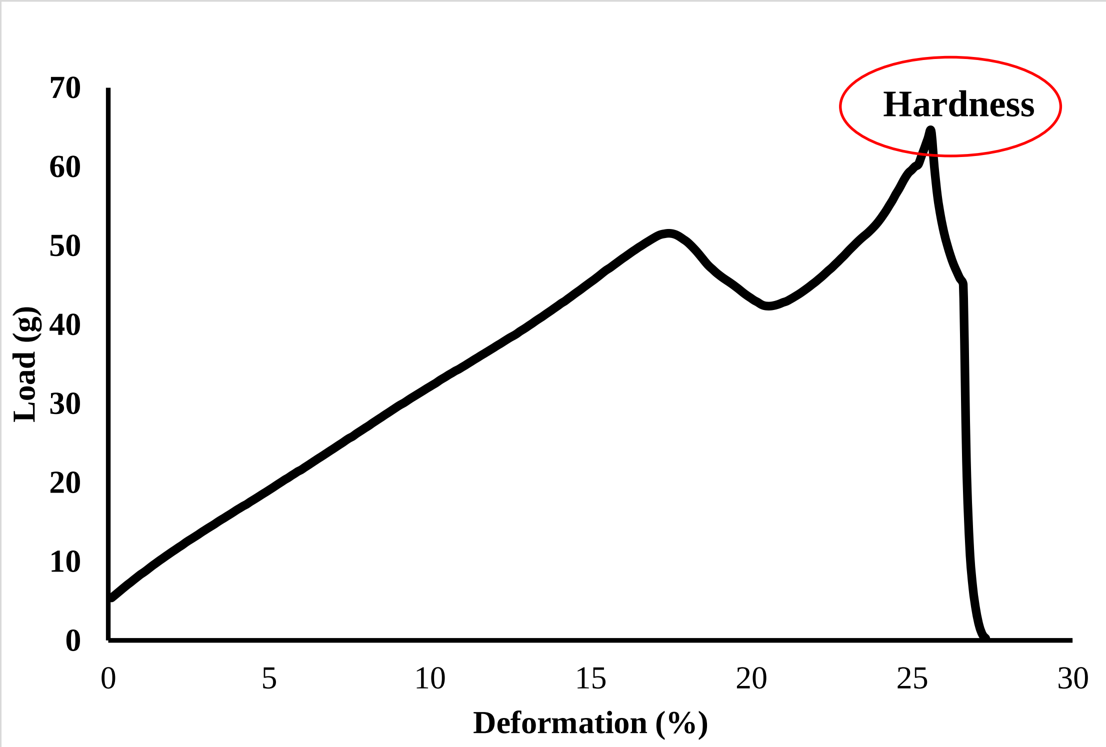


Figure 4.9 An example of the compression test, showing hardness is measured by the peak load measured during compression.

This project made some modifications of the TPA measurement compared to the standard test designed by Bourne (1987) [395]. In standard TPA measurement, the size of the probe's test surface must cover the complete surface area of the food sample. Since the hardness of the designed gel-model foods is beyond the capability of TPA compression load at high deformation, three different shaped probes of smaller surface area were selected to indent samples in this study [394].

Protocol of TPA test

Hardness instrumental tests were conducted at room temperature (~25℃) using a CT3 Brookfield Texture Analyzer (Brookfield Engineering Laboratory, Inc. Middleboro, MA, USA). The working parameters of the signal compression test were: pretest speed: 2 mm/s; test speed: 0.03 mm/s; load: 0 to 10000 g; trigger load: 0.07 N. Gel-model food were positioned on a fixed-base plate, and probes moved a distance of 90% deformation of the initial height of samples. Each of the samples was tested with five replicates and three different probes: needle, cone and cylinder. The needle probe used in this test was stainless steel, 1.0 mm diameter and 43 mm long probe (reference TA9). The cone probe used in the test was a clear acrylic, 24 mm diameter, 46 mm long and 30° probe (reference TA17). Moreover, the cylinder cone probe used in the test was a clear acrylic, 25.4 mm diameter and 35 mm long probe (reference TA11) (Figure 4.10).

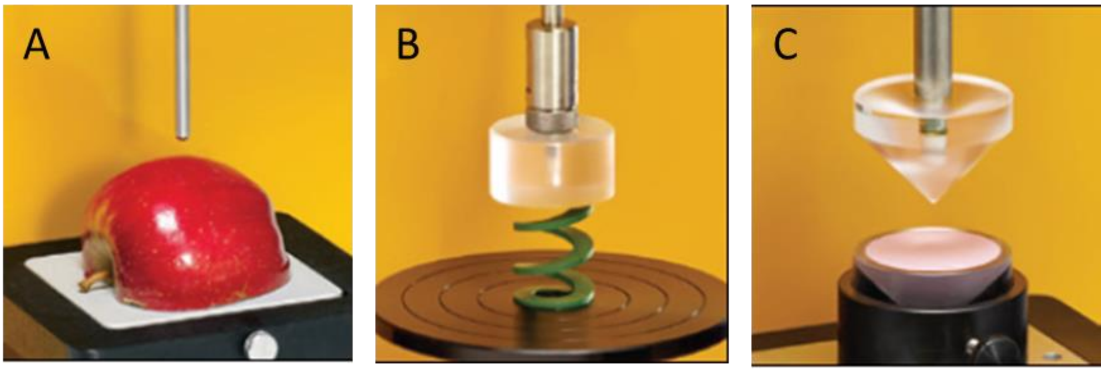


Figure 4.10 Three different types of probe in TPA. A. Needle probe (TA9); B. Cylinder probe (TA11); C. Cone Probe (TA17).

4.3.2.4 Recoverable energy test via Instron

Crumbliness is another critical mechanical property response to the texture perception of meats and gels during first to third chewing cycles [392, 396, 397]. To explore crumbliness of designed gel-based model foods, the recoverable energy test has been used to describe the texture. We expect to find the correlation between different texture properties with increased concentration of model foods and texture perception, which through linking RE test to compression tests and sensory tests.

The recoverable energy (RE) test has been used to describe the texture of semi-solid and solid foods due to the correlation between RE and sensory profiling [384, 389, 390]. The foods can be described in terms of as "spreadability", which relates to the crumbling effort needing to break the food into pieces during mastication [389]. The RE of food mechanical property also highly relates to "crumbliness" perception by sensory test [390]. The results showed that the higher RE (higher elastic component) related to a higher crumbliness perception (*crumly* score) from sensory test. In this RE test, the six main gel-based model foods have been assessed by compression test with a series of load-unload cycles of increasing compressive strain (10%, 20%, 30%, 40%, 50% of the sample height). Recoverable energy is used to characterize the energy during loading and unloading in samples before they fracture, which significantly influences samples' breakdown properties. The following balance (Equation 4.3) was described the total energy (U_s) provided to material be stored elastically (U_e), dissipated due to plastic deformation of the sample (U_p), dissipated due to other processes (U_d) or used to cause fracture (U_f) [398]:

$$U_s = U_e + U_p + U_d + U_f \qquad \text{Equation 4.3}$$

In this energy balance, the recoverable energy is defined as the elastically stored energy during the deformation. The fracture energy is used to create the new surface of the samples. Since there are no complete elastic food materials, plastic deformation occurs in the vicinity of the crack during fracture. The fracture energy should have created a new surface, but a part of it is used to generate plastic deformation. It means if the energy used in plastic deformation is significant, it can cause difficulty in fracturing the samples, such as in caramels [398].

Protocol of Recoverable energy test via Instron

Cube gel-model foods (15×15×15 mm) were compressed between a square flat plate (10 cm edge length) fitted to the Instron 5500 testing instrument (Instron Engineering Corp., Canton, MA, USA) equipped with a 1 kN load cell. The samples were compressed at a constant speed of 10 mm/min and removed at a rate of 10 mm/min with the consecutive loading-unloading cycles of increasing strain to 10%, 20%, 30%, 40% and 50% of their initial height. The percentage of recoverable energy was calculated as the ratio of recoverable energy to total work done during loading. These two parameters were measured from the area under the stress-strain curve during the compression and decompression of the samples, respectively. The maximum value of deformation was set a5 50% to avoid fracture, due to some samples fractured after 50% deformation of the initial height.

4.3.3 Sensory psychology- Sensory evaluation of model foods

Sensory evaluation of food comprises a variety of measurements that can assess the relationship between human perception and food physical properties. Considering that mastication is a highly dynamic process, the oral sensation of texture perception is commonly be measured by two sensory analysis methods: Temporal Dominance of Sensations (TDS) [381] and Time Intensity (TI) [380]. These dynamic sensory analyses are suited to investigate changes in the texture perceptions during all periods of food breakdown as a function of chewing time. However, this project is not interested in measuring dynamic texture. We focus on how texture perception of first bite links to mechanical properties of gel-model foods and maximum comfortable bite force. The first bite or only one bite can be defined as only one chewing cycle of oral processing, leading to only the initial sensory perception of gel-model foods. Our project should design a sensory evaluation differing from the dynamic measurements (TDS and TI).

Three fundamental types of sensory tests are classified based on different goals and participants requirements [399] (Table 4.2). The descriptive and discrimination tests are selected for the sensory part of this study. The descriptive test quantifies the intensity of the perceived texture for relation to mechanical properties. The discrimination test measures the minimum detectable difference in a series of gel-based samples, which was used to find the threshold of texture perception and optimise the mechanical properties of samples' preparation.

Table 4.2 Summary of three fundamental types of sensory tests: descriptive, discrimination and affective tests.

Test	Descriptive	Discrimination	Affective
Goal	The intensity of particular sensory perceptions	Difference of particular perception between two samples exists or not	The degree of liking or disliking of a sample
Type	Analytic	Analytic	Hedonic
Panelist	Sensory motivation and acuity, trained	Sensory acuity, sometime trained	Untrained

4.3.3.1 Descriptive test

Descriptive Analysis technique is one of the most sophisticated tools used to obtain detailed sensory descriptions of food products, identify underlying variables, and determine the importance of sensory attributes in product acceptance [399]. A descriptive analysis technique measuring the intensities of food attributes, is widely used in sensory tests response to mechanical properties in food texture [400]. Based on the traditional behaviour research, experimental designs and statistical analysis, the procedures of descriptive analysis establish a statistical test with independent judgement by participants. Figure 4.11 is an example of descriptive analysis using a line scale (10 cm) to capture attribute intensity. A numerical score can be determined from the distance between the left-end and the panellist's mark.

Figure 4.11 An example of descriptive analysis using a line scale.

The word anchor is chosen as the term to describe the sensory characteristics of samples, and is crucial to the descriptive analysis test. Civille and Lawless (1986) [401] listed the 11 desirable requirements of chosen terms to facilitate the concepts of sensory attributes that can be desired accurate and understandable, avoiding the failure or bias of the sensory tests. The chosen term should completely present perceived differences among a set of samples not redundant with other terms. The terms should be precise and reliable to ensure panellists easily agree on the meaning and help them de-correlate the similarities. For our study, the key point of the descriptive analysis study is to quantify *hardness* perception from panellists, which can link to the intensity of hardness by instrumental texture tests. Based on the requirements as shown on Table 4.3, “Soft” (left-end) and “Hard” (right-end) was chosen as word anchor, which helps panellists to easily mark reliable and accurate hardness perception on the line-scale.

Table 4.3 Requirement for selecting terms for descriptive analysis studies in order of importance [401].

Discriminate	More important
Non-redundant	
Relate to participant acceptance/rejection	
Relate to instrumental measurement	
Singular	
Precise and reliable	
Consensus on meaning	
Unambiguous	
Reference easy to obtain	
Communicate	
Relate to reality	Less important

Protocol of Rank&Rate test

The procedures of "Rank&Rate" test is: each participant was required to bite two identical sets of model foods, each set consisting of 6 samples, and first "rank" then "rate" these samples by hardness. During the "rank" test, participants were presented with the set of model foods in random order and were asked to bite the sample once. After one bite, they expectorated the sample into a transparent container (to be used to investigate the degree of fracture). During and after biting, they were required to rank the six samples in order of increasing hardness. Then the participants were invited to "rate" the samples via the second test. They were required to bite each sample once (and expectorate as above). During and after biting, they were required to rate the samples' hardness by making a mark for each sample on a 10 cm line scale (soft/hard). The participants can refuse to bite a sample anytime they feel uncomfortable about the hardness being too great. They could also ask for additional samples if they required help with their ranking and rating. Rank&Rate test sheet are provided in Appendix A for reference.

Inclusion criteria for participation are as below:

- 12 functional tooth units
- No gelatin allergy
- No smoking
- Good general health
- A. 20-30 years (particular for Chapter 5 preliminary study: 40 young participants) or B. 20^+ years (particular for Chapter 6: 300^+ participants)

The first requirement was relaxed for the elderly with no restrictions on dental health. This project was reviewed and approved by the University of Auckland Human Ethics Committee (Reference Number: 023536).

4.3.3.2 Discrimination test

The discrimination test aims to answer the existence of a difference between two samples, and the analysis is simple to count the answers from the binomial distribution. The binomial distribution is defined as the frequencies of events that have categorical or discrete or categorical outcomes, which only especially has only two outcomes (e.g. right/wrong answers in a triangle test) [399]. Figure 4.12 shows three different discrimination test types: Triangle test, Duo-trio test and Paired comparison test. Both the triangle and duo-trio test belong to multiple-choice difference test. The triangle test requires the panellists to judge the odd sample among three samples, with one sample different and two the same samples. The requirement of the Duo-trio test is matching the correct sample to the reference one among three samples, including two test samples and one reference sample. Paired comparison test asks participants to select which sample is more intense than another sample in one particular attribute.

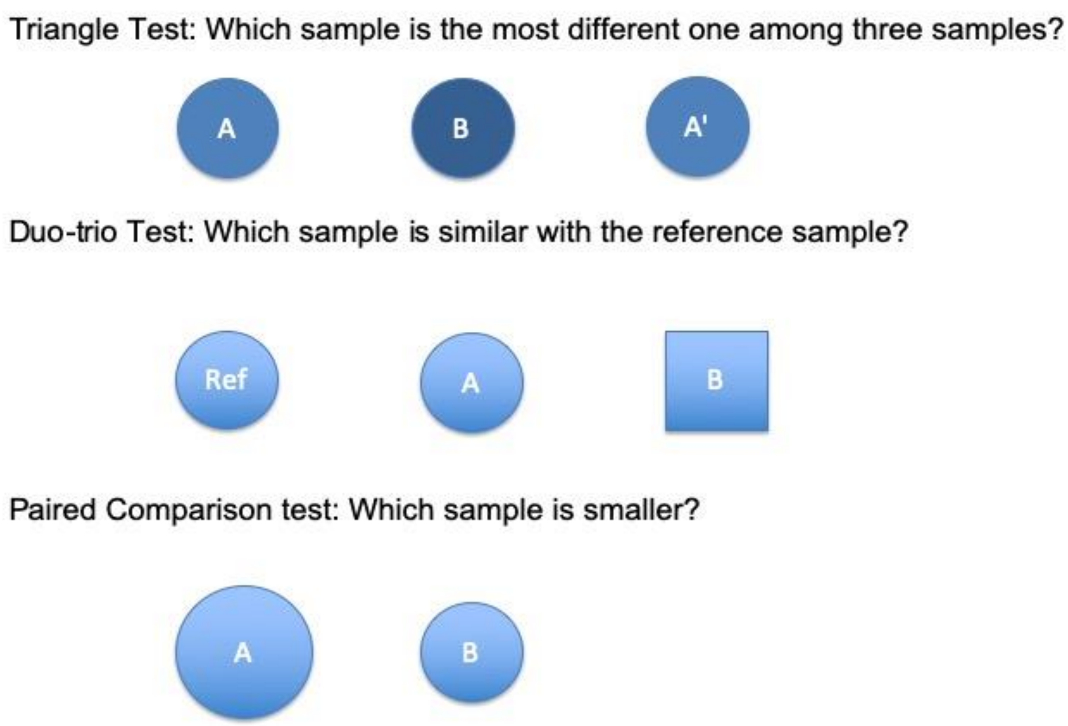


Figure 4.12 Comparison of three different types of discrimination tests.

Just-Noticeable-Difference (JND) is called the threshold value of a sensory property that can correlate the intensity of physical property to sensory perception. The JND value can be expressed by a formula (Equation 4.4) as

$$k = \frac{\triangle I}{I} \qquad \text{Equation 4.4}$$

where $\triangle I$ represented the increase/decrease in the physical property of a stimulus that is asked to be just noticeably different from a certain starting degree, I. k is called the "Weber constant", the ratio of $\triangle I$ and I, which could be same for the same sensory property but different for different products. The scale of JND could relate the sensory intensity of the stimulus to its physical intensity, logarithmically in Fechner's law:

$$s = k \log I \qquad \text{Equation 4.5}$$

where *S* is the sensory intensity and *I* is the physical intensity of the stimulus. Fechner's law was strong and useful rule for 75 years. However, Stevens (1962) [402] demonstrated that JND value should proportionally increase with the intensity of the stimulus. The Stevens law has been established as a power-law relationship between the psychological magnitude (*S*) and the physical magnitude (*I*) of a stimulus:

$$s = kI^n \; or \; \log S = n \log I + \log K \qquad \text{Equation 4.6}$$

where *n* is the characteristic index and *k* is a proportionality constant measured by the method. The exponent *n* equals to 1 represents a linear relationship between the physical and psychological magnitude of a stimulus. It means the sensitivity of human's sensory perception is equal to that of instrumental measurements. A higher *n* represents a more sensitive human perception of the stimulus.

Protocol of JND of gel-model food via Triangle test

In this study, the panellists were required to explore the just noticeable difference (JND) in hardness, using a set of "triangle tests". Samples for JND testing are based on a main set of model foods, M1 (softest) to M6 (hardest). There are five sub-sets of JND samples, with two additional samples running between each of the main samples so, for example, the subset between M1 and M2 are designated as M1, M13, M16, M2; that between M2 and M3 are designated: M2, M23, M26, M3, etc.

All the JND tests began by comparing M5 and M6; participants were required to bite three samples presented in random order and were asked to bite each sample once. After one bite, they expectorated the sample into a transparent container (to be used to investigate the degree of fracture). After biting, the participant was instructed to identify the odd sample out and record his/her answer. Based on the correctness of the answer (YES/NO), the participant was required to bite different sets of samples (triangle tests) following the process of observation schedule in Figure 4.13 and Appendix B. At the end of this step, the results were recorded, and the next step (as determined by Observation schedule: Figure 4.13 and Appendix B) were carried out.

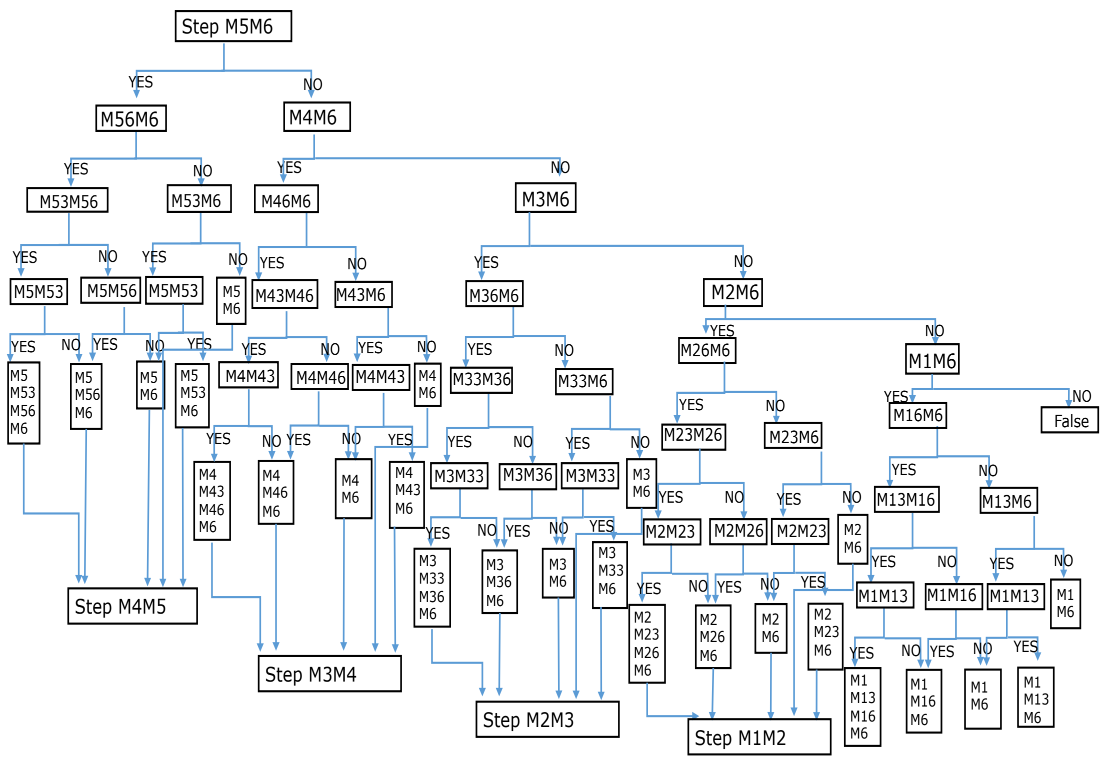


Figure 4.13 An example of JND's observation schedule.

4.3.4 Oral physiology – Maximum bite force instrumental measurement

4.3.4.1 Commercial bite force measurement

The instrumental measurements of bite force have a long history; advancements have gradually changed from mechanical instruments to electronic instruments. One of the earliest commercial devices has been invented by the Tekscan company (Boston, USA) using pressure sensors to measure the bite force of teeth contact areas [403].

Piezoelectric sensors can convert the changes of pressure, strain or force to the electrical charge by the piezoelectric effect. Because of the small size and flexible texture, the piezoelectric sensor can be directly placed on the teeth to measure maximum bite force [112]. It can also be customised to be a core part of a low-cost maximum bite force device using a commercial sensor from the Tekscan company [113 - 115, 404]. Other than measure the maximum bite force, the sensor has been used to capture the masticatory force during bruxism [405, 406] and chewing phases [186].

4.3.4.2 Maximum bite force instrumental measurement via ELF system

Using the ELF measurement system (Tekscan Inc., Boston, USA), the bite force is captured by the sensor and the electrical signal is transfer to the software ELF by an ELF USB sensor handle (Figure 4.14). The B201-H sensor (maximum capability is 4400 N) have to be calibrated before bite force measurement. The sensor calibration was done on an Instron with a compression test with 200, 500, 800 and 1100 N loads, respectively. Each of the loads was collected and saved as a calibration for measuring the bite force.

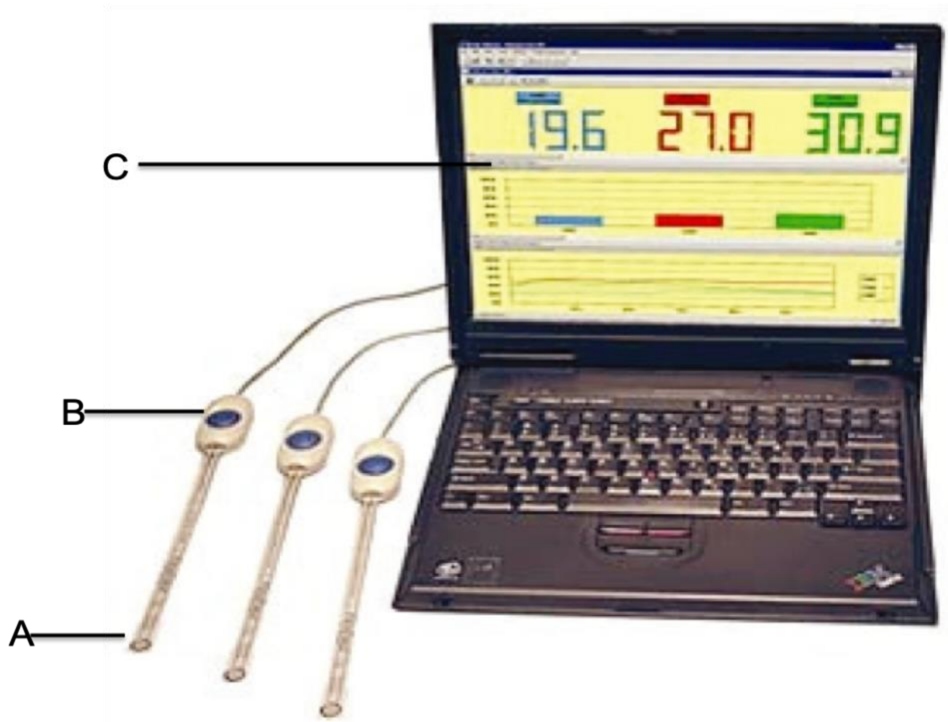


Figure 4.14 The ELF system: A. B201 sensor; B. USB sensor handle; C. ELF software.

Protocol of maximum bite force via ELF system

The participants were seated with their heads upright and in an unsupported, natural head position. The B201 sensor was carefully placed into the participant's mouth between the right side of the molars. The participant was required to clench their teeth in the intercuspal position (maximum occlusion of posterior teeth) with maximum force for 3 seconds. The results were collected and analysed by the ELF system. Furthermore, repeating the procedures on the left side of the molars.

4.4 Design of subjective masticatory measurements

4.4.1 The Quality of Masticatory Function Questionnaire (QMFQ)

The use of a questionnaire is one of the essential, subjective measurements for evaluating the masticatory function. Masticatory function can be assessed from the psychological aspects and the adapting ability aspects by the self-reported subjective techniques which objective measurements cannot capture [407]. A questionnaire called the Quality of Masticatory Function Questionnaire (QMFQ) has been established and applied to investigate the subjective masticatory function within various cultural contexts, a large population and different countries [408]. The original QMFQ was French, and was developed to measure the masticatory function of the adults who speak French and wore dentures living in Montreal. It has been translated into an English version in many studies [58, 409]. The questionnaire consists of 28 questions investigating the difficulty and frequency of the participant chewing several types of foods (beef, chicken, raw vegetables and raw fruits), which use 5 Likert-response options (from "always" to "never") (Table 4.4).

Table 4.4 English version of the QMFQ with 28 questions. [221]

1. Do you have difficulty chewing small pieces of beef?
2. Do you have difficulty chewing small pieces of chicken?
3. Do you have difficulty chewing ground beef?
4. Do you have difficulty chewing hard, raw vegetables, without cutting them?
5. Do you have difficulty chewing hard, raw fruit, without cutting them?
6. Do you have difficulty chewing hard, raw fruits, after cutting them in quarters?
7. Do you have difficulty chewing peels of hard raw fruits?
8. Do you have difficulty chewing crusted bread?
9. Do you have difficulty chewing nuts and grains?
10. Do you have difficulty chewing with your prosthesis?
11. Do you have to remove one or both of your prostheses in order to eat?
12. Do you have to drink while eating to facilitate swallowing?
13. Do you have to add sauce to your meal to facilitate swallowing?
14. Do you have to soak your food to facilitate chewing and /or swallowing?
15. Is your food choice limited because of your prosthesis?
16. In general, is the food well chewed before being swallowed?
17. Have you eaten beef cut into small pieces?
18. Has it been necessary to ground the beef before eating?
19. Have you eaten chicken cut into small pieces?
20. Has it been necessary to ground the chicken before eating?
21. Has it been necessary to convert meet into puree in order to eat?
22. Have you eaten fresh apples without cutting them?
23. Is it necessary to peel the apples before eating?
24. Is it necessary to cut the apples into quarters in order to chew them?
25. Is it necessary to cut the apples into small pieces in order to chew them?
26. Has it been necessary to convert fruits into puree in order to eat?
27. Have you eaten fresh carrots without cutting them?

28. Is it necessary to cut the carrots into small pieces in order to eat?

4.4.2 Design self-assessed masticatory function questionnaire

The questionnaire of this study consists of two parts.

The first part is the self-assessed masticatory status questionnaire comprises six domains of individual oral health and texture perception:

- Personal information including age and gender;
- The number of natural teeth loss;
- The conditions of teeth depend on the natural or replacement teeth status;
- The frequency of oral pain experience (toothache);
- The preference and limitation relating to texture (*hardness*);
- Self-rated the level of bite force.

The second part is the specific questions of the quality of masticatory function questionnaire to quantify the subjective masticatory function. The quality of the masticatory function questionnaire consists of 19 questions, which specifically related to the difficulty of masticating different types of real foods with a hard texture. The results can evaluate the subjective masticatory function by six domains:

- Mastication habits
- Meats (cooked beef)
- Raw foods (vegetable and fruit)
- Dried food (crusted bread, nuts and grains)
- Wearing dentures (dental implants, partial and complete dentures)
- Chewing influences (chewing habits affected by masticatory difficulties)

These domains have 5 Likert-responses options scored as 0 = never, 1= usually not, 2= occasionally, 3= usually, 4= always.

The questionnaires are provided in Appendix C for reference.

Chapter 5 Gel-model Foods Link to Texture Perception and Bite Force in Healthy Adults

A set of gel-model foods has been developed and optimized to link texture perception and bite force of healthy adults between 20 - 30 years of age. A better understanding of the mechanical properties of gel-based foods is critical for investigating the relationship between texture perception and bite force in the future. Therefore, the gel-model set with different intensities of perceived texture needs to be quantified by instrumental measurements (mechanical properties). With the aim of validating gel-model foods as a new measurement for evaluating bite force across lifespan, this method has been used for healthy young adults to link hardness perception with sensory bite force measurements and the commercial bite force test.

This chapter has some repetition in the “Introduction” and “Methods and Materials” sections to ensure it can be read as an individual paper.

5.1 Introduction

Model foods have been a tool for evaluating masticatory function since 1985. In general, assessed the level of masticatory function by quantifying the median particle size (after certain number of masticatory sequences), number of chewing cycles, jaw muscle activities and bolus formation when the model foods were consumed during oral processing. Furthermore, model foods are tested by various panellists to qualify the relationship between masticatory function and texture perception of foods. There is a missing link in this field that can quantify masticatory function by using model foods to assess sensory perception. However, commercial instruments have been developed to quantify the masticatory function, such as Tesckan which measures bite force, and Electromyography (EMG) which measures muscle activity. The use of these devices is still limited in the clinical field due to expertise requirements and expensive costing, which has meant the study of masticatory function study has not covered a large population panel across lifespan.

Texture is a crucial attribute of food, and it links to the sensation experienced when food is consumed during oral processing. The texture perception of food is continually altered with the chewing behaviours modified from time to time in the mastication. Hardness has been known as one attribute of texture perception that can link to the first dominating sensation when human consume foods [379]. Many studies proven that the hardness of the foods has been an essential factor related to masticatory function in the first bite or first five chewing cycles [390 - 393, 396]. Meanwhile, the relationship between masticatory functions and hardness has been widely studied. Adjusting masticatory function can adapt to the different level of hardness texture. Adjustments include extending the chewing time, increasing chewing cycles and enhanced jaw muscle activity. However, at some level, the hardness of the food goes beyond the individual's masticatory function, leading to coarser particle sizes and a "tough" bolus, which are not safe for swallowing. Except for the preference and chewing behaviours of individuals, hardness is one of the most critical food characteristics that can influence the eating process.

The maximum bite force is one of the critical determinants of masticatory function that has been studied with instrumental measurements (MBF). Pearson's correlation coefficients of the positive relationship between maximum bite force and masticatory function are as high as 0.8 [16, 130]. It means that the maximum bite force can explain more than 80% of the variance in masticatory performance. However, the definition of "comfortable maximum bite force" is defined as a combination of the objective meaning of maximum bite force from oral physiology and the subjective meaning of comfort from sensory sensation and perception. This study aims to establish a series of gel-model foods as a stimulus to assess the comfortable maximum bite force, which combines sensory perception and mechanical properties. The textural intensity of the model foods is directly investigated by mechanical properties measurements. Sensory perception is assessed by subjective analysis such as descriptive analysis and discriminative analysis (just noticeable difference analysis, JND).

The work presented in this chapter establishes a new measurement of "maximum comfortable bite force", which depends on linking hardness to the mechanical properties of a set of gel-model foods. The size, shape and mechanical properties were characterised by compression, puncture and recoverable energy tests. Texture perception of gel-model foods was quantified by descriptive analysis with a line scale and the rank test. The different levels of hardness intensity in the model foods was optimised by JND test. The subjective tests were conducted with 40 healthy adults whose age was between 20-30 years old.

5.2 Methods and Materials

5.2.1 Establishing a series of gel-model food via instrumental assessment

The processes for establishing a series of gel-based foods involved three steps.

5.2.1.1 Selection of model food shape

The gelatin-based model foods (20%, w/w) of varying hardness in two different shapes were tested by TPA test. The TPA test was conducted at the room temperature (~25℃) using a CT3 Brookfield Texture Analyzer (Brookfield Engineering Laboratory, Inc. Middleboro, MA, USA). The working parameters of single compression test were: Pretest speed: 2 mm/s; Test speed: 0.03 mm/s; Load: 0 to 10000 g; Trigger load: 0.07 N. Gel-model food were positioned on a fixed-base plate, and probes moved a distance of 90% deformation of the initial height of samples. Each of the samples was tested with five replicates and three different probes: needle, cone and cylinder. The needle probe used in this test was stainless steel, 1.0 mm diameter and 43 mm long probe (reference TA9). The cone probe used in the test was a clear acrylic, 24 mm diameter, 46 mm long and 30° probe (reference TA17). Figure 5.1 illustrates the cube shape of model food. The cube shape size of model food is 15 mm × 15 mm× 15 mm, and the cylinder shape is 10 mm (Top Diameter) ×15 mm (Bottom Diameter) × 10 mm (H). For the detailed methodology of the preparation of model foods, refer to Section 4.2.2.3. All gel-based samples were measured with 5 replicates for each sample.

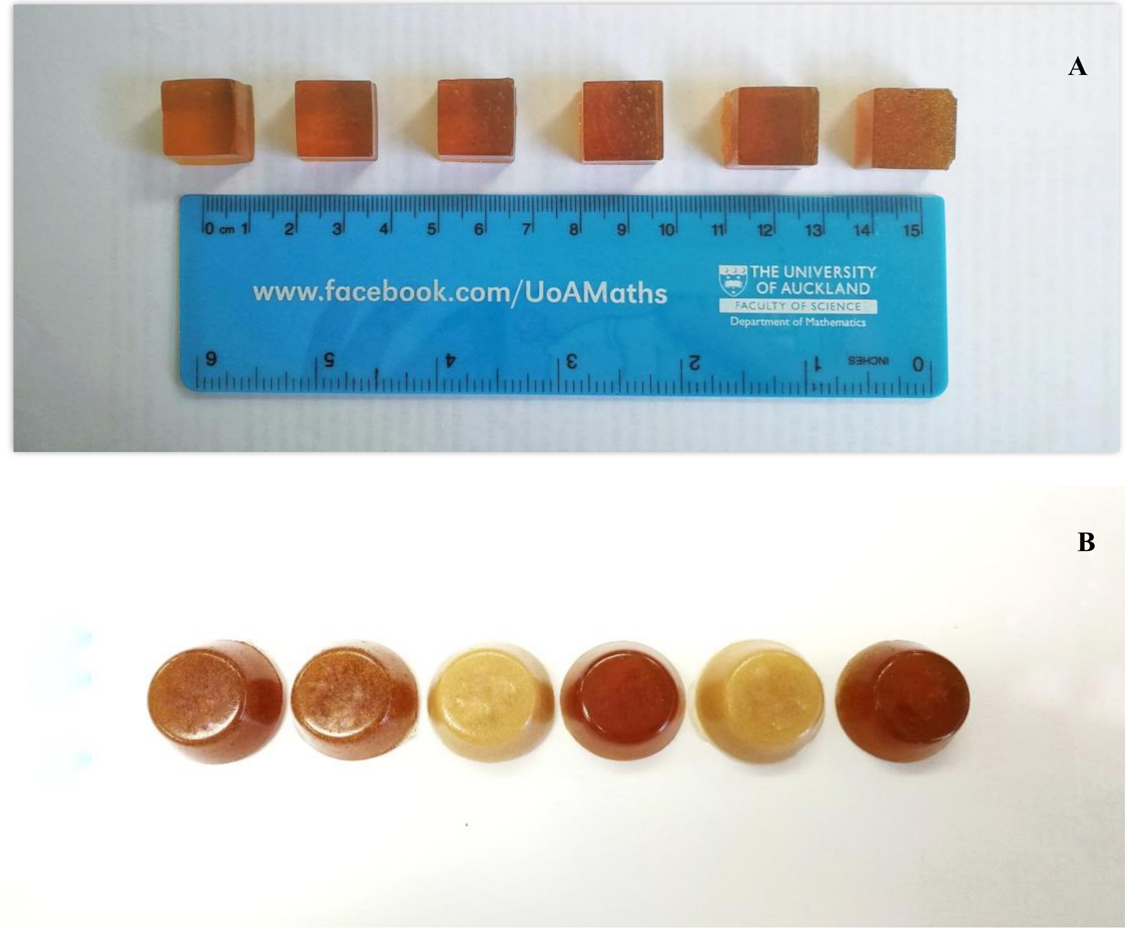


Figure 5.1 The cube (A) and muffin (B) shape of gelatin-based model foods.

5.2.1.2 Selection of model food ingredients

The hardness of agar agar-based model food and gelatin-based model food with cube shape were measured by TPA test. The TPA test was conducted at the room temperature (~25℃) using a CT3 Brookfield Texture Analyzer (Brookfield Engineering Laboratory, Inc. Middleboro, MA, USA). The working parameters of single compression test were: Pretest speed: 2 mm/s; Test speed: 0.03 mm/s; Load: 0 to 10000 g; Trigger load: 0.07 N. Gel-model food were positioned on a fixed-base plate, and probes moved a distance of 90% deformation of the initial height of samples. Each of the samples was tested with five replicates and three different probes: needle, cone and cylinder. The needle probe used in this test was stainless steel, 1.0 mm diameter and 43 mm long probe (reference TA9). The cone probe used in the test was a clear acrylic, 24 mm diameter, 46 mm long and 30° probe (reference TA17). For detailed methodology of the preparation of model foods refer to Section 4.2.2.2. All gel-based samples were measured with 5 replicates for each sample.

5.2.1.3 Selection of gel concentration in model foods

First stage: The hardness of different concentration levels of gelatin-based model foods (detailed information provided in Table 4.1) with cube shape was measured by TPA test (for the detailed protocol of the test refer to Section 4.3.2.3). All gel-based samples were measured with 5 replicates for each sample.

Second stage: The final set of gelatin-based model foods (45%, 50%, 60%, 65%, 70%, w/w) with cube shape was evaluated by the recoverable energy test. For the detailed methodology of the preparation of model foods refer to Section 4.2.2.2. Cube gel-model foods (15×15×15 mm) were compressed between flat plates (10 cm edge length) fitted to the Instron 5500 testing instrument (Instron Engineering Corp., Canton, MA, USA) equipped with a 1 kN load cell. The samples were compressed at a constant speed of 10 mm/min and removed at a rate of 10 mm/min with the consecutive loading-unloading cycles of increasing strain to 10%, 20%, 30%, 40% and 50% of their initial height. The percentage of recoverable energy was calculated as the ratio of recoverable energy to total work done during loading. These two parameters were measured from the area under the stress-strain curve during the compression and decompression of the samples, respectively. The maximum values of deformation was set as 50% to avoid fracture, due to some samples fractured after 50% deformation of the initial height. For the detailed methodology of the preparation of model foods refer to Section 4.2.2.2. All gel-based samples were measured with 3 replicates for each sample.

5.2.2 Sensory assessments

The established set of gel-based model food was applied in sensory assessments to link hardness perception to maximum comfortable bite force.

5.2.2.1 Rank&Rate test

Rank&Rate test was used to quantify the maximum comfortable bite force of each participant. The rank part of the test required a participant to rank the set of gel-based food samples in order of increasing hardness. The rate part required the participant to score hardness intensity of the gel-based foods on a line scale. During the rank test, participants were presented with the set of model foods in random order and were asked to bite the sample once. After one bite, they expectorated the sample into a transparent container. During and after biting, participants were required to rank the six samples in order of increasing hardness. Then the participants were invited to rate the samples via the second set. They were required to bite each sample once. During and after biting, they were required to rate the samples' hardness by making a mark for each sample on a 10 cm line scale (Soft/Hard). The participants could refuse to bite a sample anytime they feel uncomfortable about the hardness being to great. They could also ask for additional samples if they required help with their ranking and rating. We expect correct ranking (rank test) and hardness score (rate test) to be indicative of bite force, and thus potential parameters for evaluation.

20 male and 20 female subjects, aged between 20-30 years old, were recruited through posters advertised at the University of Auckland. All participants meet the criteria to participate, including being of good general health, having more than 12 functional tooth units of natural teeth, no smoking and no allergies to food ingredients. This project was reviewed and approved by the University of Auckland Human Ethics Committee (Reference Number: 023536).

5.2.2.2 Just-Noticeable-Difference test

Just-Noticeable-Difference (JND), a type of discriminative test, estimates the threshold value of a sensory property that correlates the intensity of physical property to sensory perception. In this study, the primary aim of the JND test was to optimise the set of gel-based food samples with the appropriate variation of hardness texture, which ensures the validity and reliability of using hardness perception to evaluate maximum comfortable bite force. The secondary aim was to explore a relationship between maximum bite force and sensitivity of hardness perception. All the JND tests began by comparing M5 and M6 (main set of model foods); participants were required to bite three samples (two M5 and one M6, or one M5 and two M6) presented in random order and were asked to bite each sample once. After biting, the participant was instructed to identify the odd sample out and record his/her answer. Based on the correctness of the answer (Yes/No), the participants were required to bite different sets of samples (triangle tests) following the detailed process of Section 4.3.3.2.

5.2.3 Maximum bite force instrumental measurement

After the sensory tests, the panellists' maximum bite force was measured by the ELF system with the B201-H sensor (Tekscan Inc., Boston, USA). The instrumental measurement of maximum bite force of healthy adults is then used to prove the validity of the sensory assessment of maximum comfortable bite force with the series of gel-based model food. The participants were seated with their heads upright and in an unsupported, natural head position. The B201 sensor was carefully placed into the participant's mouth between the right side of the molars. The participant was required to clench their teeth in the intercuspal position (maximum occlusion of posterior teeth) with maximum force for 3 seconds. The results were collected and analysed by the ELF system. Furthermore, repeating the procedures on the left side of the molars. Maximum bite force of participants were measured with 3 replicates for each side of the molars.

5.2.4 Subjective masticatory measurements

After the sensory assessments and instrumental bite force test, the participants were required to answer a questionnaire on masticatory function. The self-assessed questionnaire estimates masticatory function across two parts. The first part covers ten general questions of self-reporting oral health questionnaire, including basic information (age, gender, condition of teeth), texture level preference, and the hardest level of texture the participant is willing to bite with a visual analogue scale (VAS). The second part is 16 specific questions of the quality of masticatory function questionnaire to quantify the subjective masticatory function. The questionnaires are provided in Appex.2 for reference.

5.2.5 Data analysis

5.2.5.1 Instrumental data analysis

The data outputted by the texture analyzer are distance (mm) and load (N). The percentage distance moved by the probe was calculated using initial sample height. Compression curves were generated by plotting deformation (%) against load (N) (Excel, Microsoft Corporation, USA). The One-way ANOVA analysis of data was conducted using SPSS version 27.0, (IBM Corporation, USA) at a level of significance of $p < 0.05$ to evaluate significant differences between different gel-based model foods related to texture characteristics.

5.2.5.2 Sensory tests data analysis

All the ranking data were converted into accurate rank (%) by dividing the number of correctly ranked samples by the total number of samples. 100% means all of the ranking results are correct, 67% means 4 out of 6 ranking results are correct, 50% means half of the ranking results are correct, 33% mean 2 out of 6 ranking results are correct, 17% means 1 out of 6 ranking result is correct, and 0% presents all of the ranking results are incorrect.

All the marks of rate tests with the line scales were converted into the distance (mm) from the left endpoint of the scale (total distance is 100 mm). The intensity of rate result (maximum comfortable bite force, %) by dividing the distance of the participant's mark by total distance of the line scale. The One-way ANOVA analysis of data was conducted using SPSS version 27.0, (IBM Corporation, USA) at a level of significance of $p < 0.05$ to evaluate significant differences between hardness perception of participants related to masticatory function.

5.2.5.3 Instrumental maximum bite force data analysis

The data recorded by the ELF (Tekscan Inc, Boston, USA) were time (s) and force (N). Maximum bite force (N) is the peak value during the test. The One-way ANOVA analysis of data was conducted using SPSS version 27.0, (IBM Corporation, USA) at a level of significance of $p < 0.05$ to evaluate significant differences of maximum bite force among 40 participants.

5.2.5.4 Self-assessed questionnaire analysis

The data of QMFQ is recorded from 5 Likert-response options (from "always" to "never") were converted into score (%), and these converted into a score for analysis (%). The score is from 0% to 100%, the higher score related to better level of subjective masticatory function. The One-way ANOVA analysis of data was conducted using SPSS version 27.0, (IBM Corporation, USA) at a level of significance of $p < 0.05$ to evaluate significant differences of subjective masticatory function among 40 participants.

5.3 Results and Discussion

5.3.1 Texture perception quantification

Model foods were designed to link the mechanical properties evaluated by instrument tests, including the compression test and the recoverable energy test, to the perceived hardness assessed by sensory tests. The set of model foods must meet two critical requirements: 1. The range of hardness texture perception span from confidently/comfortably bite to challengeable/uncomfortably bite. It is necessary to build up several model foods that have a harder mechanical property. 2. The series of food models should be an appropriate substitute for real foods in terms of texture.

5.3.1.1 Shape and size

The first step of establishing a series of model food is to determine the suitable size and shape of model foods. In this study, two shapes of moulds (cube and muffin moulds), which are simple and regular commercial food size and shape, were selected to make the gel-based test foods. TPA with cone probe assessed the hardness of the two different model shapes. Figure 5.2 shows the curve of the change of load with the time measured during the compression test. As shown in Figure 5.2, the appearance of the compression curves generated from the two different patterns of gel-based foods was significantly correlated to their shape. The maximum hardness of cube and muffin samples is 2274 ± 9.8g and 1859 ± 7.1g. It means the food samples are made by the cube shape have a harder textural property than the muffin shape in the upright position, due to the surface of samples influence the hardness property.

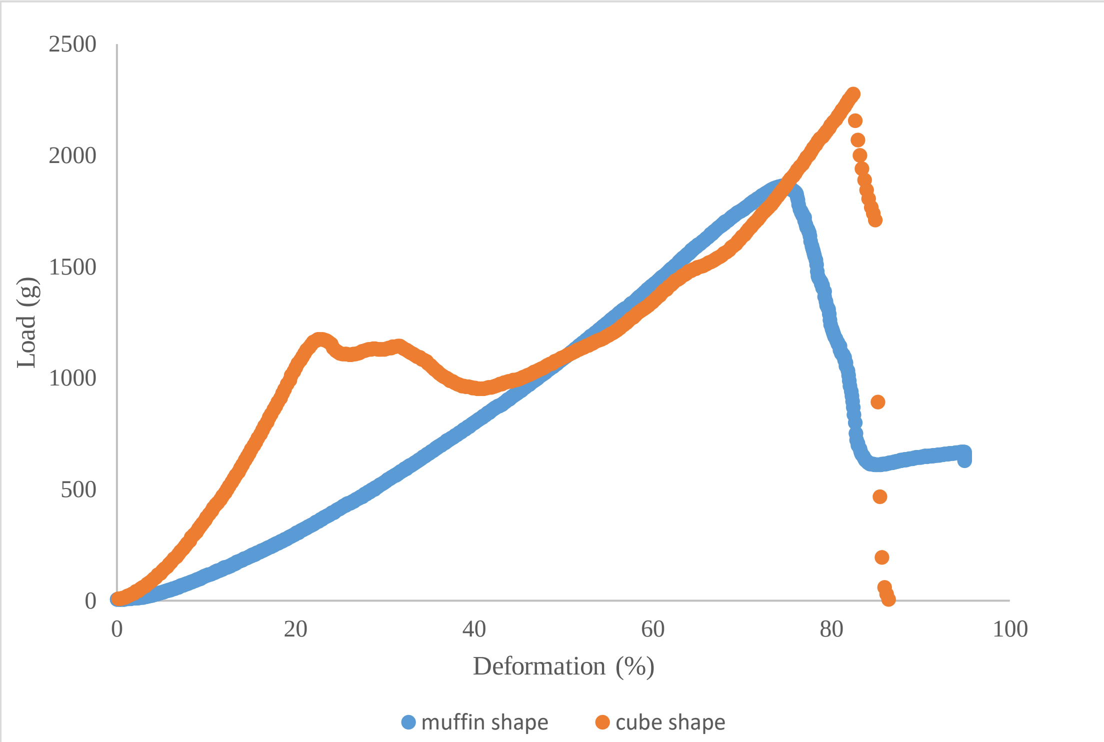


Figure 5.2 The upright position compression curves of the muffin (thickness= 10 mm) and cube shapes (thickness= 15 mm) of food samples.

The hardness of two different shapes of model foods was tested by compression test for each side of the sample. As shown in Table 5.1, the hardness of each side of the cube shape sample had no difference. In contrast, a significant difference in the muffin shape's hardness was found from different sides of the sample (p <0.05).

Table 5.1 Hardness of each side of muffin and cube food samples by TPA.

Shape	Muffin	Load (g)	Cube	Load(g)
Compressing location	Top	1859 ± 15.4	A	2274 ± 9.8
	Bottom	3546 ± 12.1	B	2283 ± 6.5
	Side	9716 ± 35.4	C	2309 ± 8.1
			D	2311 ± 8.9
			E	2198 ± 4.5
			F	2254 ± 6.7
	Average	5040.3 ± 3377.2	Average	2271.5 ± 38.3

Comparing the results from the cube and muffin shapes, the cube shape is more suitable for this research for two reasons: smaller deviation between repeated measurements, and thicker dimensions. Kohyama *et al*. (2005) [378] proven that thicker food with similar mechanical property (hardness by compression test) significantly related to a higher bite force (by a sheet sensor). The thicker dimension of the cube shape is more likely to make participants fall into the "uncomfortable" range when they are required to bite the model foods in sensory tests. The cube shape has six faces of the same dimensions (15mm × 15mm), which lead to similar contact areas of the sample between the molars across different sample orientations, causing different a similar hardness perception irrespective of how it is eaten. The similar mechanical property of each side of the cube-shaped model food is also more suitable for effectively controlling the orthogonal direction of bite during the sensory tests (e.g. self-serve test). The mechanical characteristics of cube-shaped samples can ensure the validity of sensory tests using the cube shape gel-based foods across a large population.

5.3.1.2 Food ingredients

To establish a set of model foods with a gradual increasing hardness texture, two food-grade ingredients were selected to build up the same cube shape (15mm × 15mm × 15mm) food samples. The hardness of the samples was tested by compression test to investigate which ingredients make the food samples *harder* in texture. Figure 5.3 demonstrates the hardness of different model foods with different ingredients. As Figure 5.3 shows, the hardest food sample was the gel-based model food (50%, w/w) which is 2017.1 ±10.2g, and the softest food was the agar-based model food (3%, w/w) of hardness 30.3 ± 3.2g. Although both agar and gelatin show a strong positive correlation ($r > 0.99$) between gel concentration and hardness, the increasing trend of hardness is more significant with increasing gelatin concentration. This means that gelatin has more potential to produce harder model foods. In contrast, agar-based models food would be too soft, which may not satisfy our objective to test the maximum comfortable bite force.

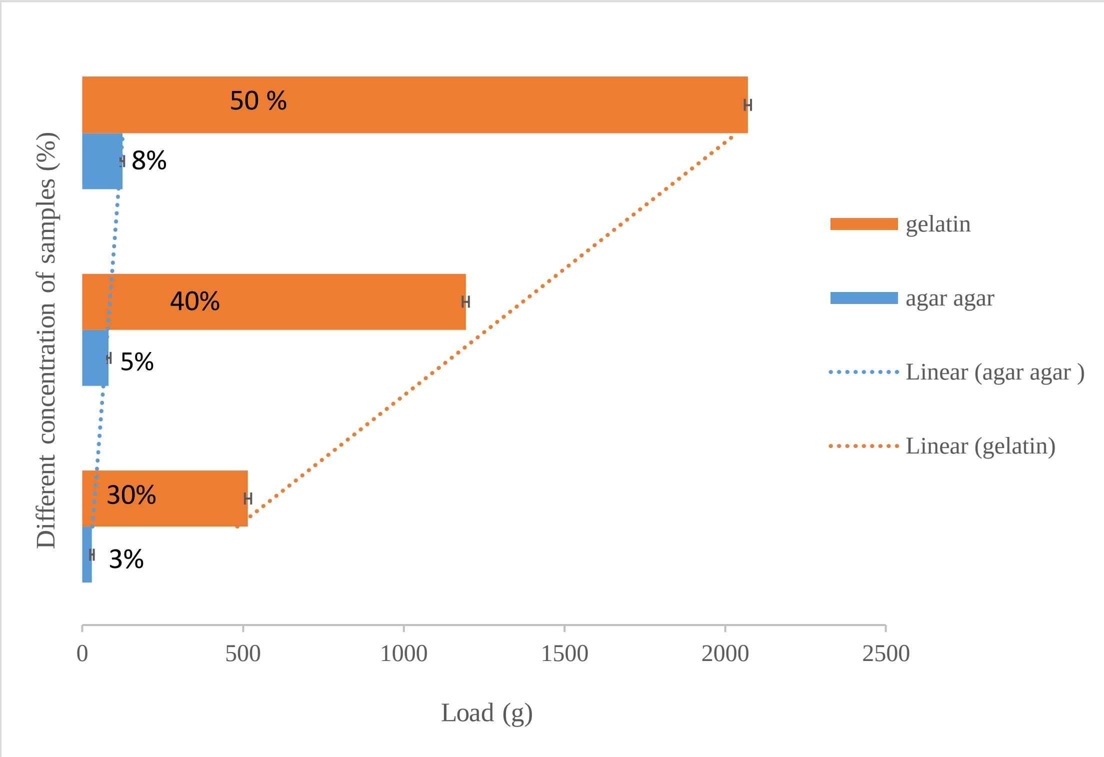


Figure 5.3 The hardness of food samples prepared by agar versus gelatin, measured by peak force with TPA. (Each sample was tested with 5 replicates)

5.3.1.3 Concentration of gel-based model foods

Three prime goals need to be fulfilled by a series of different concentrations of gel-based model foods. The first goal is to model a specific range of hardness textures model food similar that real foods. The second goal is to build up several model foods that make the participants comfortable as well as uncomfortable or unwilling to bite because of an overly hard texture. The third goal is to establish of increasing hard gel-based model foods with equal increase in hardness between consecutive samples.

Goal 1: Determining the range of hardness of gel-based model foods

Figure 5.4 illustrates the hardness of real foods and six model foods by compression testing with a cylinder probe (TA11, 25.4 mm diameter and 35 mm long). The tested real foods were chosen for an uncomfortable hard texture that people would not be willing to bite. The softest sample was 45% gelatin model food, among the 13 foods tested. As Figure 5.4 shows, the second softest sample was the 50% gelatin model food, which had a similar hardness to milk candy, a kind of soft, chewy candy that still needs effort to bite through. The hardness level of 55% gelatin was similar to M&M candy is considered medium-hard candy. The hardness texture of 60% and 65% gelatin can compare to several natural nut foods, such as hazelnut, brazil nut, which may cause some difficulty to bite. Moreover, 70% gelatin had a similar hard texture to the hardness of fruit candy, categorised as the hardest food that may be refused to consume because of the limitation of bite force. A chewing function questionnaire of elderly adults showed that 92% of panellists had difficulty or inability to chew "whole apple" [410]. Figure 5.4 demonstrates that the hardness of the gel-based model from 55 wt% to 70 wt% gelatin is harder than apple. This suggests that the series of gel-based model foods developed here can determine participants' maximum comfortable bite force.

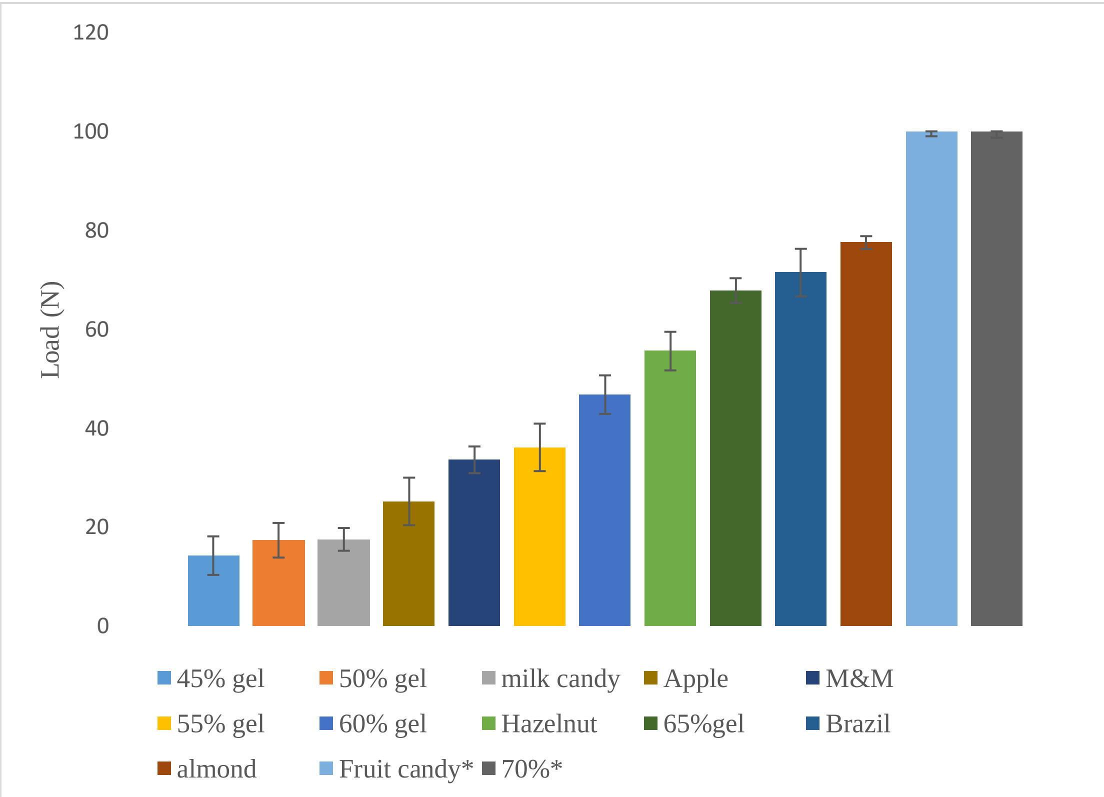


Figure 5.4 TPA measured hardness of different model and real foods (40%-70% of gel-based model foods, milk candy, apple, M&M candy, hazelnut, brazil nut, almond and fruit candy). *The hardness of fruit candy and 70% gel were more than 100 N, which is the maximum measurable load on the instrument. (Each sample was tested with 5 replicates).

Goal 2: Selection of probes for TPA testing

To compare the compression test results using different probes on the same scale, Figure 5.5 presented the normalised results of using a cylinder and cone probes measured and the original results of using needle measured. The normalised results using cylinder probe equal 10% of original hardness assessed by cylinder probe. Meanwhile, the cone probe's normalised results equal 20% of the original hardness assessed by the cone probe. In Figure 5.5, the hardest and softest model foods were discriminated by the cone probe, showing this probe was most suitable for the broad range of hardness. The cylinder probe could not be used to test the hardest texture samples, such as fruit candy and 70% gel-based sample. Although the needle probe can be applied to a similar wide range of hardness as the cone probe, the values of hardness among different model foods were narrower and so less discriminating. The selection of a probe size is smaller than the sample's size has been used in a modified TPA measurement for cereal snack bars [411]. In contrast to other instrumental measurements, the mechanical properties tested from the modified measurement had stronger coefficients with attributes of sensory texture including chewiness, crumbliness and firmness. Consequently, we expect using the cone probe to test food hardness by TPA in this research can establish a strong correlation between mechanical properties by instrumental tests and texture perception by sensory tests.

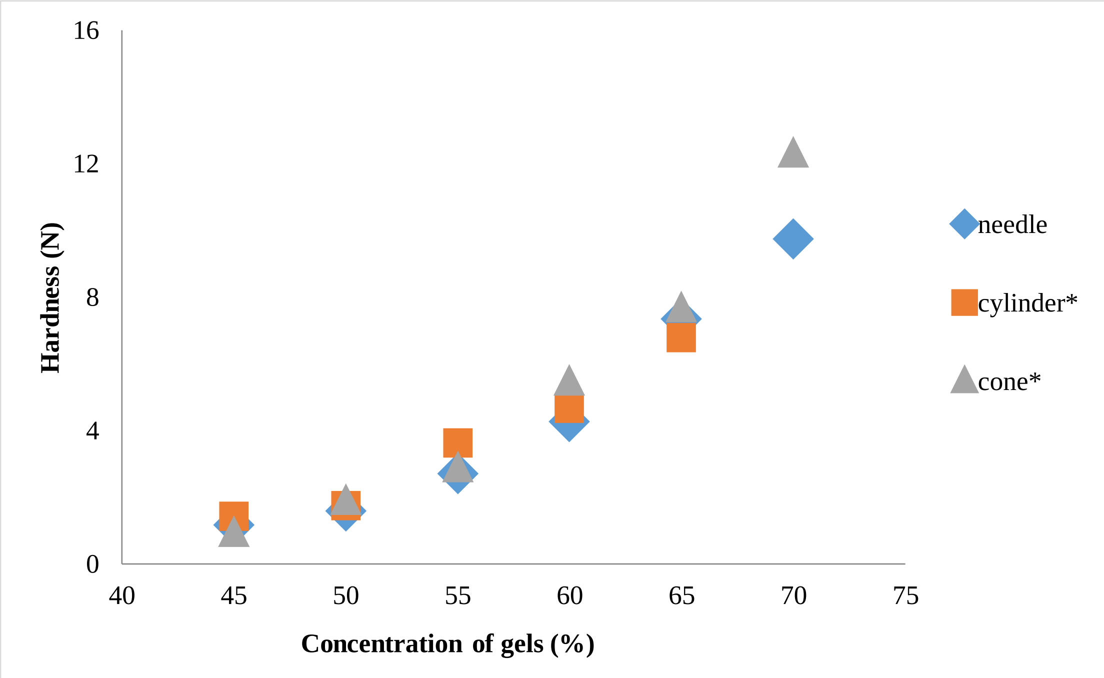


Figure 5.5 The correlation between hardness of model food (45%, 50%, 55%, 60%, 65% and 70%) and TPA probe for compression tests.

* The figure presented the hardness of different gels using the cylinder and cone probe, which equal 10% and 20% of original results assessed by compression tests using the cylinder and cone probe, respectively.

Goal 3: Hardness of gel-based model foods

After the range of model foods and the selection of probes were determined, the hardness of the set of model foods, including the wider set for JND test and final set for sensory tests, were evaluated by compressing test with a cone probe (Table 5.2). When the concentration of gelatin in the model foods increased, the hardness increased from 9.3 N to 72.0 N. The hardness of model food was analysed and optimised in Section 5.3.6 using the just noticeable difference (JND) test.

Table 5.2 The hardness of different concentration of gel-based model foods, measured by compression testing. Reported values are average and standard deviation of 5 repeats.

Name	Concentration (w/w)	Hardness (N)	STDEV (N)
M1*	45.00%	9.3	1.0
M13	46.35%	10.1	1.6
M16	48.20%	11.6	0.8
M2*	50.00%	14.7	0.7
M23	51.95%	15.7	2.0
M26	53.15%	16.4	1.8
M3*	55.00%	17.4	1.0
M33	56.70%	20.8	2.2
M36	58.40%	27.7	2.1
M4*	60.00%	32.7	1.6
M43	62.20%	38.6	2.7
M46	63.40%	45.3	3.4
M5*	65.00%	51.0	2.1
M53	66.35%	56.0	5.9
M56	69.00%	64.0	3.7
M6*	70.00%	72.0	3.8

*: The main set of gel-based model foods only applied in Rate&Rank test.

5.3.1.4 The masticatory method optimisation by JND test

Due to person-to-person variation in the threshold for discriminating hardness, it is essential to establish a set of gel-based model foods with sufficiently different hardness levels to design a valid sensory test. The just-noticeable-difference (JND) test is a method that detects the smallest perceivable change between two samples. We use it here to:

1. Investigating the just noticeable difference of hardness can be discriminated by most of the participants, which can be used to optimise the hardness texture of model foods for linking the texture perception to bite force and self-assessed masticatory function.
2. Confirm the sensory *hardness* of six different hardness levels of model foods can be discriminated by most of the participants.

Focusing on the second objective, we compare the proportion of participants who could successfully discriminate between the six main samples M1 – M6. Table 5.3 shows that 90% of the 40 participants successfully discriminated the difference between M4 and M3, which are the medium hardness levels of the six samples. For the difference between the harder texture samples (M4 - M6), 75% - 77.5% of participants could discriminate the difference in *hardness*. The lowest proportion of participants (72.5%) for discriminating the different *hardness* texture was found in softer samples because differences in hardness between softer groups were significantly smaller than samples.

Table 5.3 The proportion of correctly discriminated participants for hardness perception between six main set of gel-based model foods. Hardness difference is calculated from TPA-measured hardness of each sample.

Group	Hardness difference (N)	Proportion of discrimination (%)
M6&M5	20.98	75.0
M5&M4	18.27	77.5
M4&M3	15.37	90.0
M3&M2	2.63	72.5
M2&M1	5.4	72.5

To investigate the JND value for hardness as per our first objective, five sub-sets of JND samples within the main set of samples were tested by triangle tests. Two sub-levels of hardness were added between each pair of samples from the main set e.g. M53 and M56 were added between samples M5 and M6. For the detailed methodology of the preparation of 16 gel-based model foods refer to Section 4.2.2.3. Table 5.4 shows the proportion of participants who successfully discriminated the difference between 16 gel-based model foods with different hardness levels. In general, less than 30% of participants could differentiate the minor increases of hardness between sub-sets of samples. Given that the proportion of panellists who could discriminate the slight differences of hardness is low, we decided there was no need to add more hardness levels into the main set of model foods (M1 – M6) applied to the large population study (Chapter 6).

While Table 5.4 demonstrates the proportion of participants who could discriminate the smaller differences of hardness between samples in the sub-set of model foods, —it allows us to identify these participants whom we classify as high *hardness* sensitivity individuals (successfully discriminate any smallest different hardness in two sub-samples among two main samples (e.g. M5 VS M53; M53 VS M56; M56 VS M6). Figure 5.6 illustrates the distribution of MBF within the high sensitivity individuals. Most of the participants' MBF range from 250N to 450N, which is lower than that of the whole group of 40 participants (MBF range = 146.46-607.48 N, average = 439.63 ± 109.29 N). Participants within the MBF range of 300N and 405N of can discriminate the barely noticeable difference of hardness texture in all five sub-set of model foods. In Section 5.3.5.1 (Group 1) the *hardness* sensitivity (hardness deviation) has significantly related to MBF, the participant whose perception of hardness is most accurate (hardness deviation between 10% and 30%), the maximum comfortable bite force is most likely above 300 N. The similarities in JND test, 300N- 405N MBF (lower than average MBF) can be considered -an important parameter for identifying the more sensitive individuals of hardness texture among young and healthy adults.

Table 5.4 The proportion of correctly discriminated participants for hardness perception with medium-high levels hardness sensitivity for five sub-sets of samples (total 16 samples). Hardness difference is calculated from TPA-measured of each sample.

Group	Hardness difference (N)	Proportion of discrimination (%)	Hardness sensitivity levels
M5&M53	4.96	10	High
M53&M56	8.04	7.5	High
M56&M6	7.98	20	High
M5&M56	13	12.5	Medium
M53&M6	13	5	Medium
M4&M43	5.9	5	High
M43&M46	6.63	0	High
M46&M5	5.74	12.5	High
M4&M46	12.53	20	Medium
M43&M5	12.37	5	Medium
M3&M33	3.43	30	High
M33&M36	6.88	10	High
M36&M4	5.06	7.5	High
M3&M36	10.31	10	Medium
M33&M4	11.94	15	Medium
M2&M23	0.97	15	High
M23&M26	0.65	0	High
M26&M3	1.01	12.5	High
M2&M26	1.62	20	Medium
M23&M3	1.66	15	Medium
M1&M13	0.77	25	High
M13&M16	1.54	2.5	High
M16&M2	3.09	12.5	High
M1&M16	2.31	22.5	Medium
M13&M2	4.63	15	Medium

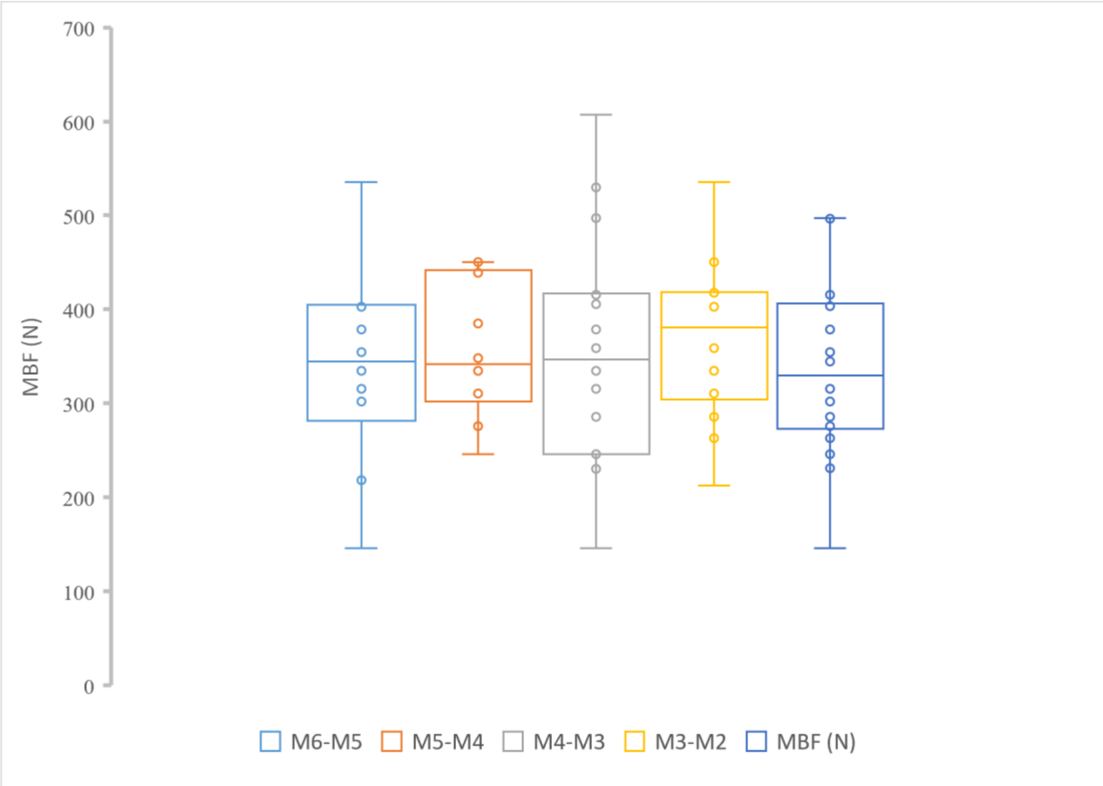


Figure 5.6 The distribution of different sub-set samples' MBF from high sensitivity individuals (*n*= 25).

5.3.1.5 Recoverable energy test

The recoverable energy (RE) test has been used to describe the texture of semi-solid and solid foods due to the correlation between RE and sensory profiling [412 - 414]. The foods can be described in terms of as "spreadability", which relates to the crumbling effort needing to break the food into pieces during mastication [412]. The RE of food mechanical property also highly relates to "crumbliness" perception by sensory test [414]. The results showed that the higher RE (higher elastic component) related to a higher crumbliness perception (*crumbly* score) from sensory test. In this RE test, the six main gel-based model foods have been assessed by compression test with a series of load-unload cycles of increasing compressive strain (10%, 20%, 30%, 40%, 50% of the sample height). Figure 5.7 shows the recoverable energy from each cycle for the main set of gel-based model foods as a function of compressive strain. At the lowest compressive strain (10%), RE of 45 wt%, 65 wt% and 70 wt% model foods remain above 90%. Although the medium gelatin concentration model foods (50, 55 and 60 wt%) have a lower RE with 10% strain, the ration of RE decreasing in the most gradual with the increasing applied strain from 10% to 50%. The sharpest reduction of RE was found in 70 wt% model food. The highest RE was observed in 45 wt% model food with 10-50% compressive strain. At higher compressive strain (30%, 40% and 50%), the significant and negative linear relationships between gelation concentration and RE are found ($p < 0.05$). RE decreasing with increased gelatin concentration from 45 wt% to 70% wt. The lowest RE (59.46%) is found in a 70 wt% gel sample with the applied strain of 50%. Van den Berg *et al*. (2008) [414] found that RE of 70% - 85% with high elasticity property of gels were compressed to 60% of the initial height, which related to a strong crumbliness perception with a high crumbly score by sensory test. As Figure 5.7 shown, with the RE reducing in the maximal strain (50%), a lower concentration of gelatin of model food had a higher RE. It can assume that the lower concentration of gelatin with a softer texture with higher RE may have a crumbly perception.

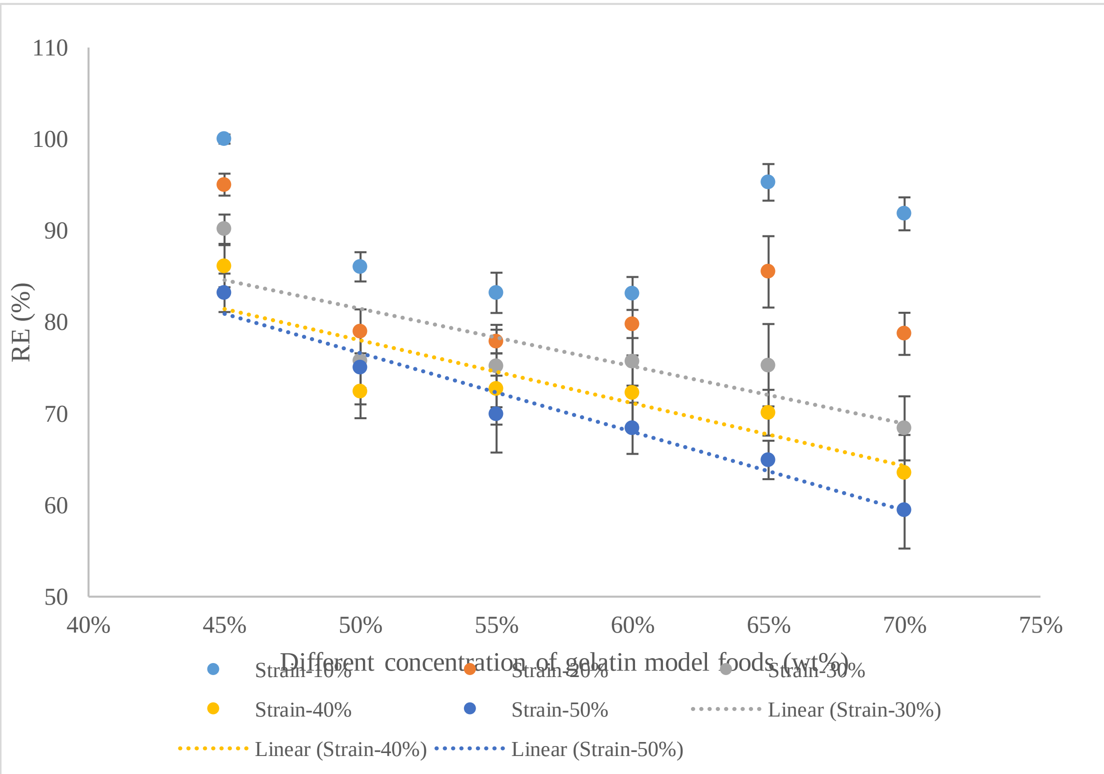


Figure 5.7 Recoverable energy (RE) of six main gel-based model foods as a function of applied compressive strain (10%-50%).

5.3.1.6 Correlation between hardness and crumbliness

Instrumental tests evaluating the mechanical properties of food can be related to texture perception. We propose that the measured hardness and crumbliness can assess the degree of uncomfortable biting for the model foods from the textural aspect. Table 5.5 demonstrates the correlation between the main set of model foods, hardness by compression test, and crumbliness by RE test (50% strain). There is a strong positive relationship between the concentration of gelatin and the hardness of the series of gel-based model foods; as gel concentration increases so does hardness. However, the correlation between crumbliness and hardness is negative, so as concentration increase crumbliness decreases. Moreover, the cross-correlation between hardness and crumbliness, is also negative.

Table 5.5 Pearson's correlation coefficient (*r*) among the concentration of gelatin, hardness and crumbliness of six main gel-base model foods.

	Concentration	Hardness	Crumbliness
	Coefficient (*p*-value)	Coefficient (*p*-value)	Coefficient (*p*-value)
Concentration	/	.963* (0.013)	-.978* (0.032)
Hardness	.963* (0.013)	/	-.906* (0.029)
Crumbliness	-.978* (0.032)	-.906* (0.029)	/

*. Correlation is significant at the 0.05 level (1-tailed) and (2-tailed).

Based on the correlation between hardness and crumbliness, Figure 5.8 illustrates the two factors of mechanical properties of the six main model foods by instrumental tests. Van den Berg *et al*. (2008) [414] illustrated that low *crumbly* perception relates to a high plastic component. As Figure 5.8 shows, M6 can be defined as the hardest and most plastic gel-based model food. In contrast to M6, the softest and the most elastic model food is M1. The second softest model food (M2) has a moderate elastic property. The medium hard model foods (M3 and M4) are prone to a slight plastic texture.

Compared to the plastic level of M3 and M4, the second hardest model food (M5) is more plastic. Foster *et al*. (2006) [156] found that hardness significantly affects muscle activity regardless of the plastic/elastic property. However, plastic food products with increasing hardness cause a reduction of the chewing frequency [78]. This means that a model food with an increased hardness and plastic level will lead to chewing difficulty. We expect that the six main model foods may cause more difficulty and uncomfortable hardness perception with increasing concentration of gelatin.

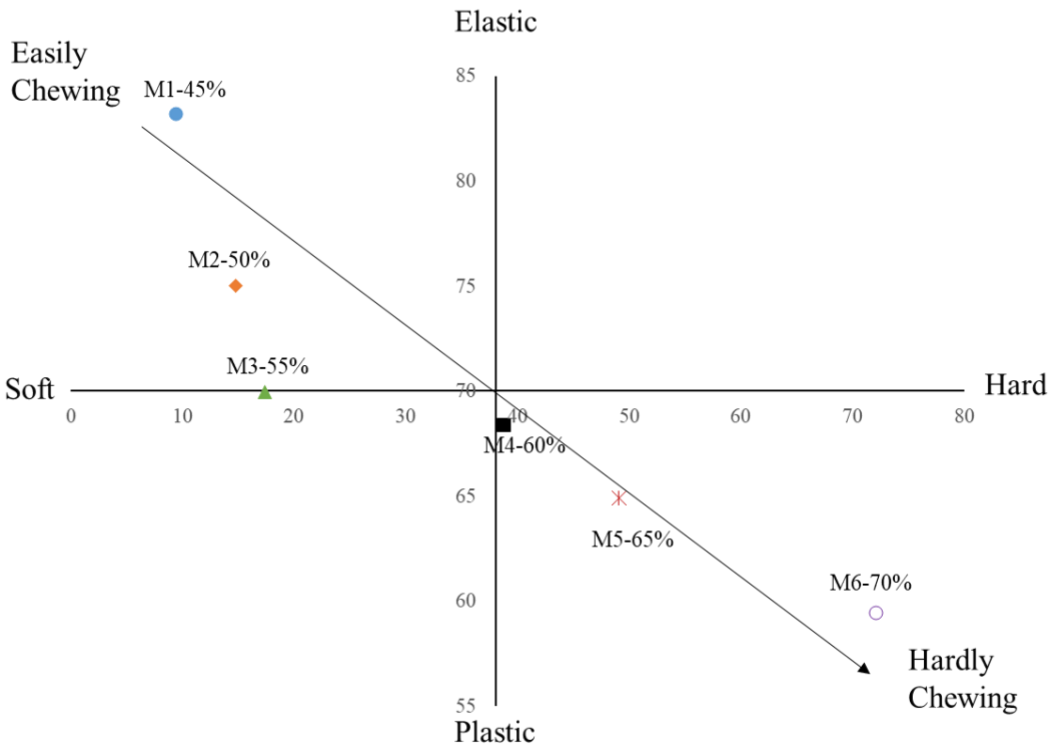


Figure 5.8 Correlation between hardness and plasticity measured instrumentally from final set of six gelatin different gelatin model foods. Note that % denotes the % concentration of gelatin in the sample.

A series of gel-based model food with different mechanical properties was established by selecting the shape, size, food ingredients and concentration of gelatin. The hardness level of the set of gel-based model foods was from medium to hard texture. Some model food makes biting difficult and uncomfortable due to the carefully selected thicker dimension of the sample, more plastic deformation behaviour, and harder texture.

5.3.2 Sensory evaluation

5.3.2.1 Rate test

The sensory *hardness* of the main set of gel-based model foods (M1, M2, M3, M4, M5 and M6) were rated by using a line scale (10 cm) by 40 participants aged between 20 to 30yrs. Participants were instructed to use a single bite and rate *hardness*. The intensity of rate *hardness* be described as rating score by dividing the distance of the participant's mark by total distance of the line scale. A higher score represents a *harder*. The hardness score of six main model foods by rate test is shown in Figure 5.9. With the mechanical hardness level of model foods reducing, the sensory rating scores also decreased. Excluding the outliers, participants have a more similar hardness perception for softer food models.

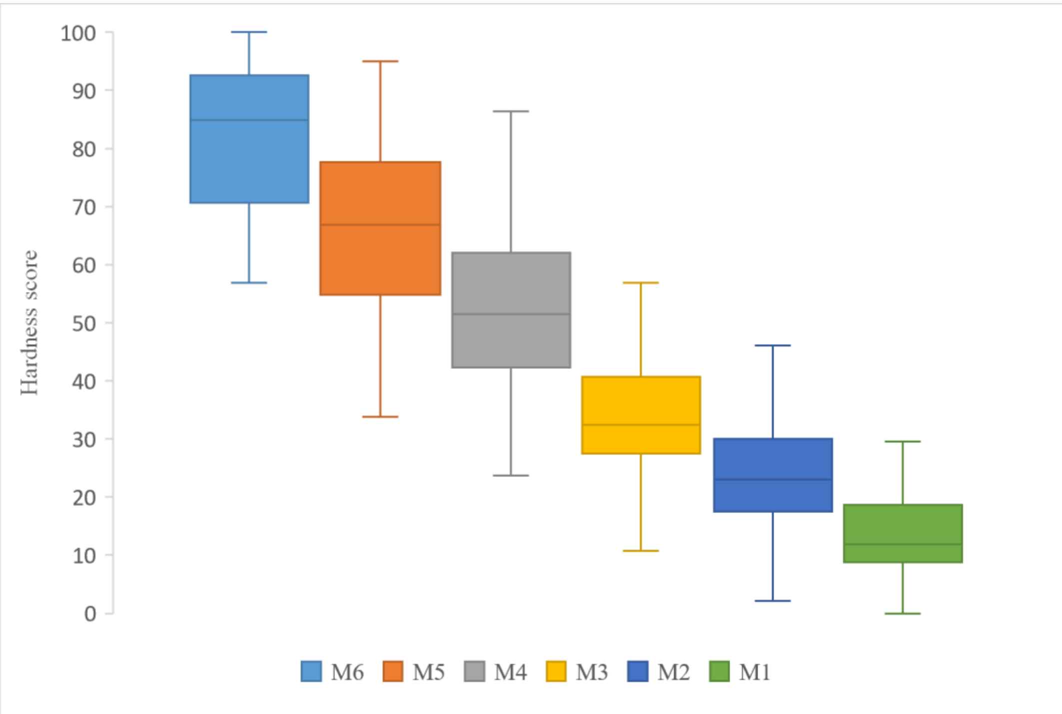


Figure 5.9 Sensory *hardness* scores for the series of gel-based model foods assessed from the Rate test.

As Table 5.6 shows, the difference in rating scores across different pairs of samples is significant ($p < 0.05$). There is a strong positive correlation between rating scores and hardness in six samples ($r > 0.9$). These results prove that the rate test can be applied for sensory evaluation, which can adequately link the hardness perception to mechanical texture properties.

Table 5.6 Difference of *hardness* rating scores between main six gel-based samples, as considered in pairs.

		Paired Differences					t	df	Sig. (2-tailed)
		Mean	Std. Deviation	Std. Error Mean	95% Confidence Interval of the Difference				
					Lower	Upper			
Pair 1	M6 - M5	16.186	9.628	1.522	13.107	19.265	10.633	39	.000
Pair 2	M5 - M4	13.366	10.509	1.662	10.006	16.727	8.045	39	.000
Pair 3	M4 - M3	17.946	12.936	2.045	13.809	22.083	8.774	39	.000
Pair 4	M3 - M2	10.107	9.379	1.483	7.108	13.107	6.816	39	.000
Pair 5	M2 - M1	9.730	6.226	.984	7.739	11.721	9.885	39	.000

5.3.2.2 Rank test

The group's (n =40) results for the rank test for the six main gel-based model foods were converted to accuracy (%), and categorised as 16%, 33%, 50%, 67% or 100% accuracy. The highest accuracy was 100%, representing the ranking of hardness levels for six samples M1-M6 is entirely correct. Two rounds of rank tests were conducted: an independent rank test (pre-rank test) and a rank test mixed with rate test (post-rank test). The distribution of these two rank tests is demonstrated in Figure 5.10.

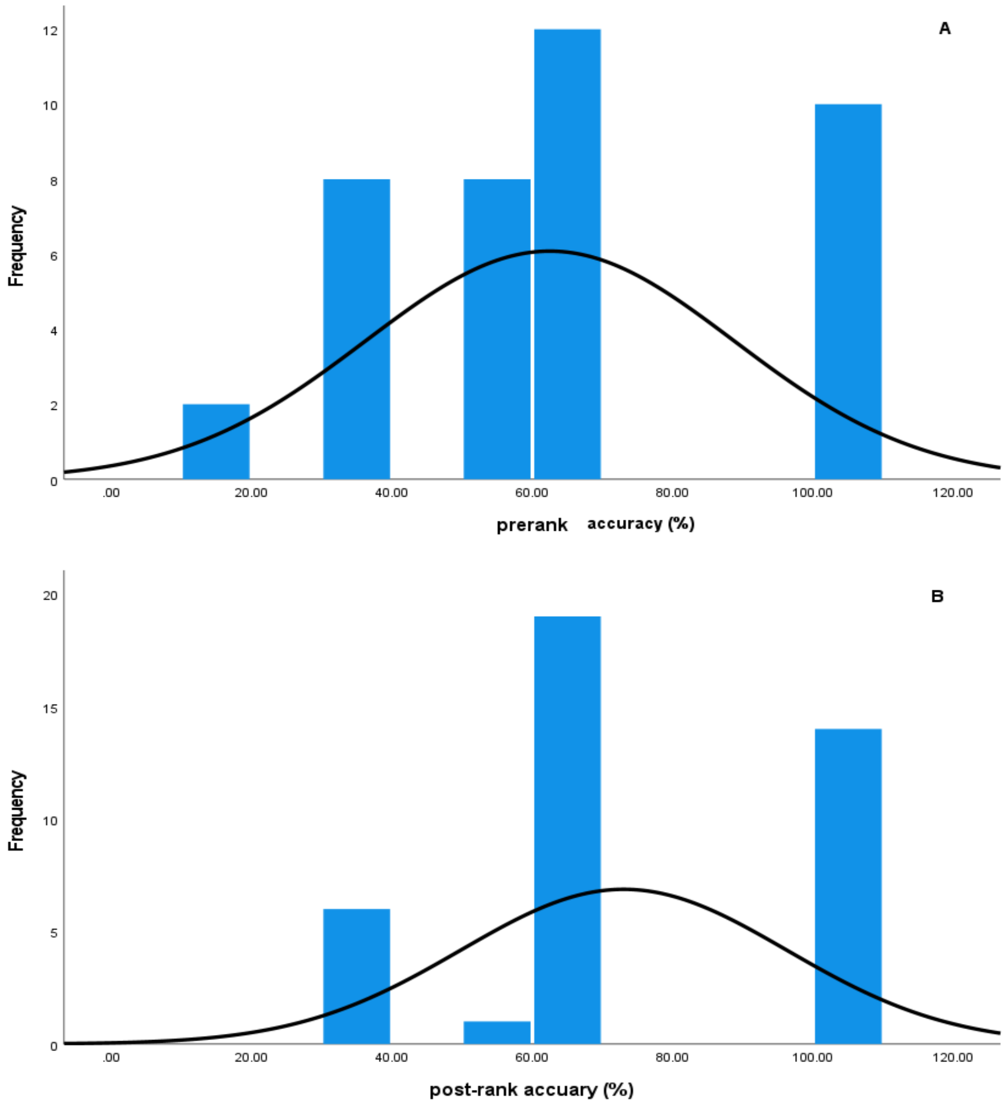


Figure 5.10 The frequency of rank tests accuracy from pre-rank test (A) and post-rank test (B).

The pre-rank test showed that only 25% of participants had 100% rank accuracy, which can be classified as those highly sensitive to discriminate hardness texture. In contrast, 25% of the panellists whose rank accuracies were 16% and 33% can be defined as low sensitivity or dysfunction of discriminating hardness texture. The rank accuracy between 50% and 60% can be evaluated as intermediate hardness sensitivity group. Comparing Figure 5.10 (A) and (B), the accuracy of ranking improved significantly in the post-rank test ($p < 0.05$). Between the pre-rank and post-rank test, the number of participants who have the intermediate and high sensitivity for discriminating hardness increased to 34, while the number of low sensitive panellists drop from 10 to 6. The results prove that it is necessary to arrange a pre-rank sensory test as a trial test to help participants become familiar with the model foods to collect more accurate and reliable results from the sensory test.

5.3.3 Maximum bite force by the instrumental measurement

The maximum bite force (MBF) of the same 40 participants was measured using commercial bite force equipment. The distribution of MBF is demonstrated in Figure 5.11. The strongest MBF is 607.5 N, the weakest one is 146.5 N, and the average MBF is 439.6 ± 109.3 N. Due to many studies using different measurements and types of equipment to investigate MBF, the range of MBF is wide from more than 800N to less than 250 N. The peak value of MBF is 870N [99] and 878N [131], which is more than 50% greater than most other studies. The value of MBF between 300 N and 500 N has been found in other studies [16, 23, 85, 132, 134 - 135, 138, 144 - 146, 148, 150, 152], which is close to the average value of young and healthy adults' MBF measured in this study. Fontijin-Tekamp *et al*. (2000) [16] claimed that the correlation coefficient of MBF and masticatory function is as high as 0.8. As Figure 5.11 (A) shows, 75% of participants' MBF were from 200 N to 450 N. So the participant whose MBF is below 200 N can be assessed as weaker masticatory function. Moreover, the MBF of extraordinary individuals may be above 450 N in 20s young adults.

To investigate the difference in MBF by gender, Figure 5.11 (B) shows the different distribution of MBF by female and male, respectively. The maximum MBF was found in the female group (Mean= 396.9 ± 97.4 N), whilst MBF below 200 N was not found. All of the weaker masticatory function participants (< 200 N) were found in the male group (Mean= 329.6 ± 107.5 N). However, there is no significant difference in MBF between the male and female groups based on averages. Lepley *et al*. (2011) [146] investigated 15 young males and 15 females' masticatory performance, which also showed no significant difference of MBF between these two groups.

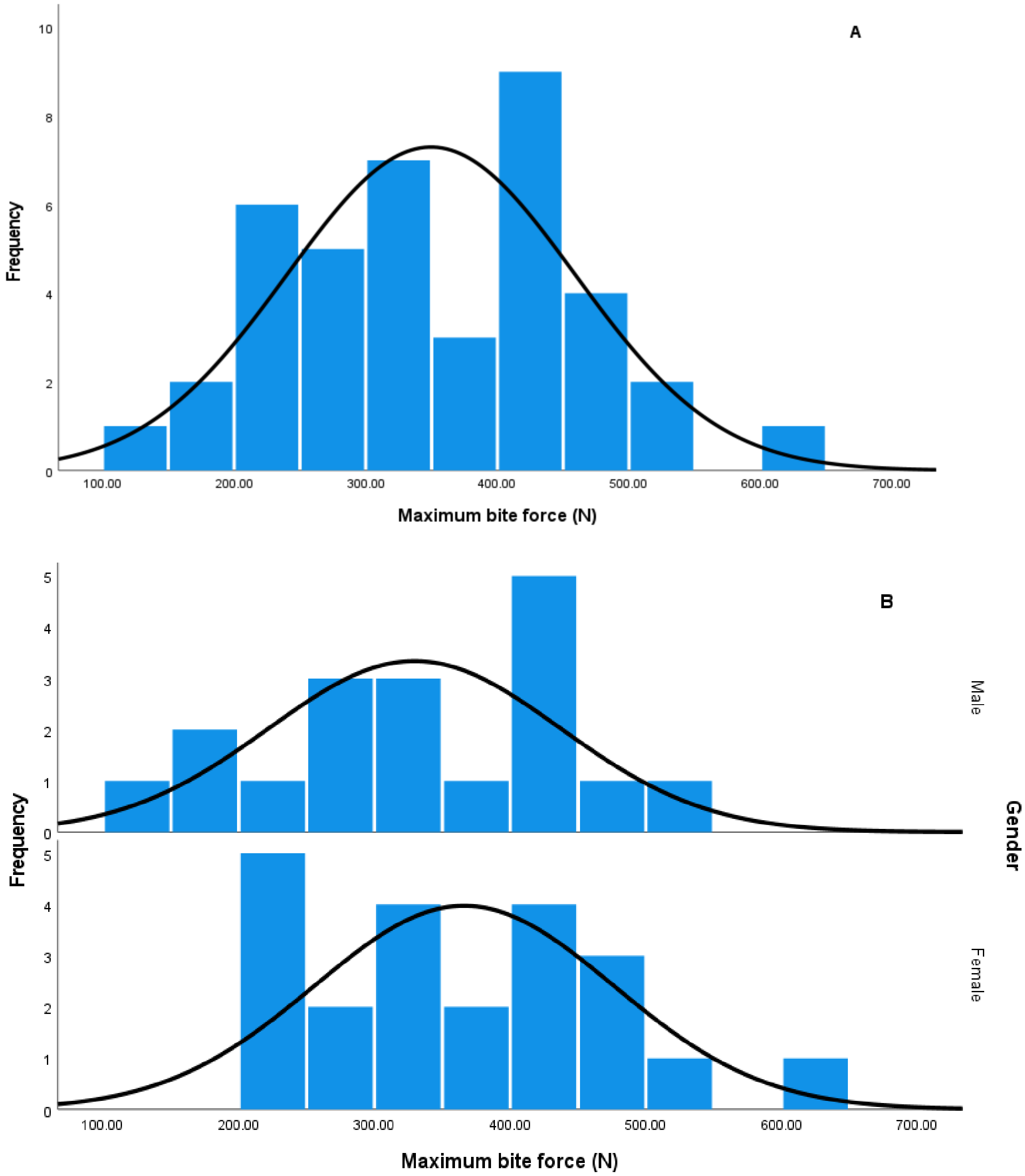


Figure 5.11 The frequency of maximum bite force from 40 participants. A: all 40 participants; B: Grouped by gender.

5.3.4 Self-assessed questionnaires (QMFQ) and self-rating scores

Since basic oral health conditions were not significantly different across the 40 young adult participants, this chapter only analysed the QMFQ and comfortable hardest texture self-rating score results. In the study of investigated the masticatory function of Brazilian adolescents, the QMFQ resulted shown caries significantly impacted the masticatory function [407]. To investigate the difference of chewing difficulty between edentulous wearing conventional dentures and implant dentures, the QMFQ found the patients who wear conventional dentures had more difficulty than of who wear implant dentures in chewing hard foods [415]. A higher QMFQ score should represent the participants who have a better self-assessed masticatory function. Figure 5.12 demonstrates QMFQ scores collected from the self-assessed questionnaires of 40 participants. The range of QMFQ was from 67.6% to 94.1% (Mean = 80.8 ±7.8%). The average QMFQ score is over 80%, which reflects the good condition of masticatory function of health consumers in the age range from 20-30yr.

The weak correlation between masticatory performance (objective masticatory function) and masticatory ability (subjective masticatory function) only was found in the patients with prosthetic treatments [4, 415]. There is still a lack of validated measurements to evaluate the relationship between subjective and objective masticatory function. Figure 5.12 cross-compares the results of MBF and QMFQ scores tested by objective and subjective masticatory function measurement methods, respectively. The participants (ID 31 - 40) whose MBF results are lower than 250 N showed more optimistic self-assessed masticatory function with higher QMFQ scores. However, most participants whose MBF lies in the normal range (250N - 450N) had more negative perception of their masticatory function with lower QMFQ scores. The extraordinary MBF participants evaluate themselves with a relatively accurate score depending on the higher MBF. Although QMFQ is a self-assessed questionnaire applied in a large population to investigate the quality of masticatory function (QMFQ), the results of QMFQ may overestimate the masticatory function of panellists with a weaker MBF.

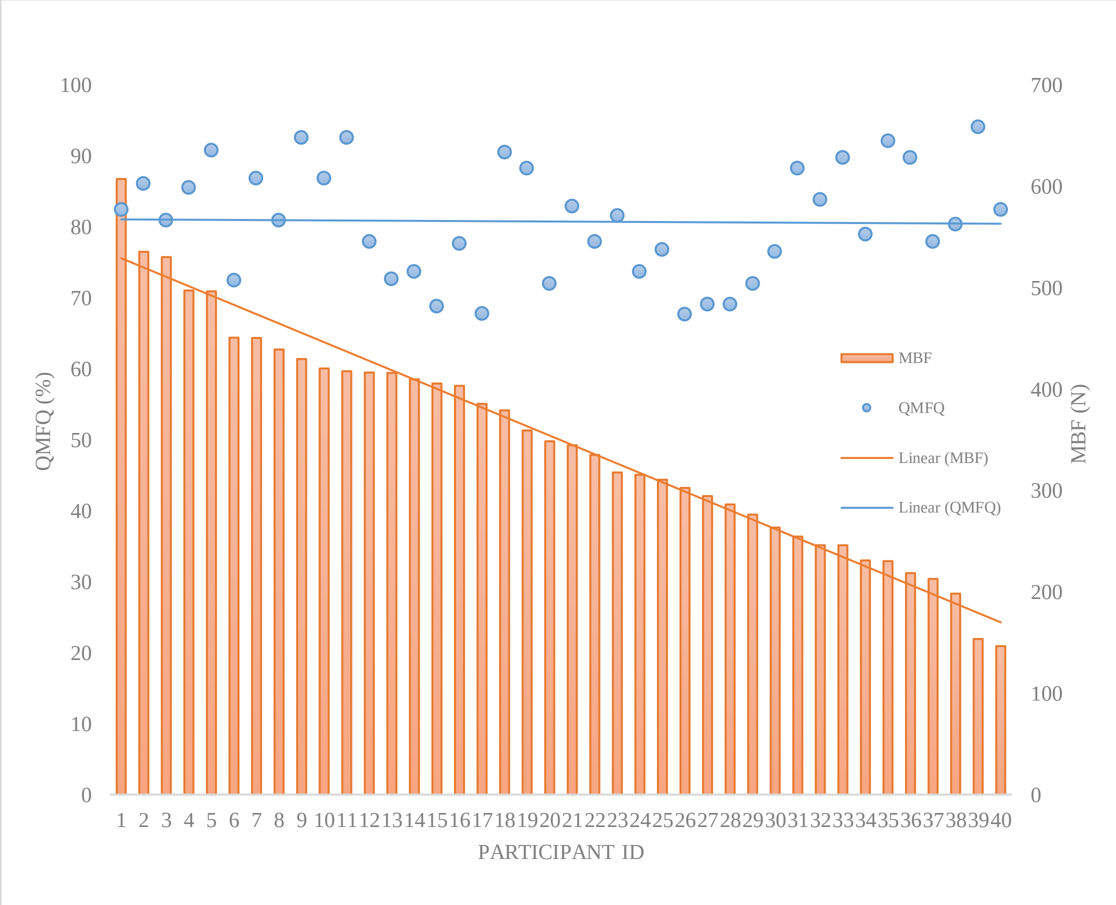


Figure 5.12 Scatter plot of QMFQ score and bar plot of MBF from 40 young adult participants.

The self-rating score was self-assessed by participants in relation to their individual limitation of individual *hardness*. A higher self-rating score represents a greater participant willingness to bite harder textures, which links to the maximum comfortable hardness texture. Figure 5.13 demonstrates the self-rating score and the hardest model food rating score (M6) from 40 participants. 52.5% of participants rated the texture of M6 as the harder or uncomfortable model food, based on their self-rating score being lower than the M6 rating score. However, 35% of healthy participants' self-assessed their maximum comfortable hardness texture beyond the M6 *hardness* score. 12.5% of participants self-assessed the hardness level of M6 is about the same of close to the maximum comfortable hardness texture they are willing to bite. The results demonstrate that the hardness of M6 successfully made more than half of panellists feel uncomfortable to bite. So this series of model foods can be adequately applied to a larger population study who represent a variety of maximum comfortable bite force.

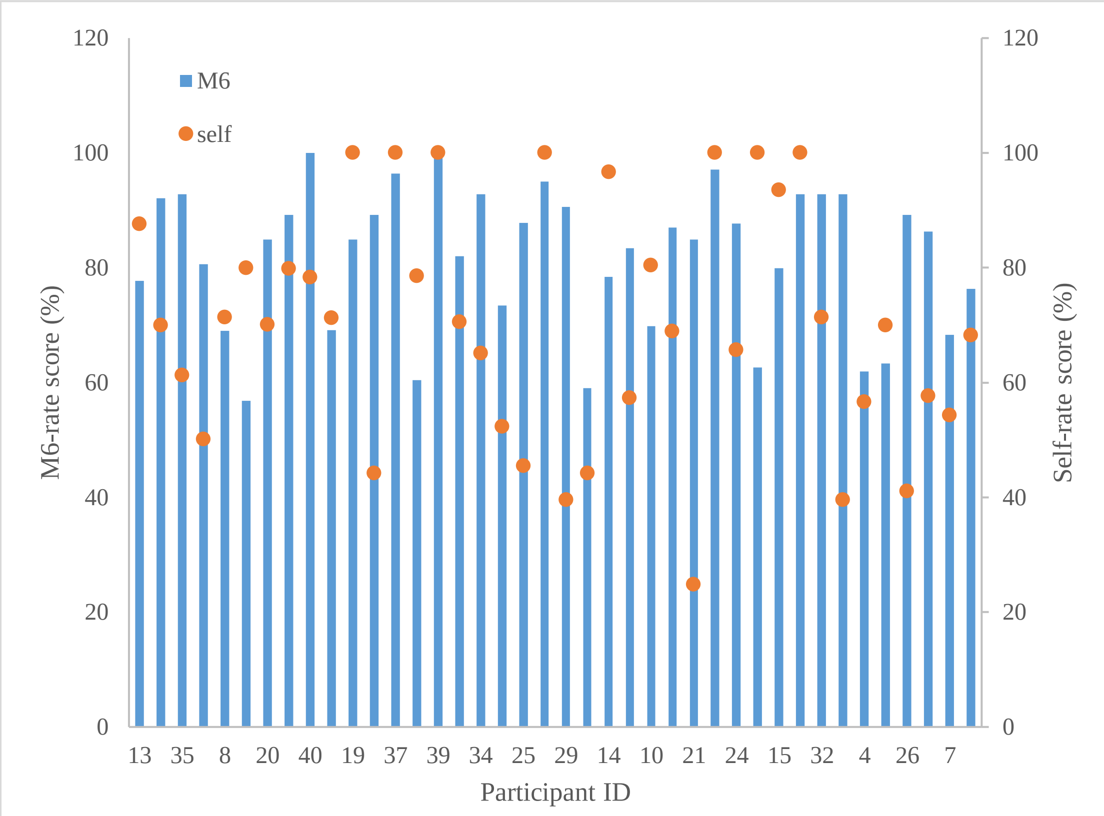


Figure 5.13 Scatter plot of the hardest self-rating score and bar plot of M6-rating score from 40 participants.

5.3.5 The relationship between texture perception and bite force

Texture perception was evaluated by the results of sensory tests, including the rating hardness score and rank accuracy of the series of model foods. There is no significant relationship between texture perception and maximum bite force in 40 young and healthy adults. One explanation that may cause the texture perception of the model foods to not directly relate to instrumental maximum bite force is that the rating *hardness* score may be affected by the individual's subjective rating pattern. Through investigating the rating scores, a part of participants unconsciously marked all of the samples in an extremely narrow range of rating scores causing these results to lack objective judgement cannot compare with the rest of the participants' rating scores. To diminish the influence of individual rating pattern, an alternative data analysis should be considered.

Although the correlation between subjective rating *hardness* score and objective maximum bite force is not significant, the scores strongly relate to the mechanical hardness of the series of gel-based model foods ($p \leq 0.05$). Depending on this strong correlation, the rating *hardness* scores were analysed by an alternative analysis, which aim to link the subjective to objective masticatory function measurement. This analysis investigated the gap, described as "hardness deviation", between rating *hardness* scores by sensory test (subjective measurement) and instrumental hardness by TPA (objective measurement). A smaller hardness deviation indicates a person's perception of hardness is more accurate, assuming that sensory hardness should match TPA-measured hardness. The Equation is as below:

$$\text{Hardness deviation} = \frac{|\text{Rating } hardness \text{ score (\%)} - \text{Instrumental hardness (\%)}|}{\text{Instrumental hardness (\%)}} \times 100\% \qquad \text{Equation 5.1}$$

*Instrumental hardness (%) has been normalised by hardness (N): The softest hardness 0 N equal to 0 % instrumental hardness; the hardest hardness 100 N (maximum hardness from TPA) equal to 100%.

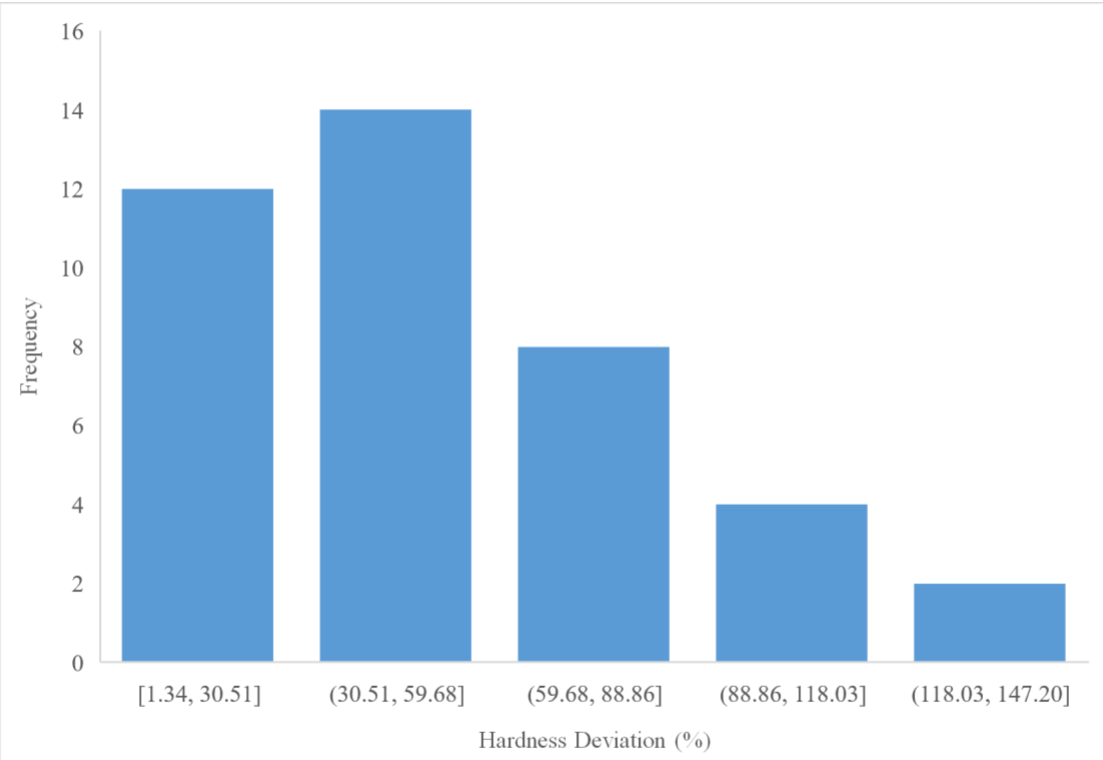


Figure 5.14 The distribution of 40 participants' hardness deviation measured in the average of six main gel-based model foods per participant. The range of hardness deviation is between 1.34% and 147.20% among all the participants.

The hardness deviation presents the degree of difference between subjective texture perception and objective mechanical property in the hardness of the main set of model foods. Based on the average of six samples' hardness deviation distribution (Figure 5.14 shown), the 40 participants were divided into three groups. Group 1 was defined as the minimum difference between perceived *hardness* and instrumental hardness for which the range of hardness deviation from 1.34% to 30.51%. 35% of participants' hardness deviation is 30.51% to 59.68%, which was defined as the normal group (Group 2). The panellists whose hardness deviation are larger than 59.68% formed Group 3. Table 5.7 presents the summary of masticatory conditions in the three groups as analysed by objective tests (instrumental bite force test) and subjective tests (sensory tests and self-assessed questionnaires). The highest pre-rank accuracy, the lowest QMFQ score and self-rating score were found in Group 2. The strongest mean MBF was found in Group 2, which was significantly different to the MBF from Group 1 ($p < 0.05$). The proportion of gender in Group 3 was different from the other two groups, which had more female participants than males.

Table 5.7 Panellist characteristics according to age, gender and average of results (hardness deviation, MBF, rank accuracy, QMFQ, and comfortable self-rating score).

Group	*n*	Gender (F/M)	Hardness Deviation	MBF	Pre-rank Accuracy	Post-rank Accuracy	QMFQ	Self-rating
			Mean (SD)	Mean (SD)	Mean (SD)	Mean (SD)	Mean (SD)	Mean (SD)
1	12	5/7	12.34 (8.42)	298.70 (84.29)	52.75 (19.22)	59.75 (23.20)	82.12 (8.77)	78.75 (21.86)
2	14	7/7	44.63 (9.00)	392.90 (114.53)	71.43 (27.13)	76.36 (19.59)	76.14 (11.63)	61.56 (20.85)
3	14	10/4	88.62 (27.78)	350.02 (99.86)	64.36 (22.70)	81.07 (20.71)	82.12 (6.78)	71.41 (14.12)

5.3.5.1 Correlations on group basis

Group 1

Table 5.8 shows Spearman's correlation analysis between the measurements from sensory tests, self-assessed questionnaires and instrumental bite force test for Group 1. In this group, MBF was significantly related to hardness deviation, post-rank accuracy and QMFQ score, respectively. Hardness deviation has a strong positive correlation with MBF ($r = 0.622$, $p < 0.05$), which suggests that as maximum bite force increases, participants are not as accurate at rating hardness when compared to instrumental hardness. When the average MBF of Group 1 (298.70 N) is set as the threshold value, there is a significant difference of hardness deviation between two sub-groups of participants that MBF above 300 N or below 300 N by t-test ($p < 0.05$). The range of hardness deviation is between 1.34% and 9.63% when participants' MBF are below 300 N. The young adult whose hardness deviation is below 10% most likely corresponds to a maximum comfortable bite force below 300 N. For hardness deviation between 10% and 30%, the maximum comfortable bite force is most likely above 300 N. Moreover, MBF had a strong negative relationship with post-rank accuracy and QMFQ. The increased MBF with decreased QMFQ and ranking accuracy can assume that people with a stronger bite force (≥ 300 N) may be less perception to small variations in hardness. The self-assessed questionnaire results showed a positive correlation between QMFQ and the comfortable hardest textural self-rating score. The better condition of oral health with the higher QMFQ and harder comfortable texture related to daily consuming foods, which can suggest that oral health significantly influences individuals' masticatory function and hardness-related dietary foods. A deteriorated oral health including tooth loss, malocclusion and periodontal disease is the main cause of deficiencies in masticatory function was found [214]. Furthermore, decreased masticatory performance causes individuals to consume mainly soft and easy-to-chew food. This particular diet tendency may induce marginal nutrition intakes and poor dietary [217, 219].

Table 5.8 the subjective and objective tests in Group 1 (Hardness deviation: 1.34%- 30.51%).

Group 1		Hardness Deviation	MBF	Pre-rank accuracy	Post-rank accuracy	QMFQ	Self-rating
		Coefficient (p-value)	Coefficient (p-value)	Coefficient (p-value)	Coefficient (p-value)	Coefficient (p-value)	Coefficient (p-value)
	Hardness Deviation	/	0.622* (0.015)	0.292 (0.178)	-0.059 (0.427)	-0.326 (0.150)	-0.207 (0.259)
	MBF	0.622* (0.015)	/	0.157 (0.313)	-0.604* (0.019)	-0.533* (0.037)	-0.121 (0.354)
	Pre-rank Accuracy	0.292 (0.178)	0.157 (0.313)	/	0.511* (0.045)	-0.236 (0.230)	0.061 (0.425)
	Post-rank Accuracy	-0.059 (0.427)	-0.604* (0.019)	0.511* (0.045)	/	0.041 (0.450)	-0.200 (0.266)
	QMFQ	-0.326 (0.150)	-0.533* (0.037)	-0.236 (0.230)	0.041 (0.450)	/	0.506* (0.047)
	Self-rating	-0.207 (0.259)	-0.121 (0.354)	0.061 (0.425)	-0.200 (0.266)	0.506* (0.047)	/

*. Correlation is significant at the 0.05 level (1-tailed) and (2-tailed).

**. Correlation is significant at the 0.01 level (1-tailed) and (2-tailed).

Group 2

Table 5.9 showed that there was a correlation between MBF and post-rank accuracy, pre-rank accuracy and post-rank accuracy, and QMFQ and self-rating score for Group 2. However, there is no significant relationship between hardness deviation and MBF in this group. Compared to Group 1, the comfortable hardest texture rating score has a relationship with QMFQ and both rounds of rank accuracy. Similar to Group 1, a significant negative relationship is observed between MBF and ranking accuracy for Group 2. Because of the negative relationship between MBF and post-rank accuracy, the highly sensitive to hardness participants with a 100% post-rank accuracy mostly correspond to a normal MBF (300 N to 420 N).

Table 5.9 Spearman's correlation coefficient (*r*) between subjective and objective tests in Group 2 (Hardness deviation: 30.51%- 59.68%).

Group 2		Hardness Deviation	MBF	Pre-rank accuracy	Post-rank accuracy	QMFQ	Self-rating
		Coefficient (*p*-value)	Coefficient (*p*-value)	Coefficient (*p*-value)	Coefficient (*p*-value)	Coefficient (*p*-value)	Coefficient (*p*-value)
	Hardness Deviation	/	0.037 (0.450)	0.502* (0.034)	0.225 (0.219)	0.172 (0.279)	0.405 (0.075)
	MBF	0.037 (0.450)	/	-0.217 (0.228)	-0.488* (0.038)	0.478* (0.042)	0.011 (0.485)
	Pre-rank Accuracy	0.502* (0.034)	-0.217 (0.228)	/	0.815** (0.000)	0.041 (0.445)	0.465* (0.047)
	Post-rank Accuracy	0.225 (0.219)	-0.488* (0.038)	0.815** (0.000)	/	0.0093 (0.376)	0.481* (0.041)
	QMFQ	0.172 (0.279)	0.478* (0.042)	0.041 (0.445)	0.0093 (0.376)	/	0.506* (0.033)
	Self-rating	0.405 (0.075)	0.011 (0.485)	0.465* (0.047)	0.481* (0.041)	0.506* (0.033)	/

*. Correlation is significant at the 0.05 level (1-tailed).

**. Correlation is significant at the 0.01 level (1-tailed).

Group 3

Group 3 of which hardness deviation is the largest, but MBF has no significant relationship with other evaluated factors (Table 5.10). However, hardness deviation and QMFQ has a strong negative correlation. ($p < 0.05$). As hardness deviation increases, QMFQ (the ability of masticatory function) decreases. It can assume that people with less perception to small variations in hardness relate to a low level of masticatory function. The relationships of Pre-rank accuracy/post-rank accuracy and QMFQ/self-rating score were found in Group 3.

Table 5.10 Spearman's correlation coefficient (*r*) between subjective and objective tests in Group 3 (Hardness deviation: > 59.68%).

Group 3		Hardness Deviation	MBF	Pre-rank accuracy	Post-rank accuracy	QMFQ	Self-rating
		Coefficient (*p*-value)	Coefficient (*p*-value)	Coefficient (*p*-value)	Coefficient (*p*-value)	Coefficient (*p*-value)	Coefficient (*p*-value)
	Hardness Deviation	/	0.130 (0.329)	0.014 (0.481)	0.029 (0.460)	-0.543* (0.022)	-0.288 (0.159)
	MBF	0.130 (0.329)	/	0.018 (0.475)	0.285 (0.162)	0.327 (0.127)	0.090 (0.380)
	Pre-rank Accuracy	0.014 (0.481)	0.018 (0.475)	/	0.503* (0.033)	0.280 (0.160)	0.062 (0.416)
	Post-rank Accuracy	0.029 (0.460)	0.285 (0.162)	0.503 (0.033)	/	0.167 (0.284)	-0.133 (0.326)
	QMFQ	-0.543* (0.022)	0.327 (0.127)	0.280 (0.160)	0.167 (0.568)	/	0.512* (0.031)
	Self-rating	-0.288 (0.159)	0.090 (0.380)	0.062 (0.416)	-0.133 (0.651)	0.512* (0.031)	/

*. Correlation is significant at the 0.05 level (1-tailed).

**. Correlation is significant at the 0.01 level (1-tailed).

Since hardness deviation has been analysed and considered as a means for differentiating groups, we find that participants whose hardness deviation is below 31% have a strong, positive relationship with MBF. It can infer that participants with a lower bite force are more sensitive to hardness. In addition, this suggests that a small difference between the subjective rating score and objective hardness is the critical requirement for establishing the relationship between texture perception and MBF by a series of model foods.

5.3.5.2 Correlations across entire dataset

Across all participants, the relationship between subjective texture perception and objective maximum bite force is not significant (Table 5.11). The similarity of no correlation between objective masticatory function and self-assessed chewing ability was found [415 - 417]. The different texture perception does not relate to the level of MBF due to the individual mostly like to have a normal/good masticatory function (average QMFQ> 80%) prevalent in age between 20-30 yr. We can infer that differences in *hardness* perception no tend to correlate to MBF for young healthy adults, who are not expected to have impaired masticatory function.

Table 5.11 Spearman's correlation coefficient (*r*) between subjective and objective tests across entire dataset.

Participant (n = 40)		Hardness Deviation	MBF	Pre-rank accuracy	Post-rank accuracy	QMFQ	Self-rating
		Coefficient (p-value)	Coefficient (p-value)	Coefficient (p-value)	Coefficient (p-value)	Coefficient (p-value)	Coefficient (p-value)
	Hardness Deviation	/	0.225 (0.081)	0.275* (0.043)	0.376** (0.008)	-0.054 (0.371)	-0.106 (0.257)
	MBF	0.225 (0.081)	/	0.075 (0.323)	-0.093 (0.283)	0.017 (0.457)	-0.162 (0.159)
	Pre-rank Accuracy	0.275* (0.043)	0.075 (0.323)	/	0.646** (<0.01)	-0.021 (0.450)	0.007 (0.482)
	Post-rank Accuracy	0.376** (0.008)	-0.093 (0.283)	0.646** (<0.01)	/	0.009 (0.478)	-0.089 (0.292)
	QMFQ	-0.054 (0.371)	0.017 (0.457)	-0.021 (0.450)	0.009 (0.478)	/	0.578** (<0.01)
	Self-rating	-0.106 (0.257)	-0.162 (0.159)	0.007 (0.482)	-0.089 (0.292)	0.578** (<0.01)	/

*. Correlation is significant at the 0.05 level (1-tailed).

**. Correlation is significant at the 0.01 level (1-tailed).

5.4 Conclusions

A series of gel-based model food with different mechanical properties was established by optimising the shape, size, gel type, and gelatine concentration. The final set of model foods met three critical requirements:

1. The range of hardness level of the main set of gel-based model foods was spread across medium to hard texture. The softest sample was softer than milk candy, and the hardest one was comparable to hard fruit candy.
2. The difference between each model food sample's hardness was confirmed by modified TPA test (objective measurement) and JND test (subjective measurement). The correlation between TPA-measured hardness and subjective

hardness score is strong and positive, successfully building the relationship between mechanical properties and texture perception.

3. Some of the model food samples caused difficulty in biting, as designed by thicker dimensions of sample size, more plastic deformation behaviour and harder texture. The uncomfortable feeling caused by biting difficulty may link the texture perception to maximum comfortable bite force.

In the MBF test, the maximum bite force of 40 participants was tested by instrumental measurement. For young adults between 20 – 30 years of age, the strongest MBF is 607.5 N, the weakest one is 146.5 N, and the average MBF is 439.6 ± 109.3 N. There is no significant difference in MBF between the male and female groups. 75% of participants' MBF is among the range from 200 N to 450 N. In the sensory test, a strong positive correlation was found between subjective *hardness* rating score and objective TPA-measured hardness in the six gelatin samples. The accuracy of the post-rank test improving significantly compared to the pre-rank test proves that it is necessary to arrange a trial test to help participants familiarise themselves with the model foods and collect more accurate and reliable results from the sensory test. In the JND test, it was found that a low proportion of panellists (< 30%) can discriminate small differences of hardness, proving that there is no need to add more hardness levels of samples into the main set of model foods for the large population sensory tests. In general, the correlation between subjective *hardness* perception and objective maximum bite force is not significant. However, by converting the *hardness* rating score to the hardness deviation, we find that participants whose hardness deviation is below 10% had a strong and positive relationship with MBF.

This chapter found that for healthy individuals in their 20s who have a normal/good masticatory function, *hardness* perception does not necessarily relate to MBF by this new measurement method using gel-based samples. The key finding for young, healthy adults can be summarised as below:

1. the *hardness* rating scores and objective hardness of gel-based model foods have a significant, positive correlation;

2. the post-rank accuracy is above 67% for the six samples;

3. self-assessed QMFQ score is above 67.7%;

4. no missing natural teeth (excluding the third molars) were noted in this group.

These findings are relevant for comparison across different age groups in the large population study (Chapter 6).

Chapter 6 Texture Perception and Bite Force across the Lifespan

In this chapter, I explore how the relationship between objective masticatory function by maximum comfortable bite force and subjective masticatory function by questionnaire vary across the lifespan. I attempt to find the potential relationship between masticatory function and ageing by linking maximum comfortable bite force to hardness texture. The study applied this new measurement to a large panel comprising 317 participants from six different age groups living in Auckland (20-30 yr, 31-40 yr, 41-50 yr, 51-60yr, 61-70 yr and above 70yr). The chapter contains two parts. In the first part, the subjective texture perceptions of gel-based foods with different hardness levels have been assessed by sensory tests, which links texture perception to maximum comfortable bite force. In the second part, a questionnaire survey for evaluating masticatory ability is discussed. The questionnaire consists of a self-assessed oral status questionnaire and a quality of masticatory function questionnaire (QMFQ). Variables of masticatory function were collected for each panellist and analysed by the new measurement in order to establish an assessment profile of a healthy individual's masticatory function.

This chapter has some repetition in the "Introduction", "Methods and Materials" and "Gel-model foods link to Texture Perception and Bite Force in Health Adults" sections to ensure it can be read as an individual paper.

6.1 Introduction

Mastication is an essential function in human daily intake of food, and is highly correlated with nutritional ingestion and food selection [28, 29, 368, 369], so there are numerous studies [3 – 5] which evaluate masticatory function according to two aspects: masticatory performance and masticatory ability. Various measurements evaluate masticatory performance as an objective function, including chewing efficiency, jaw activity, bite force, particle size and saliva flow. On the other hand, masticatory ability has been self-assessed as a subjective function using questionnaires and interviews, including questions on chewing habits, oral status and chewing difficulties [15, 20, 38, 39]. The objective evaluation is direct, reliable and accurate through the use of technical equipment. The subjective assessment reflects functional bite force through the eyes of the chewer and can collect information on the influence of oral health (e.g. condition of teeth and chewing difficulties) [237], which the conventional measurement of bite force generally disregards.

Self-assessed masticatory ability relates to oral status, dental health, general health, and other personal factors including psychological, physiological, economic, social and cultural aspects. In this way, subjective masticatory function is analysed by self-assessment through questionnaires and interviews about an individual's health status, chewing habits and basic personal profiles [15, 16, 18 - 21]. Subjective measurements are widely applied in epidemiological research and are more crucial for the individual's food selections. The quality of the masticatory function questionnaire (QMFQ) has been established and applied to investigate subjective masticatory function within various cultural contexts, a large population and different countries [408]. Since many studies of objective masticatory function [4, 72, 73] showed that masticatory ability is overly optimistic, different measures of masticatory performance have been developed to evaluate mastication efficiency, jaw muscle activity, salivary flowrate and neuromuscular activity. Maximum bite force is one of the critical determinants of masticatory function that has been studied with instrumental measurements (MBF). The correlation coefficients of maximum bite force and masticatory function are as high as 0.8 [16, 130], which means that the maximum bite force can explain more than 80% of the variance in masticatory performance. However, the relationship between masticatory performance and masticatory ability has not been previously proven [3, 5].

Age may be a source of gradual reduction in masticatory function across the lifespan, but ageing itself rarely has an impact on self-perceived mastication [18, 169, 265, 418]. Healthy, elderly subjects are still satisfied with their masticatory function despite a deterioration in oral health, which can be explained by their adaption of chewing to compensate for functional losses. Some researchers [5, 265 – 267] have claimed that the older adults who have healthy oral status can extend the duration of chewing and increase the number of chewing cycles to reach the required particle size that forms a food bolus ready for swallowing. Ageing comes with reduction of other physical and psychological functions, including an increased number of missing teeth, periodontal disease, degenerated muscle strength and decreased motor skills, all of which lead to a decline of masticatory function in elderly individuals [1, 23 - 26, 177]. In most countries, individuals aged over 75 were found to be very likely to retain less than 20 of their natural teeth [246]. Partial denture wearers cannot completely recover their lost masticatory function when compared to their counterparts who have retained than 20 of their natural teeth [244]. Decreased chemical sensitivity with ageing causes a reduction in sensory acuity, which leads to a loss of taste rather than smell [340]. Such losses unavoidably result in less satisfaction derived from eating [341], changes in the perception and preference of sensations and eventually have a detrimental effect on food intake and appetite [340]. Many studies have proven that when individuals alter their food choice to easier-to-chew and softer foods, this leads to a lack of essential nutrients like fibre and iron [228, 419]. The reduction and dysfunction of masticatory performance can affect the quality of life who prefer hard textures [420].

Except for individual preference and the noxious possibility of food, hardness is one of the most crucial food characteristics that can influence the eating process. Hardness/toughness can be defined by the universal measurement of peak force, but also depends on Young's modulus [421]. Detailed results of the relationship between hardness and masticatory function have mostly focused on artificial, model foods. With increasing hardness, an increasing trend in chewing duration (time), number of chewing cycles, and bite force were found in many research studies using different types of artificial foods: gelatin-based [156, 161], gullan gum [162], tablets with $CaCO_3$ and cellulose [163], and hydrocolloid gels [164]. Foster *et al.* (2006) [156] explained that artificial model foods are pure and valuable stimuli for chewing studies, and allow you to manipulate one textural attribute at a time. In addition, they found the difference between elastic and plastic model foods of similar hardness is the frequency of vertical and lateral movements during chewing, by which the elastic food needs higher frequency chewing. However, both artificial and natural food measurements require the subjects to chew through samples, which reflect their true and comfortable masticatory function. Furthermore, the hardness of artificial foods in many recent studies cannot cover the entire range of an individual's bite force.

This chapter aims to investigate the correlation between masticatory ability and performance across the lifespan for the NZ population in Auckland using the new method described in Chapter 5, which evaluates masticatory function by linking subjective texture perception with objective bite force through a series of gel-based model foods. The self-assessed questionnaire used alongside included QMFQ and oral health status to assess dominant factors of masticatory function, including oral health, gender, age, habits, texture preference, and self-assessed quality of masticatory function. Using the new measurement technique, this chapter evaluated the maximum comfortable bite force and explored the turning point of masticatory function with increasing age.

6.2 Methods and Materials

6.2.1 Participants

A panel of approximately 300 participants, aged over 20 years old, were recruited through digital and printed posters advertised in communities across Auckland. Participants were divided into six groups according to age: 20-30 years; 31-40 years; 41-50 years; 51-60 years; 61-70 years and above 71 years. Each group was expected to contain 25 females and 25 males. All participants met the criteria to participate, including being of good health, having more than 12 functional units of natural teeth (relaxed for the elderly subjects), no smoking and no allergies to food ingredients. This project was reviewed and approved by the University of Auckland Human Ethics Committee (Reference Number: 023536).

6.2.2 Model foods

Different concentrations of gelatin-based model foods (M1: 45%, M2: 50%, M3: 55%, M4: 60%, M5: 65%, M6: 70%, w/w) in cube shape were made (for the detailed protocol of the test, refer to Section 4.2.2.3). Each set of gel-based model foods contained six samples of different hardness levels, and were packaged in preparation for sensory assessments.

6.2.3 Sensory assessments

The established set of gel-based model foods was applied in sensory assessments linking *hardness* perception to maximum comfortable bite force. The sensory assessment of maximum comfortable bite force consists of two major domains: Rate test and Rank test. To evaluate individual masticatory function by assessing maximum comfortable bite force, we link the *hardness* perception of six gel-based model foods to mechanical property-hardness. The participants from six age groups were recruited to complete the sensory assessment and also to fill the questionnaires described in Section 6.3.1. For a detailed breakdown of the participants, refer to Section 6.3.1.1.

Rank&Rate test was used to quantify the maximum comfortable bite force of each participant. The rank part of the test required a participant to rank the set of gel-based food samples in order of increasing hardness. The rate part required the participant to score the *hardness* intensity of the gel-based foods on a line scale. During the rank test, participants were presented with the set of model foods in random order and were asked to bite the sample once. Samples were identified with a three-digit code to hide any information indicative of their hardness. After one bite, they expectorated the sample into a transparent container. During and after biting, participants were required to rank the six samples in order of increasing *hardness*. Then the participants were invited to rate the samples via a second set of the same samples, once again presented in randomized order. They were required to bite each sample once. During and after biting, they were required to rate the samples' *hardness* by making a mark for each sample on a 10 cm line scale (0 = Soft / 10 = Hard). The participants could refuse to bite a sample anytime they felt uncomfortable about the hardness being too great. They could also ask for additional samples if they required help with their ranking and rating. We expect correct ranking (rank test) and *hardness* score (rate test) to be indicative of bite force, and thus potential parameters for evaluation (for the detailed protocol of the test, refer to Section 4.3.3.1).

To link *hardness* perception from the sensory test (rate test) to hardness texture from instrumental measurement (compression test), a biting difficulty score was created and applied to all six model foods using the equation below:

$$\text{Biting difficulty score of } M_x = \frac{\text{Rating } \textit{hardness} \text{ score of Mx} - \text{Instrumental hardness score of Mx}}{\text{Instrumental hardness score of M}x} \times 100\%$$

where x = 1, 2, 3, 4, 5 and 6

* Instrumental hardness (%) has been normalised by hardness (N): The softest hardness 0 N equal to 0% instrumental hardness; the hardest hardness 100 N (maximum hardness from TPA) equal to 100%.

A higher biting difficulty score represents that the participant rated the sample as more uncomfortable and higher perceived *hardness*, since the rating *hardness* score was a higher intensity when compared to instrumental hardness score for the same sample. Based on each sample's maximum and minimum biting difficulty scores, the difficulty of biting the sample was classified into five levels by evenly dividing the gap between maximum and minimum score into five segments.

6.2.4 Maximum bite force instrumental measurement

Thirty participants aged above 70-year-old were tested for maximum bite force, measured by the ELF system with the B201-H sensor (Tekscan Inc., Boston, USA). The instrumental measurement of maximum bite force of healthy adults is then used to prove the validity of the sensory assessment of maximum comfortable bite force with the series of gel-based model food. The participants were seated with their heads upright and in an unsupported, natural head position. The B201 sensor was carefully placed into the participant's mouth between the molars on the right side. The participant was required to clench their teeth in the intercuspal position (maximum occlusion of posterior teeth) with maximum force and hold for 3 seconds. The procedures were then repeated on the left side molars. The results were collected and analysed by the ELF system. Maximum bite force of participants were measured with 3 replicates for each side, right and left. The maximum bite force of the elderly participants by instrumental measurement can also be compared with the young adults' MBF from Chapter 5. It can be used to explore the relationship between the objective and subjective masticatory function with ageing. For the detailed protocol of maximum bite force instrumental measurement, refer to Section 4.3.4.2.

6.2.5 Self-assessed questionnaire measurements

After the sensory assessments (and instrumental bite force test), the participants were required to answer a questionnaire on masticatory function. The self-assessed questionnaire estimates masticatory function across two parts. The first part covers ten general questions of self-reporting oral health, including basic information (age, gender, condition of teeth), *texture* level preference, and the *hardest* level of texture the participant is willing to bite on a 10 cm line scale. There were five categories for number of teeth loss: retained full set of natural teeth; lost 1-2 teeth; lost 3-4 teeth; lost 5-6 teeth and lost more than 6 teeth. For condition of teeth, seven types were classified according to the condition of wearing dentures: retained full set of natural teeth; missing 1-2 teeth without replacement; missing several teeth without wearing a denture; wearing a fixed partial denture; wearing a removable partial denture; having an implant-supported prosthesis; and wearing a complete denture. The frequency of toothache was described as four levels: Level 0 (never have toothache experience), Level 1 (had toothache experience more than one year ago), Level 2 (had a toothache during last year) and Level 3 (had a toothache in last three months). The participant who never experiences toothache (level 0) represents a healthy oral status. With the frequency of toothache experienced increasing from Level 1 to 3, the participant may have more risk of oral health problems. Three levels of *texture* preference were presented, including *soft*, *medium* and *hard*. The hardest level the participant was willing to bite was assessed on a 10 cm line scale (0 = Soft / 10 = Hard). The participants were required to rate their bite force on a 5-point scale: '5 = excellent', '4 = very good', '3= good', '2= fair', or '1= poor'.

The second part is specific questions on the quality of masticatory function in order to quantify subjective masticatory function. The quality of the masticatory function questionnaire consists of 19 questions, which specifically relate to the difficulty of masticating different types of real foods with a hard texture. The results can evaluate subjective masticatory function across six domains:

- Mastication habits
- Meats (cooked beef)

- Raw foods (vegetable and fruit)
- Dried food (crusted bread, nuts and grains)
- Wearing dentures (dental implants, partial and complete dentures)
- Chewing influences (chewing habits affected by masticatory difficulties)

These domains have 5 Likert-responses options scored as 0 = never, 1= usually not, 2= occasionally, 3= usually, 4= always. Each dimension's score was between 0 and 4, so that the range of the overall score (six dimensions) was from 0 to 24. (The questionnaires are provided in Appendix. C for reference.)

6.2.6 Data analysis

6.2.6.1 Sensory tests data analysis

All the ranking data were converted into an accurate rank percentage (%) by dividing the number of correctly ranked samples by the total number of samples. 100% means all of the ranking results are correct, 67% means 4 out of 6 ranking results are correct, 50% means half of the ranking results are correct, 33% means 2 out of 6 ranking results are correct, 17% means 1 out of 6 ranking result is correct, and 0% represents that all of the ranking results are incorrect.

All the marks of rate tests with the line scales were converted into a score using the length (mm) measured from the left endpoint of the scale. The intensity of rank (maximum comfortable bite force, %) was calculated by dividing the length of the participant's mark by total length of the line scale (100 mm).

6.2.6.2 Instrumental maximum bite force data analysis

The outputted data of maximum bite force recorded by the ELF (Tekscan Inc, Boston, USA) were time (s) and force (N).

6.2.6.3 Self-assessment questionnaire analysis

The data of QMFQ, which is 5 Likert-response options (from "always" to "never"), were converted into a percentage score (%). All marks of "what is the *hardest* food texture you think you are willing to eat" in the self-reported masticatory status questionnaire (VAS, 10 cm) were converted into the length (cm) from the left endpoint scale. The lengths were used as a measure of intensity, such that 0 = least *hard* and 10 = most *hard*.

Data analysis was conducted using SPSS version 27.0 (IBM Corporation, USA) at a significance level of $p < 0.05$ (One-way ANOVA). The descriptive statistics include mean, median, first quartile (25%), third quartile (75%), proportions/percentages, and standard deviation. Bivariate correlation was used to investigate possible correlations between independent variables, including Pearson correlation and Spearman correlation. Regression was used to explore possible relationships between dependent variables (e.g. rank accuracy, %) and independent variables (e.g. age), including linear, cubic, quadratic correlations. Multiple linear regression was used to explain that several independent variables (e.g. age and magnitude of bite force) can predict the outcome of a dependent variable (e.g. QMFQ). Blank or alternative responses were collected from the questionnaires as missing data, and removed from the average results.

6.3 Results and Discussion

Given that significant volumes of data was collected in this study, the analysis used to establish a new method for evaluating masticatory function is outlined in a flowchart (Figure 6.1). The method consists of two dimensions: questionnaires and sensory tests. The questionnaire included the self-assessed masticatory status and the quality of masticatory function. The series of gel-based model foods were applied in the sensory tests (Rank and Rate test). In addition, a conventional measurement of masticatory function tested the maximum bite force in the youngest and oldest age groups to validate the difference of masticatory function with advancing age via objective measurements.

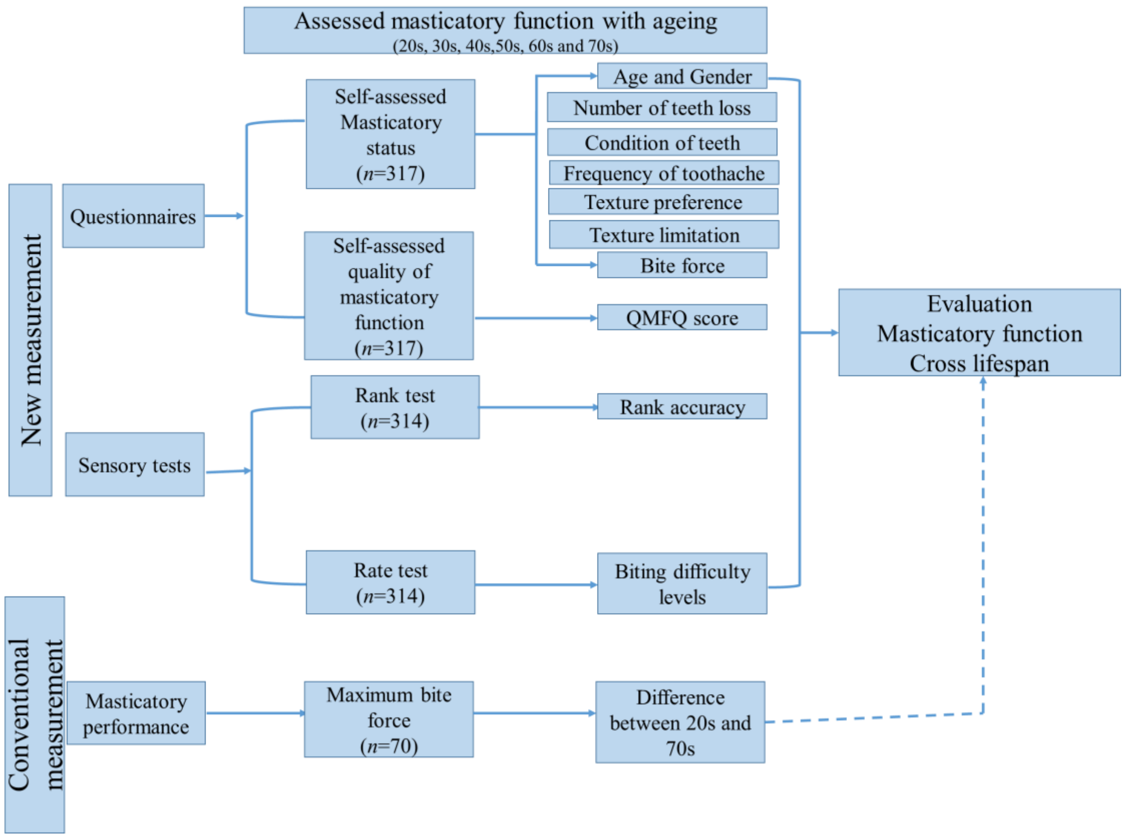


Figure 6.1 Flow diagram for processing of large population study data.

6.3.1 Link between Self-assessed masticatory status questionnaire and Texture perception

The self-assessed masticatory status questionnaire comprises six domains encompassing an individual's oral health and texture perception:

1. Personal information including age and gender;
2. The number of natural teeth lost;
3. The condition of teeth depends on the natural vs replacement teeth status;
4. The frequency of oral pain experience (toothache);
5. Preference and limitation in terms of texture (*hardness*);
6. Self-rated maximum level of bite force (i.e. *hardest* texture willing to bite).

6.3.1.1 Age and gender

Based on the questionnaire, of the 317 participants, 302 (95%) self-reported their bite force as excellent to fair, while 16 (5%) self-reported their bite force as poor. Seventy percent (*n*= 221) of the participants did not wear a denture. Thirty percent (*n*=96) of participants wore dentures, including implant-supported prosthesis, partial dentures (fixed/removable) and complete dentures. The weighting of gender in each age group is as displayed in Table 6.1. Age group sizes were not significantly different (p= 0.414). However, there was a higher proportion of females than males across all groups (p< 0.05). The average gender ratio (1.38, female/male) is slightly higher than the 2018 national census in New Zealand, which reported that the sex ratio is 1 to 1.16 with age increasing from 15 to over 65 years old. The higher proportion of females may be caused by the life expectancy of females (74.2 years) being 4.4 years longer than that of which males (69.8 years) on average at a global scale (U.D, 2019). So the gender ratio (female/male) does naturally tend to increase with age. Although the number of males is less than females for each age group, there is no significant difference in the number of each gender between different age groups (p= 0.801).

Table 6.1 The proportion of each age group in 317 participants and the gender proportion in six age groups.

Groups	Age	Number (%) of participants	Number (%) of female	Number (%) of male
20s	20-30	17 (*n*=53)	57 (*n*=30)	43 (*n*=23)
30s	31-40	17 (*n*=54)	55 (*n*=30)	45 (*n*=24)
40s	41-50	16 (*n*=51)	57 (*n*=29)	43 (*n*=22)
50s	51-60	17 (*n*=53)	66 (*n*=35)	34 (*n*=18)
60s	61-70	17 (*n*=54)	57 (*n*=31)	43 (*n*=23)
70s	≥71	16 (*n*=52)	56 (*n*=29)	44 (*n*=23)
Average	/	16.7±0.3 (*n*=52±1)	58±4 (*n*=31±2)	42±4 (*n*=22±2)

6.3.1.2 Number of teeth loss

From the self-reported results of 317 participants, 148 (47%) participants who had a full set of their natural teeth comprised the most significant proportion, while losing 5-6 teeth was the most minor proportion of participants at only 5%. The proportion of participants who had lost 1-2 and 3-4 teeth accounted for 24% and 14%, respectively. 33 (10%) participants lost over six natural teeth, which was the maximum number of teeth lost in this study. Figure 6.2 shows the proportion of five different levels of teeth loss across the six age groups. The majority of the youngest participants kept their full set of natural teeth, which is the largest proportion of the participants in this category across the six age groups. Compared to the proportion of 20s who lost 1-2 teeth, the proportion of 30s in this category rapidly increased. This increasing trend of losing 1-2 teeth was found in the age range between the 20s and 40s. The probability of losing 3-4 teeth in the 40s group was four times as great as in the 30s group, whilst the trend generally increased from the 30s to 50s age group. Many research studies found that masticatory ability is strongly related to the number of teeth [227, 228]. Based on increasing trends of the proportions of participants losing 1-2 teeth and losing 3-4 teeth with increased age, we can infer that masticatory ability of individuals in their 20s is better than other age groups. Participants who lost 5-6 teeth was sporadically found between 41 to 70 years old, and the proportion of the 70s group's participants who lost this number of teeth is the highest across the six age groups. The participants who lost the most teeth (>6 teeth) were first found between 41 and 50 yrs. With age increasing to over 71 years old, the proportion of the 70s group's participants who lost more than six teeth is the most significant. Previous research has reported that older adults who have lost more than eight teeth have a higher probability of eating difficulties [243]. As Figure 6.2 shows, the 51-60 years old may be a turning point of decreased masticatory function because six teeth loss was first discovered in the 50s age group. With advanced age over 71 years old, individuals are most likely to suffer from deterioration of masticatory function, given that a large proportion (> 35%) of the 70s group lost more than six teeth.

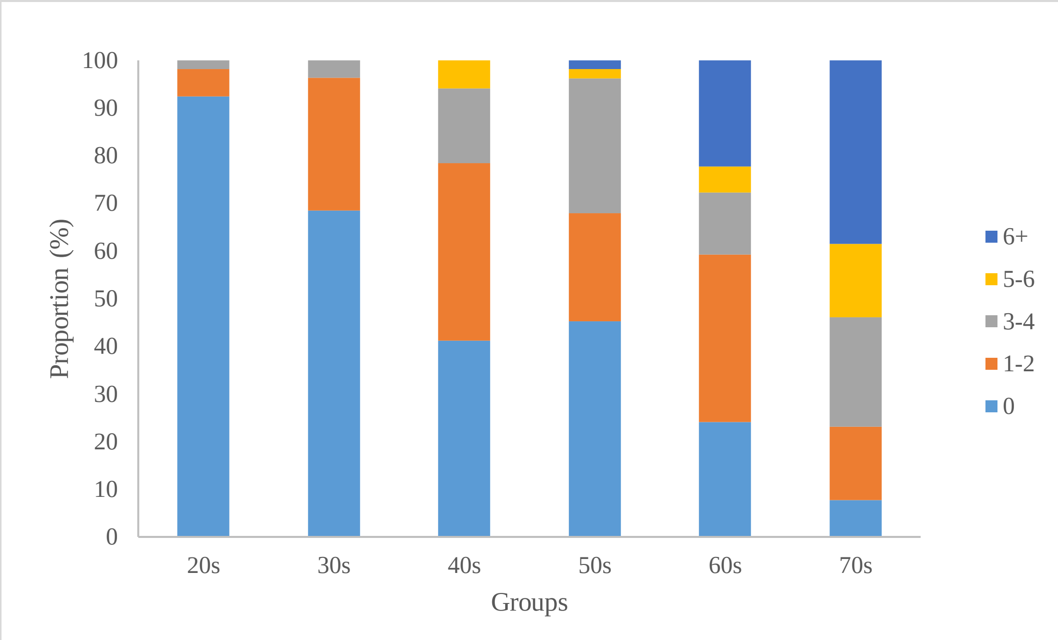


Figure 6.2 Proportion of five different number of teeth loss across the six age groups.

An analysis of teeth loss by gender shows males are more likely to have tooth loss across all the age groups (Figure 6.3). A study with similar results found that gender is significantly correlated to the prevalence of edentulism, where that of males is higher than females [422]. It can indicate that gender is not a significant factor influencing the reduction of masticatory function, rather it is the number of teeth loss which differs between males and females.

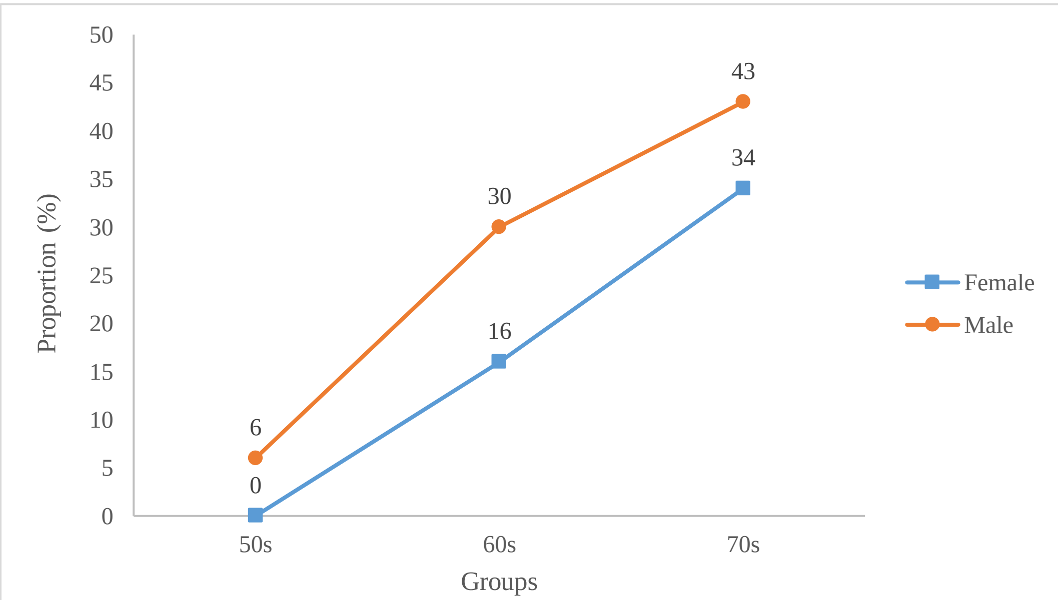


Figure 6.3 Proportion of female and male participants who lose over six teeth in 50s, 60s and 70s groups.

6.3.1.3 Condition of teeth

The condition of teeth included only natural teeth compared against replacing lost natural teeth with certain types of dentures. As Figure 6.4 shows, the number of participants keeping only natural teeth decreased significantly with age (R^2= 0.94). Meanwhile, there was a strong positive correlation between age and the number of participants who replaced natural teeth with different types of dentures (R^2= 0.94). As the trendlines show on Figure 6.4, the proportion of participants (≤70 yrs) wearing dentures were below 40%. However, the condition of teeth in the eldest group dramatic shifted so that the proportion of participants wearing dentures increased to approximately 70% for individuals in their 70s. It can infer that the 70s age group is a crucial turning point in terms of condition of teeth.

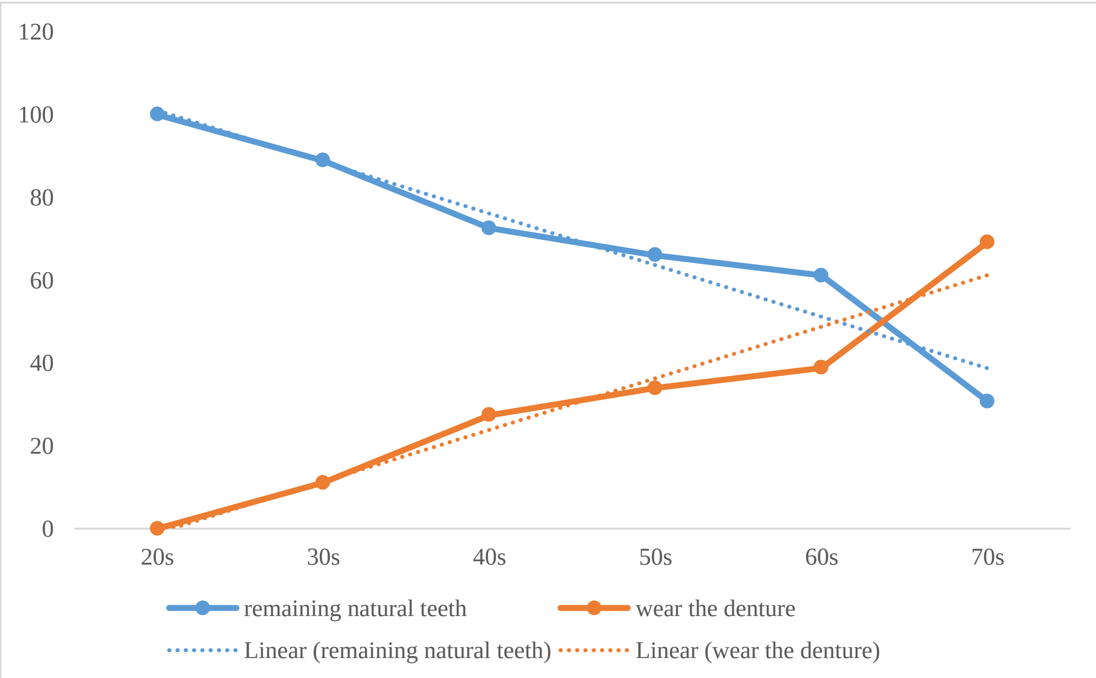


Figure 6.4 Trends of two main conditions of teeth among different age groups. Blue: the proportion of participants remaining natural teeth without any type of replacement. Orange: the proportion of participants wearing different types of dentures.

To further explore different conditions of teeth with ageing, Figure 6.5 demonstrates the proportion of seven conditions of teeth among the six age groups. Seven different conditions of teeth can be classified based on number of natural teeth and replacement status, comprising three conditions when classified by the number of natural teeth remaining for participants without dentures (no tooth loss, 1-2 teeth loss and several teeth loss) as compared to four conditions when classified by types of dentures for participants who wear dentures (implanted prosthesis, partial denture and complete denture). The proportions of participant wearing implanted prosthesis and a fixed partial denture between 50s and 60s are significantly different. In the 50s group, more participants have an implanted prosthesis rather than wear fixed dentures, which is opposite in the 60s group. For the proportion of complete denture wearers, only 2% of participants were reported until 51 years of age. This proportion does not increase with ageing from 51yrs to 70yrs. However, the proportion rapidly increases to approximately 20% in the 70s groups whose age is above 71yrs. Individuals who wear complete dentures may be a red flag if age is below 71yrs, reflecting an unusual condition of teeth.

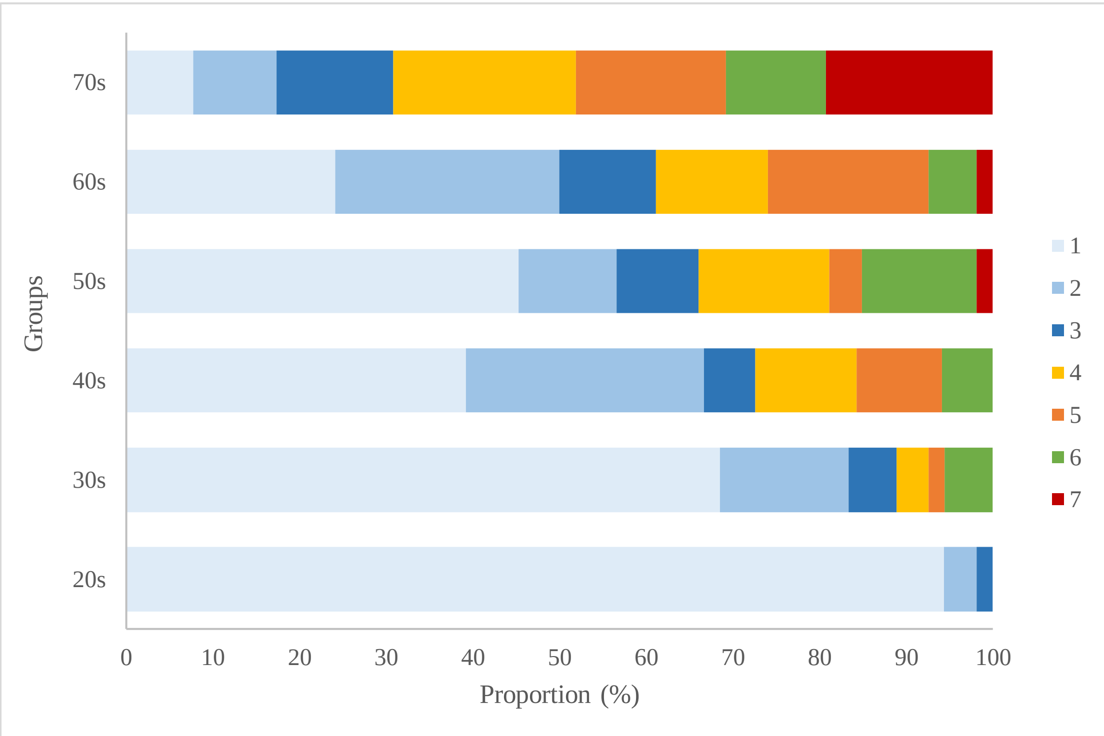


Figure 6.5 the proportion of seven conditions of teeth among different age groups. 1: remaining full of nature teeth; 2: missing 1-2 teeth without replacement; 3: missing several teeth without wearing a denture; 4: wearing a fixed partial denture; 5: wearing a removable partial denture; 6: having the implant-supported prosthesis; 7: wearing a complete denture.

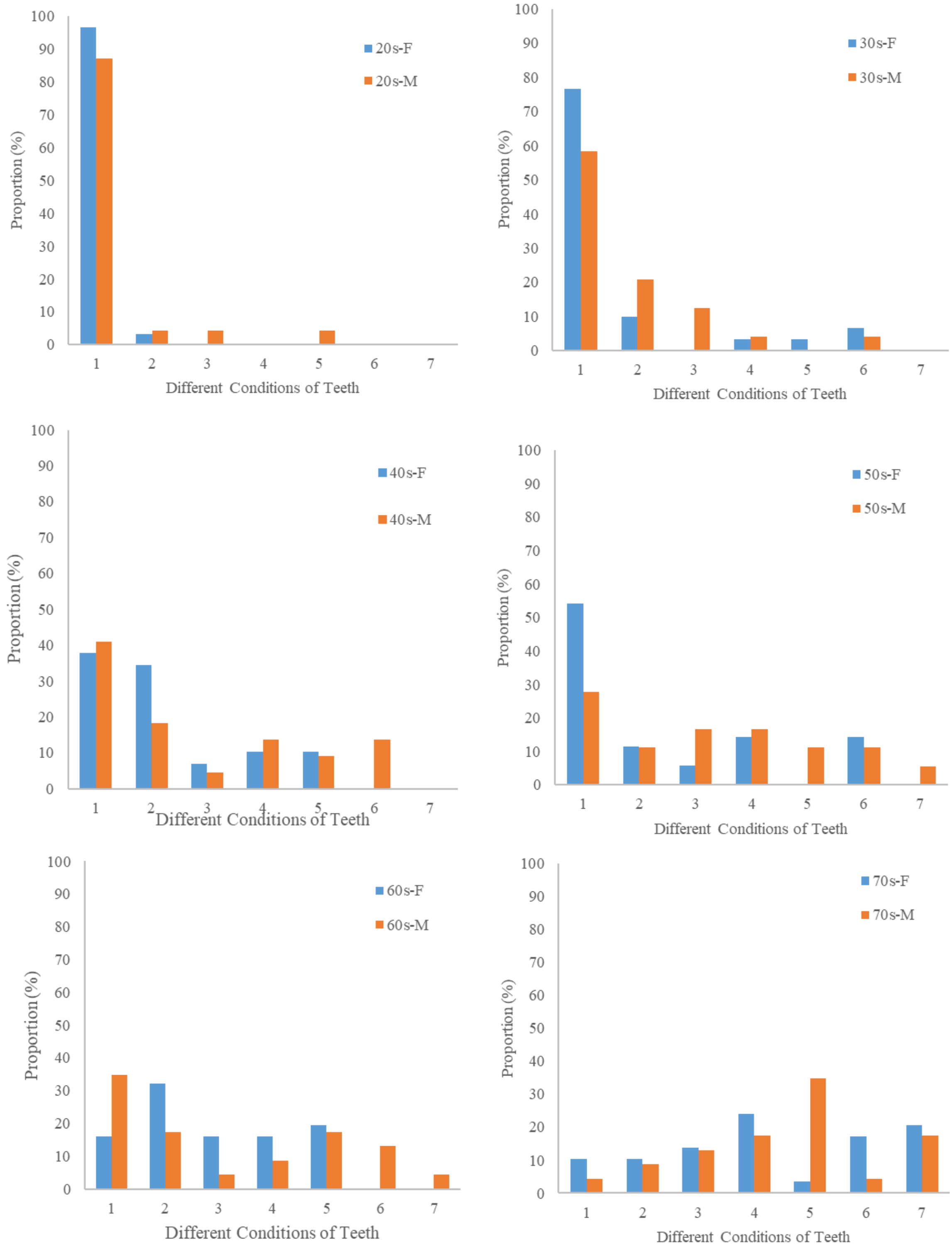


Figure 6.6 Proportion of seven conditions of teeth among different age groups with gender. 1: remaining full of nature teeth; 2: missing 1-2 teeth without replacement; 3: missing several teeth without wearing a denture; 4: wearing a fixed partial denture; 5: wearing a removable partial denture; 6: having the implant-supported prosthesis; 7: wearing a complete denture.
*label subplot: different age group-gender (i.e. 20s-F: the 20s female group)

6.3.1.4 The frequency of oral pain experience (toothache)

Toothache is one of the most critical sources of oral health problems, which cause millions of individuals to suffer a low quality of life [423]. Toothache represents any feelings of pain, ache or soreness in or around a tooth. The increasing frequency of toothache increases with level up from Level 0 to Level 3. As Figure 6.7 shows, Level 1 was the most frequent toothache experienced in all age groups, ranging between 36.5% and 60.8% (Mean= 47.9 ±9.5%). Level 0 was the second most frequent toothache experienced in the four younger age groups, from 27.5% to 39.6% (Mean= 34.6±4.4%). The lowest frequency of toothache experienced was Level 2 in the 30s, 40s, 50s and 60s groups, of which average was 5.8± 1.5%. However, only three groups (the 20s, 40s and 50s) had a lower frequency (< 10%) for Level 3.

The two middle-aged groups (40s and 50s) demonstrated the lowest frequency of toothache experienced during the last year and three months, which suggests that the relative oral health of middle-aged individuals has minor problems. Compared with the middle-aged groups, the 30s and 60s group had a relatively high frequency of toothache experiences that occurred in the last three months. However, the highest frequency of toothache in 30s and 60s group is Level 1 (more than one year ago). In contrast, the oldest age group had a similar frequency of toothache experienced in Level 1, 2 and 3. It may reflect that individuals over 71yrs have a higher risk of suffering from a toothache, which can relate to the reduction of masticatory function.

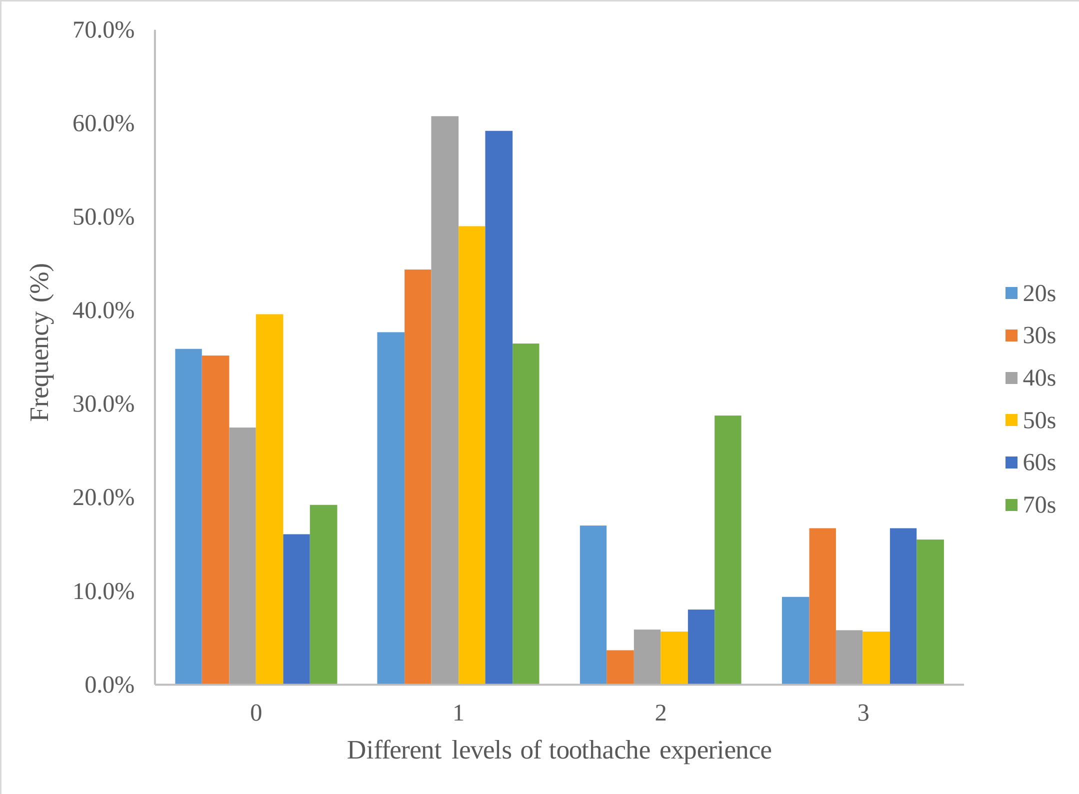


Figure 6.7 Frequency of four levels of the oral health status among six age groups due to the last toothache experience. Level 0: Never toothache experience; Level 1: more than one year ago; Level 2: during last year; Level 3: during last 3 months.

6.3.1.5 Preference and limitation in terms of texture (*hardness*)

Figure 6.8 shows the distribution of 317 participants' chewing preference of hard textures, comprising three *hardness* levels (*soft*, *medium* and *hard*). 245 participants (77%) preferred to chew *medium* texture foods in their daily lives. 15% and 8% of participants' texture preference was *soft* and *hard*, respectively. Although the majority of participants preferred *medium* texture foods, the proportion of participants preferring *medium* texture food had a strong, negative relationship with increasing age (r= 0.7119), whilst the percentage of preferring *soft* texture increased with ageing (r= 0.6298) in Figure 6.9. There was no relationship between *hard* texture preference and ageing. 17% of the 60s group preferred *hard* texture, which was the highest proportion among all age groups. So masticatory function may not be a limiting factor of biting *harder* foods for individuals in their 60s.

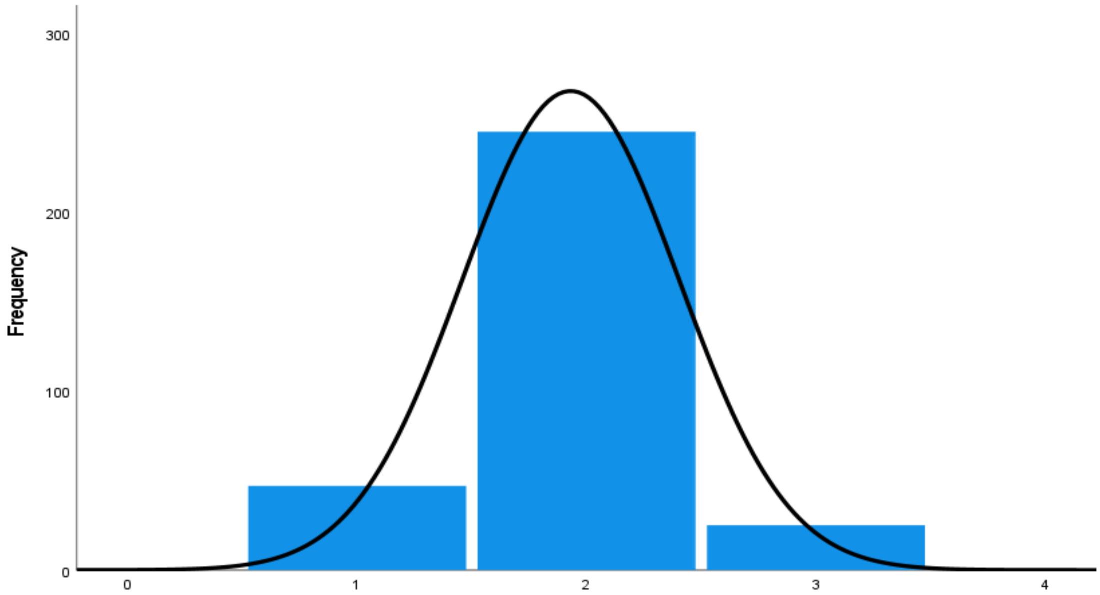


Figure 6.8 Frequency of three levels of preference *hardness* texture. 1: *soft* texture; 2: *medium* texture; 3: *hard* texture.

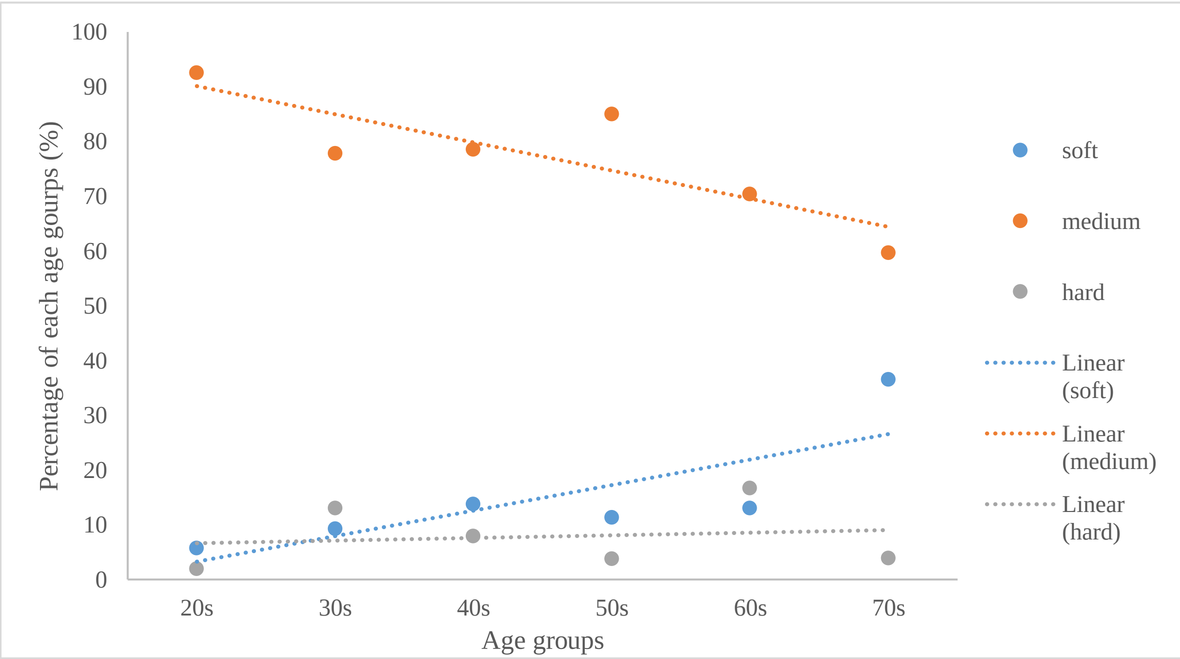


Figure 6.9 The relationship between *texture* preference and age.

The masticatory status questionnaire explored participants' self-perceived limitations/difficulties in masticatory function through self-reported maximum *hardness* texture ability. A higher score reflects the participant's self-perceived ability to bite a *harder* texture and may correspond to a better masticatory function. Figure 6.10 compared the score of maximum hardness texture among six different age groups. The highest average score (80.35±17.32) was found in the youngest group, while the average score of the other five groups ranged from 52.79 to 62.43. The difference in scores between the youngest age group and the other five groups was significant ($p < 0.05$). However, there was no significant difference in self-perceived *hardness* limitation among the 30s, 40s, 50s, 60s and 70s groups. It may represent that 20s individuals report they can bite harder foods due to better masticatory function. Comparing the range of scores (25% - 75% range) among age groups, the 60s and 70s group reported more of the lower scores in Figure 6.10. It means that some elderly individuals self-reported a lower maximum *hardness* texture score, potentially due to more difficulties/limitations of eating *harder* food which may link to the masticatory dysfunction at this age. The decreasing trend of the score of maximum *hardness* texture may be a signal for reducing masticatory function with ageing. With advanced age, self-perceived masticatory function decreases due to decreased jaw muscle activity. Legrand *et al*. (2013) [275] observed that decreased muscle mass and impaired muscle tissue relate to ageing. The reduction and dysfunction of masticatory performance can affect the quality of life who prefer to intake hard food [420].

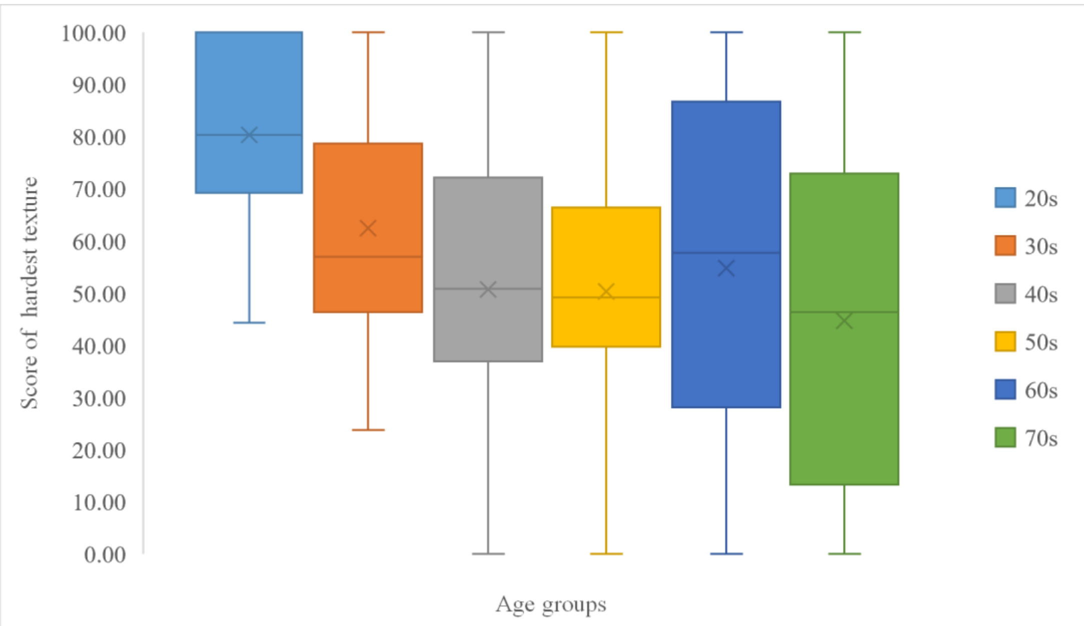


Figure 6.10 Box plot of score of self-perceived maximum *hardness* texture among each age groups.

Linking the individuals' limitation of *hardness* texture to real food, Table 6.2 demonstrates the different types of food that participants reported avoiding because of self-perceived decreased maximum comfortable bite force. In Table 6.2, 28 participants (highest frequency) reported that nuts are the type of real food they avoid consuming because of the *hard* and uncomfortable texture. Moreover, raw vegetable, fruit and ice cube were the second-highest frequency which participants avoid eating. Dried foods and hard candy were two processed foods that were considered challenging to eat because of their texture. A higher level of hardness is one of the characteristics in common among all foods reported in Table 6.2, which is likely to be an important factor that leads individuals to refuse these foods and may relate to a weaker maximum comfortable bite force. Prinz (1999) [282] found that the elderly have some difficulty chewing tough food such as meat, and the reduction of jaw muscle activity (EMG) with the extension of chewing time results in inefficient mastication and a coarser bolus. In addition, due to the significantly reduced jaw muscle activity with ageing, certain foods (dry bread and meat) were difficult to chew [31, 32].

Table 6.2 Summarised the foods that participants avoiding to eat due the *hard* texture.

Name	Example	Frequency of response
Nut	Peanuts	28
Raw vegetable and fruit	Carrot, Sugar cane, Apple	14
Ice cube	/	14
Dried food	Rusk, Dates	13
Hard candy	Toffee	12
Tough meat	Grilled steak	9
Lobster/Crab	/	3
Biscuits	Muesli bar	2

6.3.1.6 Self-rated level of bite force

The final section of the masticatory status questionnaire is self-assessed level of bite force. The participants were required to rate their bite force on a 5-point scale: '5 = excellent', '4 = very good', '3= good', '2= fair', or '1= poor'. Table 6.3 shows the average self-rated score of bite force among different age groups. The youngest group had the highest score (approximately 4 points), and more than 70% of 20s participants self-assessed their bite force to be between 'very good' and 'excellent'. However, the eldest group had the lowest score of 2.38, and over 60% of 70s' participants self-assessed to have a 'poor' or 'fair' level of bite force. There are significant Pearson's correlations between ageing and proportions of three different levels of bite force ('poor', 'fair' and 'very good'). The increasing proportion of 'fair' level of bite force strongly relate to the older age groups ($p < 0.05$). At the same time, there was a negative correlation between the proportion of 'very good' level of bite force and ageing ($p < 0.05$). To explore the threshold of subjective masticatory function by self-assessment of bite force, Table 6.4 compared the difference of the level of bite force among different age groups. The table showed that the self-rated bite force of the 20s group was significantly different from other age groups. It can assume that 31yrs is the threshold that the bite force level gradually shifts from above average condition ('very good' level) to normal condition ('good' level). In addition, the self-rated level of bite force in the 70s group was significantly different from the four age groups on Table 6.4 ($p < 0.05$). The significant and positive Pearson's correlation between 'poor' level of bite force and different age groups ($p < 0.05$) suggests that the proportion of poor bite force significantly increased in the 70s group. These results can assume that 71yrs is the second threshold of bite force, which indicates that participants between 31yrs and 70 yrs remain with a good/fair bite force. There is a high probability that individuals over 70yrs perceive their masticatory dysfunction through an insufficient level of bite force. With increased age, an impairment of muscle mechanical performance and muscle mass has been reported [279], as well as reduction of density and cross-sectional area of masseter and pterygoids [424] that severely impact masticatory ability, particularly in edentulous subjects [278].

Table 6.3 Summary of average score of self-assessed bite force, the percentage of participants rating in five different levels among age groups, and Pearson's correlation coefficient between a given level of bite force and age.

Groups	20s (*n*= 53)	30s (*n*= 54)	40s (*n*= 51)	50s (*n*= 53)	60s (*n*= 54)	70s (*n*= 52)	
Mean score	3.91±0.92	3.24±0.87	2.94±0.97	2.91±1.18	2.85±1.15	2.38±0.94	
			Proportion of participants (%)				*r* (*p*-value)
Poor(1)	0	0	5.9	3.8	7.5	14.0	0.916* (0.010)
Fair(2)	9.4	20.4	27.5	45.3	41.5	48.0	0.985** (0.004)
Good (3)	18.9	42.6	37.3	24.5	18.9	28.0	-0.210 (0.689)
Very good (4)	43.4	29.6	25.5	9.4	22.6	6.0	-0.874* (0.023)
Excellent (5)	28.3	7.4	3.9	17.0	9.4	4.0	-0.579 (0.229)

r: Pearson correlation coefficient.

*: Correlation is significant at the 0.05 level (2-tailed).

**: Correlation is significant at the 0.01 level (2-tailed).

Table 6.4 Cross-comparison of the difference in self-rated levels of bite force among different age groups.

Significant difference (*p*-value)	20s	30s	40s	50s	60s	70s
20s	-	0.000*	0.000*	0.000*	0.000*	0.000*
30s	-	-	0.107	0.084	0.040*	0.000*
40s	-	-	-	0.832	0.757	0.002*
50s	-	-	-	-	1.000	0.012*
60s	-	-	-	-	-	0.007*
70s	-	-	-	-	-	-

*: Correlation is significant at the 0.05 level (2-tailed).

**: Correlation is significant at the 0.01 level (2-tailed).

6.3.2 Link between Quality of masticatory function questionnaire (QMFQ) and Texture perception

Each dimension was scored between 0 (never) and 4 (always), such that the range of the overall score (six dimensions) was from 0 to 24. All dimensions of QMFQ scores are shown in Table 6.5 with different age groups. The differences in six dimensions and total QMFQ scores among different age groups are shown in Table 6.6. In the 20s group, the majority of individuals had no difficulty chewing raw or dried-processed foods, while they reported that occasionally or usually difficulty occurred when chewing cooked meats. The 30s, 40s, 50s and 60s groups had a lower median score on the meat dimension than the 20s, but there was no significant difference among these groups. However, these three dimensions' scores for the 70s were significantly different from other age groups. The results indicate that the 70s have more difficulties chewing these three types of hard foods due to reducing masticatory function.

Table 6.5 Median (25-75%) range of each dimension of Quality of Masticatory Function Questionnaire (QMFQ).

Age groups	Mastication Habits	Meats	Raw foods	Dried foods	Dentures	Chewing influences	Total
20s	1.0 (0.7-1.3)	0.6 (0.2-0.8)	0.0 (0.0-0.5)	0.0 (0.0-0.5)	0.0 (0.0-0.0)	0.8 (0.8-1.2)	3.1 (2.3-4.0)
30s	0.7 (0.3-1.3)	0.4 (0.0-0.9)	0.0 (0.0-1.0)	0.3 (0.0-1.0)	0.0 (0.0-0.0)	0.6 (0.2-1.0)	2.5 (1.0-4.8)
40s	0.7 (0.3-1.3)	0.2 (0.0-1.0)	0.0 (0.0-1.0)	0.0 (0.0-1.0)	0.0 (0.0-0.0)	0.4 (0.0-0.8)	2.2 (0.7-4.8)
50s	0.7 (0.0-1.3)	0.2 (0.0-1.1)	0.0 (0.0-1.3)	0.5 (0-1.0)	0.0 (0.0-0.0)	0.4 (0.0-1.0)	2.5 (0.1-5.5)
60s	0.5 (0.0-1.3)	0.2 (0.0-0.8)	0.25 (0.0-2.0)	0.0 (0.0-1.5)	0.0 (0.0-0.0)	0.4 (0.0-0.8)	1.8 (0.3-6.1)
70s	1.0 (0.3-1.7)	1.2 (0.4-1.6)	1.5 (0.5-2.5)	1.5 (0.5-2.0)	0.0 (0.0-1.0)	0.6 (0.2-1.2)	6.3 (3.1-9.1)

As Table 6.6 shows, the median score of chewing raw foods from the 50s group was significantly different from the 20s and 40s, which suggests that the 50s is the threshold of masticatory function when chewing raw foods. Moreover, there was a strong and positive Spearman's correlation between the score of raw foods and age (r=0.845, p< 0.05). It may prove that ageing affects subjective masticatory function when chewing raw vegetables and fruits (raw foods). In the other domains of QMFQ and total QMFQ score (Table 6.6), there was a significant difference (p< 0.05) between the 70s group and other age groups (excluding chewing domains from 20s and 40s). The age above 70yrs may be the threshold for these three domains (mastication habits, dentures and chewing influence) that relate to decreased masticatory function.

Table 6.6 Pairwise cross-comparison of the difference in each dimension of QMFQ among different age groups.

Ages	20s	30s	40s	50s	60s	70s
Mastication Habits						
20s	-	0.94	0.109	0.091	0.07	0.448
30s	-	-	0.988	0.91	0.709	0.038*
40s	-	-	-	0.929	0.369	0.076
50s	-	-	-	-	0.876	0.037*
60s	-	-	-	-	-	0.029*
70s	-	-	-	-	-	-
Meats						
20s	-	0.916	1	0.799	0.062	0.000*
30s	-	-	0.9	0.913	0.185	0.000*
40s	-	-	-	1	0.139	0.001*
50s	-	-	-	-	0.306	0.000*
60s	-	-	-	-	-	0.000*
70s	-	-	-	-	-	-
Raw foods						
20s	-	0.949	0.752	0.151	0.005*	0.000*
30s	-	-	0.956	0.157	0.064	0.000*
40s	-	-	-	0.153	0.032*	0.000*
50s	-	-	-	-	0.387	0.001*
60s	-	-	-	-	-	0.006*
70s	-	-	-	-	-	-
Dried foods						
20s	-	0.194	0.45	0.109	0.119	0.000*
30s	-	-	0.557	0.551	0.957	0.000*
40s	-	-	-	0.242	0.738	0.000*
50s	-	-	-	-	0.665	0.001*
60s	-	-	-	-	-	0.000*
70s	-	-	-	-	-	-
Dentures						
20s	-	-	0.033*	0.011*	0.001*	0.000*
30s	-	-	0.033	0.012*	0.001*	0.000*
40s	-	-	-	0.118	0.028*	0.000*
50s	-	-	-	-	0.768	0.027*
60s	-	-	-	-	-	0.071
70s	-	-	-	-	-	-
Chewing influences						
20s	-	0.116	0.000*	0.001*	0.000*	0.066
30s	-	-	0.041*	0.189	0.016*	0.801
40s	-	-	-	0.491	0.425	0.047*
50s	-	-	-	-	0.234	0.183
60s	-	-	-	-	-	0.007*
70s	-	-	-	-	-	-
Total QMFQ						
20s	-	0.616	0.393	0.841	0.982	0.000*
30s	-	-	0.607	0.611	0.9	0.000*

40s	-	-	-	0.3	0.707	0.000*
50s	-	-	-	-	0.858	0.000*
60s	-	-	-	-	-	0.000*
70s	-	-	-	-	-	-

6.3.3 Multiple linear regression of the Effect of Ageing

QMFQ overall scores for different age groups, different parameters of oral health status, and texture preference and limitation were analysed with regression models (Table 6.7). In the multiple linear regression, residues were independent (Durbin-Watson<2.167) whilst there was no multicollinearity (TOI>0.79; VIF<1.265), and significant outliers were detected. Four models were established for investigating the relationship between subjective masticatory function and age. In Model 1, "age" was the independent variable; in Model 2, "age + toothache status" , "age + *texture* preference" and "age + *texture* limitation score" were independent variables, respectively; in Model 3, "age + toothache status + *texture* preference", "age + toothache status + *texture* limitation score" and "age + *texture* preference + *texture* limitation score" were independent variables, respectively; in Model 4, "age + toothache status + *texture* preference + *texture* limitation score" were variables. Although the multiple regression analysis in Model 1 revealed that a higher QMFQ score significantly relates to the older age group (Model 1: F[315,1]= 17.921; $P<0.005$, $R^2=0.054$), age as a single independent variable can only explain 5.4% of the variability in subjective masticatory function. With a different independent variable added in Model 2, *texture* preference is an identical, independent variable associated with age (Model 2-B: F[314,2]= 24.587; $P<0.005$, $R^2=0.135$). When the age-associated with *texture* preference and limitation score are included as three independent variables (Model 3-C: F[293,3]=21.698; $P<0.005$, $R^2=0.182$), the model can explain 18.2% of the variability in masticatory function. When the QMFQ overall score was set as the dependent variable, age, condition of teeth, the number of teeth loss, toothache status, *texture* preference and *texture* limitation score were inserted in the initial model as independent variables. This analysis retrieved a significant model (Model 4: F[292,4]=21.519; $P<0.005$, $R^2=0.228$) with the frequency of toothache, *texture* preference and *texture* limitation score and different age groups as variables that could predict the 22.8% outcome when combined.

When the analysis was conducted with the condition of teeth as the outcome, the predictor variables added in the initial models were age, the number of teeth loss, toothache status, *texture* preference, texture limitation score and self-rated bite force score. In the multiple linear regression, residues were independent (Durbin-Watson<2.167) whilst there was no multicollinearity (TOI>0.79; VIF<1.265) and no significant outliers were detected. Three models were established for investigating the relationship between the condition of teeth and different age groups (Table 6.7). In Model 1, "age" was the independent variable; in Model 2, "age + toothache status", "age + *texture* limitation score" and "age + self-rated bite force score" were independent variables, respectively; in Model 3, "age + toothache status + *texture* limitation score". Model 1 revealed that a worse condition of teeth relate to increasing age (Model 1: $F[315,1]= 123.825$; $P<0.005$, $R^2=0.282$). Age as the single independent variable can explain 28.2 % of the variability of the condition of teeth. In Model 2, the increasing age associated with a more frequent toothache or *softer* level of texture can explain a worse condition of teeth. Model 2-C may be the almost identical Model that explains 33.0% of the variability of the outcome, which inserted the age and bite force score as the independent variables (Model 2-C: $F[311,2]=76.428$; $P<0.005$, $R^2=0.330$). An elderly individual who has a lower level of bite force can be predicted to have a worse condition of teeth. However, the relationship between the condition of teeth and "age + toothache status + *texture* limitation score" (Model 3) was not significant (Constant's $P=0.221$).

With the number of teeth loss considered as the dependent variable, the independent variables inserted in the models were age, toothache status, condition of teeth, *texture* preference, *texture* limitation score and self-rated bite force score. Three models were established for investigating the relationship between the number of teeth loss and different age groups (Table 6.7). Model 1 shows a significant increasing trend of the number of teeth loss with increasing age (Model 1: F[315,1]= 191.977; $P<0.005$, $R^2=0.379$). Age as the single independent variable can explain 37.9 % of the variability of the number of teeth loss. There was no significant relationship between the number of teeth loss and "age + *texture* preference", "age + self-rated bite force" and "age + toothache status + self-rated bite force", respectively. However, older age is associated with worse toothache status ($R^2=0.401$) as well as a *softer* level of texture limitation ($R^2=0.374$), which is significantly related to a larger number of teeth loss. This analysis also retrieved a significant model (Model 3-B: F[293,3]=64.682; $P<0.005$, $R^2=0.398$) with toothache status, *textur*e limitation score and different age groups as the variables that could predict the 39.8% of the outcome.

When the analysis was conducted with the self-rated bite force score as the outcome, the independent variables inserted in the models were age, toothache status, condition of teeth, *texture* preference and *texture* limitation score. Three models were established for investigating the relationship between the level of bite force and different age groups (Table 6.7). Model 1 demonstrates a significant negative correlation between the level of bite force and different ages (Model 1: F[312,1]= 55.540; $P<0.005$, $R^2=0.151$). Age as the single independent variable can explain 15.1 % of the variability of the level of bite force. Three combinations of Model 2 including "age + toothache status", "age + *texture* preference" and "age + *texture* limitation score" as independent variables, which significantly relate to bite force levels. The increased age whether associated with more frequency of toothache, or *harder* texture preference, or *harder* texture limitation score can predict a lower level of bite force. Three combinations of Model 3 including "age + toothache status + *texture* preference", "age + toothache status + *texture* limitation score" and "age + *texture* preference + *texture* limitation score" as independent variables, also significantly relate to bite force level. The analysis retrieved a more ideal and significant model (Model 3-B: F[293,3]=38.344; P<0.005, R^2=0.282) with toothache status, *texture* preference and different age groups as the variables that could predict the 28.2% of the outcome.

Table 6.7 Multiple regression models indicating age as independent variable associating with different independent variables when related to dependent variables.

Dependent Variable	Independent Variable	Standardized β	t	P	R^2
QMFQ overall score	Model 1:				0.054
	Age	0.232	4.233	<0.005	
	Constant	-	3.347	0.001	
	Model 2-A:				0.097
	Age	0.204	3.773	<0.005	
	Toothache	0.210	3.876	<0.005	
	Constant	-	2.243	0.026	
	Model 2-B:				0.135
	Age	0.186	3.490	0.001	
	Texture	-0.289	-5.443	<0.005	
	Constant	-	6.467	<0.005	
	Model 2-C				0.105
	Age	0.189	3.307	0.001	
	Hardest	-0.218	-3.821	<0.005	
	Constant	-	4.973	<0.005	
	Model 3-A				0.166
	Age	0.166	3.145	0.002	
	Toothache	0.177	3.367	0.001	
	Texture	-0.267	-5.072	<0.005	
	Constant	-	5.539	<0.005	
	Model 3-B				0.167
	Age	0.164	2.955	0.003	
	Toothache	0.250	4.671	<0.005	
	Hardest	-0.222	-4.012	<0.005	
	Constant	-	4.147	<0.005	
	Model 3-C				0.182
	Age	0.164	2.982	0.003	
	Texture	-0.290	-5.251	<0.005	
	Hardest	-0.145	-2.568	0.011	
	Constant	-	7.380	<0.005	
	Model 4				0.228
	Age	0.145	2.697	0.007	
	Toothache	0.217	4.165	<0.005	
	Texture	-0.260	-4.796	<0.005	
	Hardest	-0.155	-2.824	0.005	
	Constant	-	6.421	<0.005	
Conditions of teeth	Model 1:				0.282
	Age	0.531	11.128	<0.005	
	Constant	-	-0.224	0.823	
	Model 2-A				0.298
	Age	0.514	10.780	<0.005	
	Toothache	0.129	2.695	0.007	
	Constant	-	-0.948	0.344	
	Model 2-B				0.286
	Age	0.488	6.566	<0.005	
	Hardest	-0.125	-2.452	0.015	
	Constant	-	1.794	0.074	

	Model 2-C				0.330
	Age	0.443	8.782	<0.005	
	Self-rated	-0.232	-4.604	<0.005	
	Constant	-	3.641	<0.005	
	Model 3				0.305
	Age	0.474	9.361	<0.005	
	Toothache	0.141	2.872	0.004	
	Hardest	-0.127	-2.517	0.012	
	Constant	-	-	0.221	
Number of Teeth loss	Model 1				0.379
	Age	0.615	13.856	<0.005	
	Constant	-	-6.368	<0.005	
	Model 2-A				0.401
	Age	0.595	13.509	<0.005	
	Toothache	0.151	3.438	0.001	
	Constant	-	-7.166	<0.005	
	Model 2-B				0.388
	Age	0.600	13.405	<0.005	
	Texture	-0.099	-2.204	0.028	
	Constant	-	-1.476	0.141	
	Model 2-C				0.374
	Age	0.578	12.106	<0.005	
	Hardest	-0.099	-2.063	0.040	
	Constant	-	-2.409	0.017	
	Model 2-D				0.434
	Age	0.513	11.074	<0.005	
	Self-rated	-0.260	-5.626	<0.005	
	Constant	-	0.894	0.372	
	Model 3-A				0.445
	Age	0.507	11.024	<0.005	
	Overall	-0.241	-5.181	<0.005	
	Toothache	0.106	2.448	0.015	
	Constant	-	0.144	0.886	
	Model 3-B				0.398
	Age	0.563	11.937	<0.005	
	Hardest	-0.101	-2.144	0.033	
	Toothache	0.157	3.455	0.001	
	Constant	-	-3.074	0.002	
Overall self-rated score	Model 1				0.151
	Age	-0.389	-7.453	<0.005	
	Constant	-	25.752	<0.005	
	Model 2-A				0.175
	Age	-0.369	-7.117	<0.005	
	Toothache	-0.156	-2.998	0.003	
	Constant	-	25.883	<0.005	
	Model 2-B				0.175
	Age	-0.365	-6.993	<0.005	
	Texture	0.157	3.004	0.003	
	Constant	-	11.101	<0.005	
	Model 2-C				0.248
	Age	-0.327	-6.238	<0.005	
	Hardest	0.301	5.746	<0.005	
	Constant	-	13.550	<0.005	
	Model 3-A				0.260
	Age	-0.317	-6.064	<0.005	
	Hardest	0.272	5.063	<0.005	
	Texture	0.115	2.184	0.030	
	Constant	-	8.467	<0.005	
	Model 3-B				0.282
	Age	-0.308	-5.984	<0.005	

Hardest	0.303	5.915	<0.005	
Toothache	-0.185	-3.710	<0.005	
Constant	-	14.297	<0.005	
Model 3-C				0.194
Age	-0.350	-6.737	<0.005	
Texture	0.141	2.705	0.007	
Toothache	-0.140	-2.698	0.007	
Constant	-	11.532	<0.005	

6.3.4 Link between Sensory assessment of maximum bite force and Texture perception

6.3.4.1 Rate test

Figure 6.11 demonstrates the median hardness score collected from participants who rated six gel-based model foods on a line scale (VAS, 10 cm), after converting them into 100 scale. There was a decreasing trend in median hardness rating scores from each age group with the decreased mechanical hardness of samples. The highest hardness median rating score (87.77) was found from the 50s age group rating of M6, and the lowest score was 7.19 rated from 70s age groups rating of M1. However, there was no significant difference between hardness scores of each model food among the six age groups from the rate test.

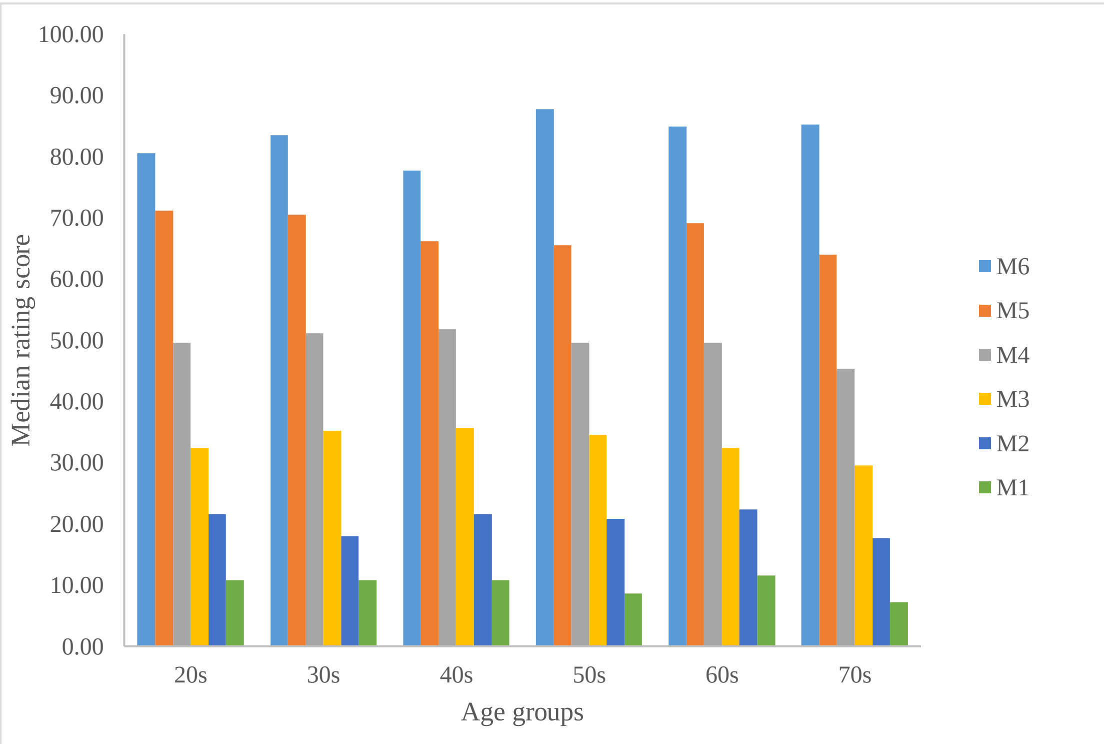


Figure 6.11 Median rating scores collected from each gel-based model food and from the average of six samples among different age groups.

The biting difficulty score presents the difference between *hardness* perception from the sensory test (rate test) and hardness texture from instrumental measurement (compression test) across all six model foods. A higher biting difficulty score represents the participant rated the sample as a more, uncomfortable and *harder* texture, since the rating *hardness* score was of higher intensity than the instrumental hardness score for the same sample. The range of biting difficulty levels for the set of gel-based model foods is demonstrated in Table 6.8. It is proposed that a higher biting difficulty level may be indicative of a weaker maximum comfortable bite force and a softer maximum comfortable biting hardness texture.

Table 6.8 Five levels of biting difficulty (1-5), classified by biting difficulty scores M_x for samples M1 – M6.

Level	5	4	3	2	1
Difficulty	Hard	Challenge	Moderate	Easy	Very easy
M6 score's range (38.9~-100.0)	38.9~11.1	11.0~-16.7	-16.8~-44.5	-44.6~-72.3	-72.4~-100.0
M5 score's range (96.1~-100.0)	96.1~56.9	56.8~17.7	17.6~-21.5	-21.6~-60.7	-60.8~-100.0
M4 score's range (205.8~-100.0)	205.8~144.6	144.5~83.4	83.3~22.2	22.1~-39.0	-39.1~-100.0
M3 score's range (474.7~-100.0)	474.7~359.8	359.7~244.9	244.8~130.0	129.9~15.1	15.0~-100.0
M2 score's range (580.3~-100.0)	580.3~444.3	444.2~308.3	308.2~172.3	172.2~36.3	36.2~-100.0
M1 score's range (975.3~-100.0)	975.3~760.2	760.1~545.1	545.0~330.0	329.9~114.9	114.8~-100

As categorised in terms of biting difficulty levels (Table 6.8), the distributions of participants in each level are shown in Figure 6.13 sample-by-sample. The proportion of participants' biting difficulty levels for M6 (the most intensive hardness) is demonstrated in Figure 6.12(A). 58.9% of participants marked M6 as the most difficult to bite (Level 5). In comparison, less than 15% of participants rated M6 between 'moderate' (Level 3) to 'very easy' (Level 2) to bite. Consequently, we can assume that more than half of the 317 participants struggle with biting through M6, which suggests M6 has a less comfortable and harder texture. Compared with M6's result, the most significant proportion of participants (50.2%) rated M5's biting difficulty as Level 4 while 17.5% of participants rated it to have the same biting difficulty as M6 (Level 5). This suggests that the remaining 30% of individuals had a maximum comfortable biting hardness greater than M5's hardness. Figure 6.12(C) shows the proportion of participants biting difficulty levels for M4. Although more than 70% of participants rated the sample's biting difficulty between Levels 1 to 3, 27.1% of participants rated the sample as challenging (Level 4) and difficult to bite (Level 5). This indicates that approximately 30% of individuals cannot bite foods of a texture equal to M4 with a comfortable bite force. The distribution of participants biting difficulty levels for M3 is shown in Figure 6.12(D). The largest proportion of participants' biting difficulty level for M3 was Level 2, whereby half of the adults can easily bite the hardness texture equal to M3. The results collected from M1 and M2 showed that more than 98% of participants rated the two softest texture model foods as easy to bite with a Level 1 or Level 2 biting difficulty. Less than 2% of participants have difficulty biting M1 and M2, indicating that the hardness texture of M1 and M2 was in and/or below the range of most individuals' comfortable biting texture. The broader distribution of participants biting difficulty levels was found in M5, M4 and M3, which can be attributed to differences in the biting difficulty levels of these model foods for different age groups. The variation of maximum comfortable texture and bite force with ageing can be discriminated from the difference in the proportions of biting difficulty levels among these three intermediate samples.

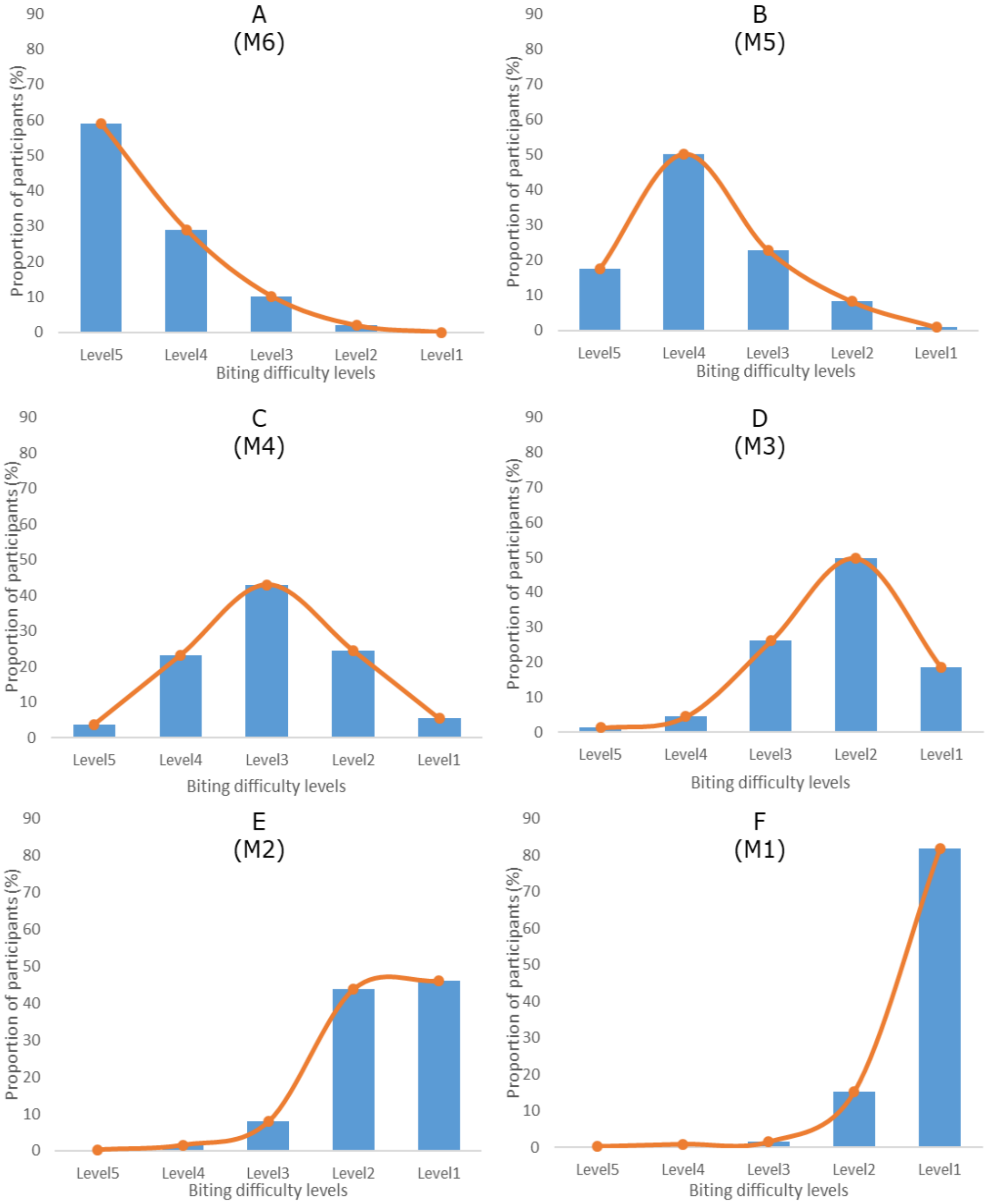


Figure 6.12 Proportion of different difficulty levels of biting M*x* among all of the participants. A: M6; B: M5; C: M4; D: M3; E: M2; F: M1.

For investigating the influence of ageing on the maximum comfortable bite force using biting difficulty level, significant correlations between age and the proportion of participants' whose biting difficulty for M5 was above Level 4 are compared in Figure 6.13. A strong quadratic correlation exists between the proportion of participants (%)

who have the most difficulty to bite M5 and age (p=0.02, R^2=0.94). With ageing, 11.3% of participants in the 30s group had Level 5 difficulty biting M5. This increased to 26.9% in the 70s age group who have Level 5 difficulty biting M5. The higher proportion of 20s participants have Level 5 biting difficulty of M5 may relate to a more sensitive discrimination of hardness. Research has proven that younger adults are more sensitive to hardness than adults using agar-agar-based model foods [425]. The proportion of participants who rated M5 as a Level 4 biting difficulty model food also significantly related to age (p=0.002, R^2=0.92). The trend lines of the correlations reflect that the elderly may have more difficulty biting the hardness of M5, which can link to weaker maximum comfortable bite force. In contrast, the younger participants whose maximum comfortable bite force may be stronger find biting through M5 to be challenging but not uncomfortable. When the rate test is applied to the younger age groups, participants who have Level 5 biting difficulty of M5 and M4 can be estimated to either have a lower level of masticatory function or heightened sensitivity to hardness. From the cross over between Level 4 and 5 beyond 70yrs, we can hypothesis that the turning point of masticatory function may be the age over 70s, attributed to the decrease in maximum comfortable bite force with ageing. This may present a critical age range to assess the possibility of masticatory dysfunction.

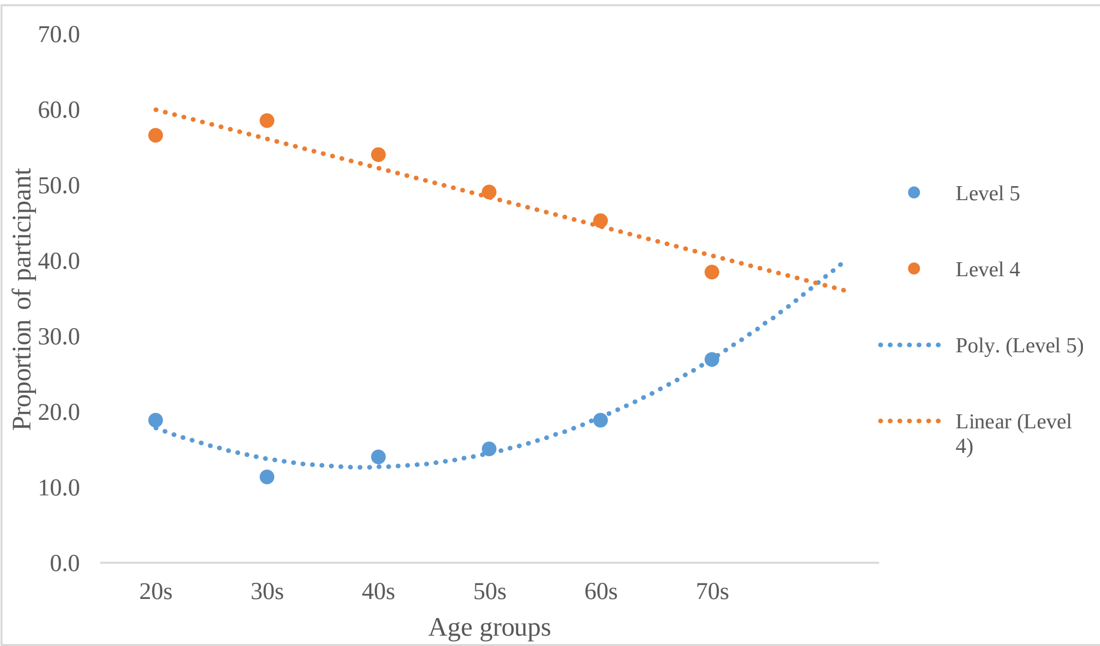


Figure 6.13 Significant correlations of the proportion of Level 5 and Level 4 difficulty to bite M5 with age.

Figure 6.14 shows significant correlations between the proportion of participants biting difficulty of Level 5 and Level 1 for M4 as a function of age. A strong and positive quadratic correlation exists between the proportion of participants who have the most intense difficulty biting M4 and ageing (p=0.047, R^2=0.87). In comparison, no participant had Level 5 biting difficulty for M4 from the youngest age group (the 20s). A small proportion (1.9%-3.8%) of participants in the 30s to 60s age rated M4 as Level 5 biting difficulty. In contrast, 11.5% of 70s participants had the same level of biting difficulty. The proportion of participants who have no difficulty (Level 1) of biting M4 also strongly related to age (p=0.043, R^2=0.68). Based on the distribution of M4 shown in Figure 6.12(C), most participants rated M4 as between Level 4 and Level 2. The participants who have Level 1 biting difficulty of M4 may relate to extraordinary bite force. When M4 is applied in evaluating masticatory function, the participant who rate M4 as Level 1 biting difficulty may relate to a good condition of masticatory function. The largest proportion (7.7%) of participants' rating M4 as Level 1 is seen the 70s age group, which suggests a number of the elderly population have an equivalent maximum comfortable bite force similar to M4 as compared to younger individuals (2%). However, this could also be the result of a loss of sensitivity to hardness in the older age group. Depending on the crossover point of two trend lines, the turning point of masticatory function may occur in the 60s.

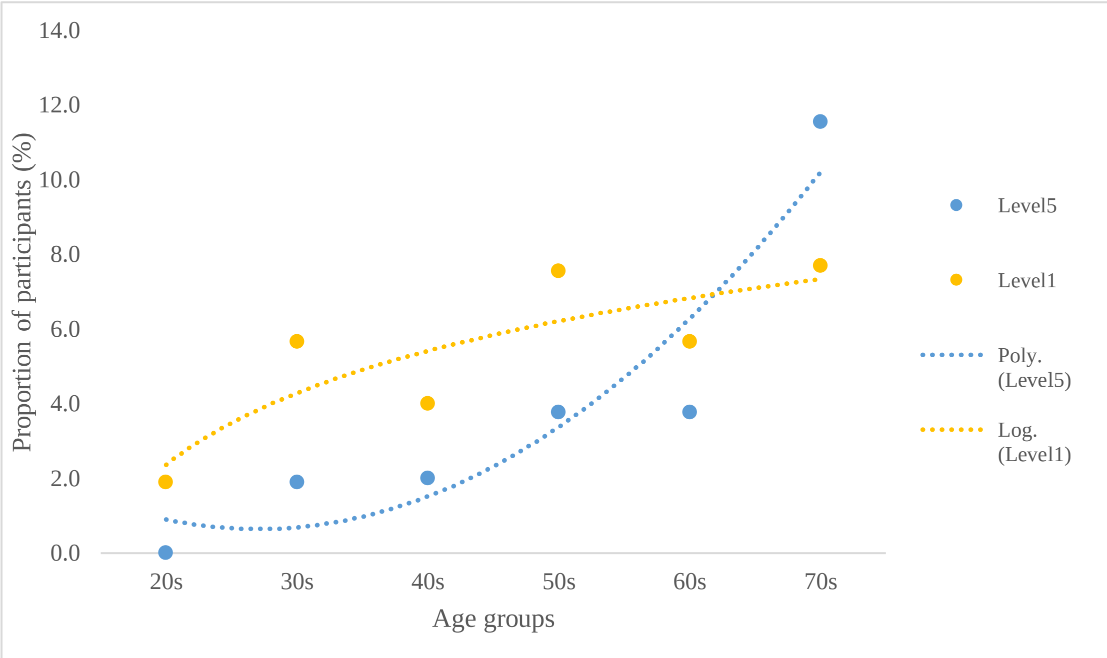


Figure 6.14 Significant correlations of the proportion of Level 5 and Level 1 difficulty to bite for M4 with age.

Significant cubic correlations between the proportion of participants biting difficulty levels of M3 are shown in Figure 6.15 as a function of age (Level 3: p<0.001, R^2=1.0; Level 1: p=0.019, R^2=0.99). The turning point is in the 50s age groups, based on Level 3's trend line. The proportion of participants who rate M3 as a Level 3 biting difficulty model food dramatically decreased from the 60s to the 70s age group, whilst the largest proportion of participants whose biting difficulty was Level 1 is in the 70s age group. Based on the results, the hardness texture of M3 is comfortable for little over 10% of elderly individuals. However, 7.7% of elderly participants had a Level 5 biting difficulty of M3 whereas no younger inviduals (the 20s-60s) expressed the same level of biting difficulty. The elderly individual who rates a medium hardness texture as M3 as Level 5 difficulty may relate to a decreased maximum comfortable bite force and suffer from the reduced masticatory function. As Figure 6.12 (D) shows, the majority of the participants biting M3 rated its difficulty as Level 2. Participant who had a biting difficulty greater than Level 2 may correspond to a weaker maximum comfortable bite force. In contrast, those whose biting difficulty is Level 1 may correspond to a stronger maximum comfortable bite force. Based on this assumption, the 50s age may be the start point of reduced maximum comfortable bite force, because this age group has the largest proportion of Level 3 and the smaller proportion of Level 1 biting difficulty.

There were no significant correlations between the proportions of participants biting difficulty levels for M6 (hardest), M2 and M1 (softest) with age ($p > 0.05$). However, a small proportion of the 70s express a Level 5 biting difficulty of M1 and M2. In contrast, Level 5 biting difficulty of the softest model foods (M1 and M2) have not been found in other age groups. 70s individuals have a higher risk of suffering from biting difficulty for softer texture foods associated with reduced masticatory function.

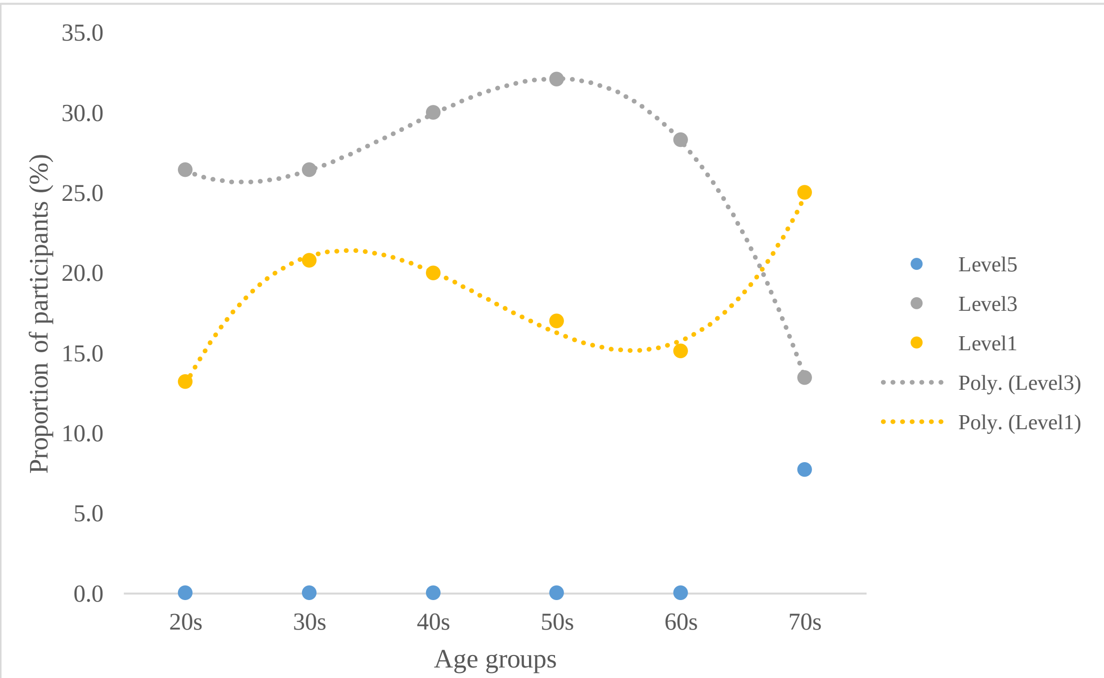


Figure 6.15 Significant correlations of the proportion of Level 5, Level 3 and Level 1 difficulty to bite M3 with age.

6.3.4.2 Rank test

The results of the rank test ($n = 314$) for the six gel-based model foods were converted to accuracy (%), and categorized as 0%, 17%, 33%, 50%, 67% or 100% accuracy. The highest accuracy was 100%, representing the ranking of hardness levels for all six samples M1-M6 is entirely correct. Two rounds of rank tests were conducted: an independent rank test (pre-rank test) and a rank test combined with a rate test (post-rank test). The distribution of results from these two rank tests is demonstrated in Figure 6.16. In the pre-rank test, the most frequent score of rank accuracy was 33%, of which 24% of participants can correctly rank two samples based on the hardness levels. In comparison, 66 participants (21%) have 67% accuracy ranking the six model foods, which was the second most frequent score from the pre-rank test. The lowest frequency of the pre-rank test is 0%, of which 11% of participants failed to correctly rank the set of samples by different hardness. Compared to the pre-rank test, the distribution of results from post-rank test accuracy showed improvement. The most frequent accuracy of the post-rank test was 67%, with an increase from 66 (pre-rank) to 87 (post-rank) participants, whilst the number of participants who had 100% accuracy increased from 43 (pre-rank) to 57 (post-rank). The frequency of 33% rank accuracy decreased by less than 1%, which means more than 23% of participants had a lower post-rank accuracy. However, the frequency of both 0% and 17% accuracy reduced to less than 30 participants, which indicates an improvement in rank accuracy from pre-rank to post-rank test. A positive correlation between pre-rank and post-rank accuracy is shown in Table 6.9 that proves the improvement is significant. The first round rank test provides a learning experience of the rank test which assists in discriminating the different hardness levels of samples in the second round rank test. Hence, it is necessary to design two round rank tests into the new measurement of maximum comfortable bite force.

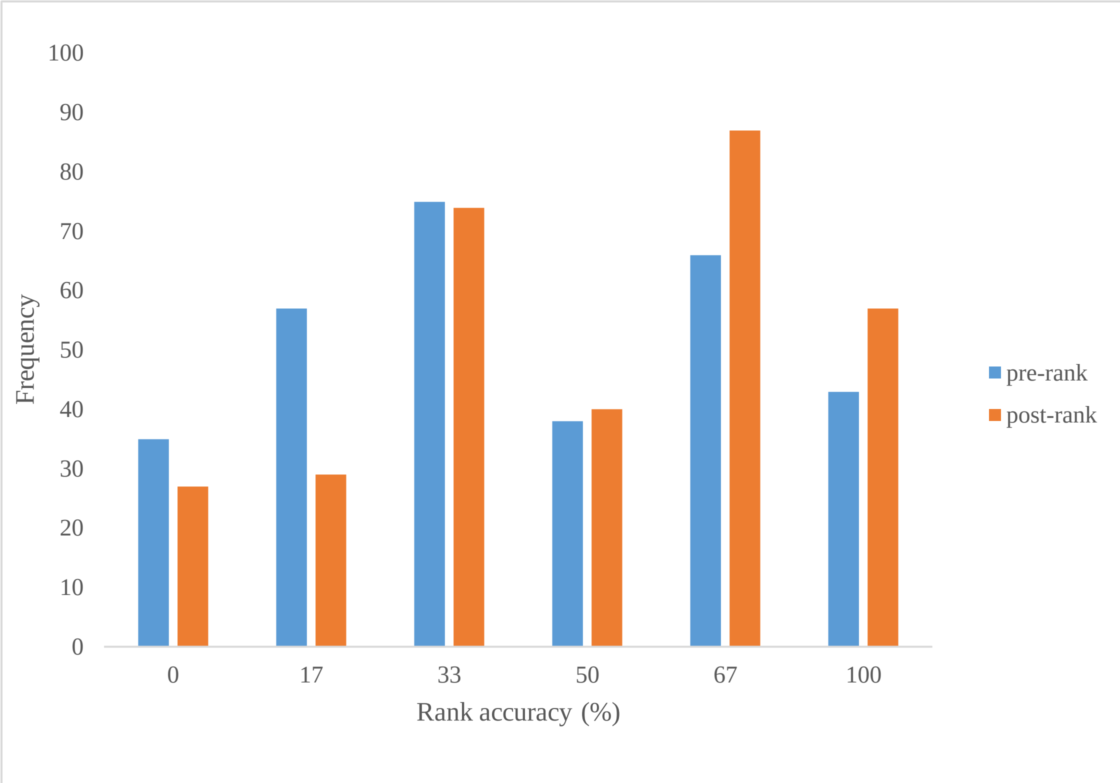


Figure 6.16 Frequency of rank tests accuracy from pre-rank and post-rank test, representing number of participants in each category (n = 314).

To explore the potential relationship of rank accuracy and masticatory function with ageing, Table 6.9 shows the relationship between the two rounds of rank accuracy split across the six different age groups. As Table 6.9 shows, the rank accuracy from pre-rank and post-rank tests is significantly related to ageing ($p< 0.05$). The older participants are more likely to present a lower rank accuracy by the rank hardness test. The negative correlation supports our hypothesis that ageing affects the sensory *hardness* because of the reduction in masticatory function.

Table 6.9 Pearson's correlation coefficient (r) between two rounds rank accuracy and six different age groups (20s, 30s, 40s, 50s, 60s and 70s).

	Pre-rank accuracy r (p)	Post-rank accuracy r (p)	Age r (p)
Pre-rank accuracy r (p)	/	0.494** (<0.001)	-0.315** (<0.001)
Post-rank accuracy r (p)	0.494** (<0.001)	/	-0.215** (<0.001)
Age r (p)	-0.315** (<0.001)	-0.215** (<0.001)	/

**: Correlation is significant at the 0.01 level (2-tailed).

Based on the results of rank accuracy, the participants' sensitivity to *hardness* can be evaluated from low to high. We assume a higher sensitivity corresponds to a more accurate rank test result. The different thresholds of hardness sensitivity can be linked to ageing by comparing the proportion of pre-rank accuracy from the six age groups (Figure 6.17). For regular *hardness* sensitivity participants whose pre-rank accuracy was 67% (p= 0.012, R^2=0.82) and the highest sensitivity participants whose pre-rank accuracy was 100% (p= 0.013, R^2=0.82), rank accuracy is negatively correlated to ageing. In contrast, the proportion of 0% accuracy participants (~ lowest *hardness* sensitivity) had a positive relationship with age (0%: p= 0.002, R^2=0.92; 33%: p= 0.0045, R^2=0.67). Given that the trend lines for 0% and 100% accuracy cross over in the 50s age group, age 50s may be considered to be the turning point for the highest level of *hardness* sensitivity (rank accuracy=100%). However, the regular *hardness* sensitivity (rank accuracy=67%) significantly decreases after age 60yrs based on the crossover of the 0% and 67% trendlines. Therefore, linking *hardness* sensitivity to masticatory function by the pre-rank test, age 50s can be considered as the starting point of reduced masticatory function while age 60s may be the start of significant masticatory dysfunction. Since the difference in pre-rank accuracy among the 50s, 60s and 70s groups were not significant (Table 6.10), this assumption is further analysed with the results from the post-rank test.

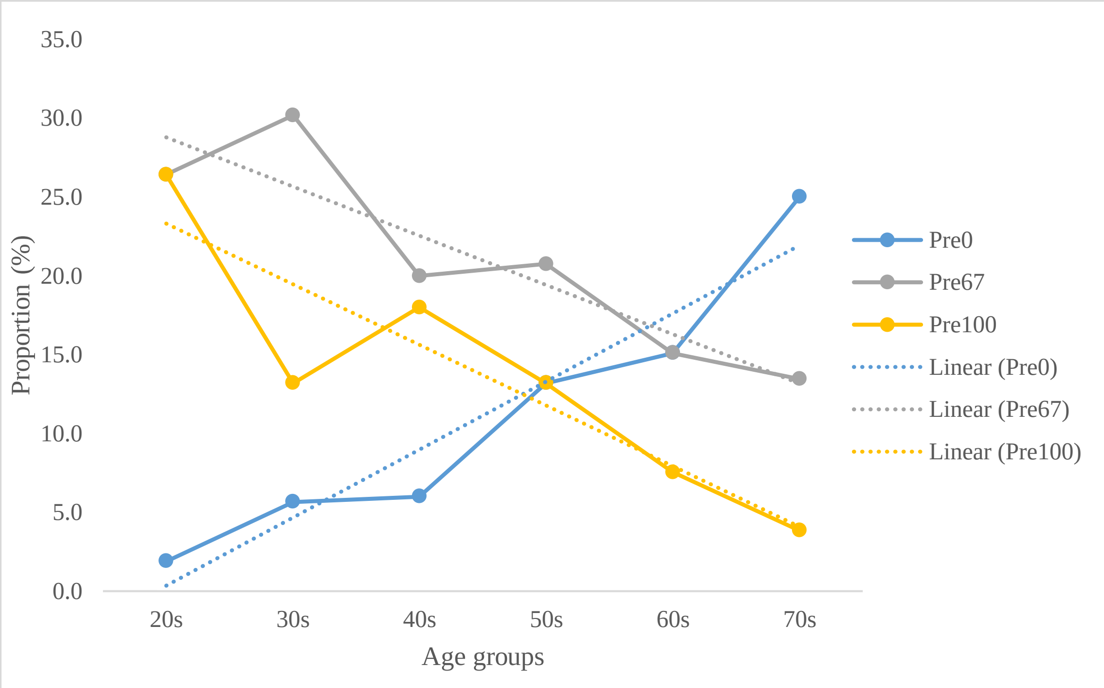


Figure 6.17 Correlations between the proportion of participants with pre-rank accuracy (0%, 33%, 67% and 100%) and different age groups.

Table 6.10 Pairwise cross-comparison of the difference of accuracy from pre-rank test among different age groups.

Significant difference (*p*-value)	20s	30s	40s	50s	60s	70s
20s	-	0.256	0.157	0.007*	<0.001*	<0.001*
30s	0.256	-	0.276	0.044*	0.001*	<0.001*
40s	0.157	0.276	-	0.423	0.020*	<0.001*
50s	0.007*	0.044*	0.423	-	0.243	0.014*
60s	<0.001*	0.001*	0.020*	0.243	-	0.195
70s	<0.001*	<0.001*	<0.001*	0.014*	0.195	-

Figure 6.18 shows significant correlations between the proportion of participants who had the lowest and highest *hardness* sensitivity with age based on the accuracy of the post-rank test. The highest *hardness* sensitivity had a quadratic correlation with ageing (p= 0.003, R^2=0.98). The trend line shows that the proportion of the highest *hardness* sensitivity decreases after age 40s. The proportion of the lowest hardness sensitivity participants is less than 10% until the age 50s (Linear correlation: p= 0.016, R^2=0.80).

Based on the crossover point between the two trend lines, the age 60s can be considered as the turning point of a reduction in masticatory function according to the different levels of *hardness* sensitivity. Significant differences between the 60s and other age groups is shown in Table 6.11. Combining the results from pre-rank and post-rank tests, the age 60s is suggested to be the turning point of reduced *hardness* sensitivity, and may link to a higher possibility of masticatory dysfunction.

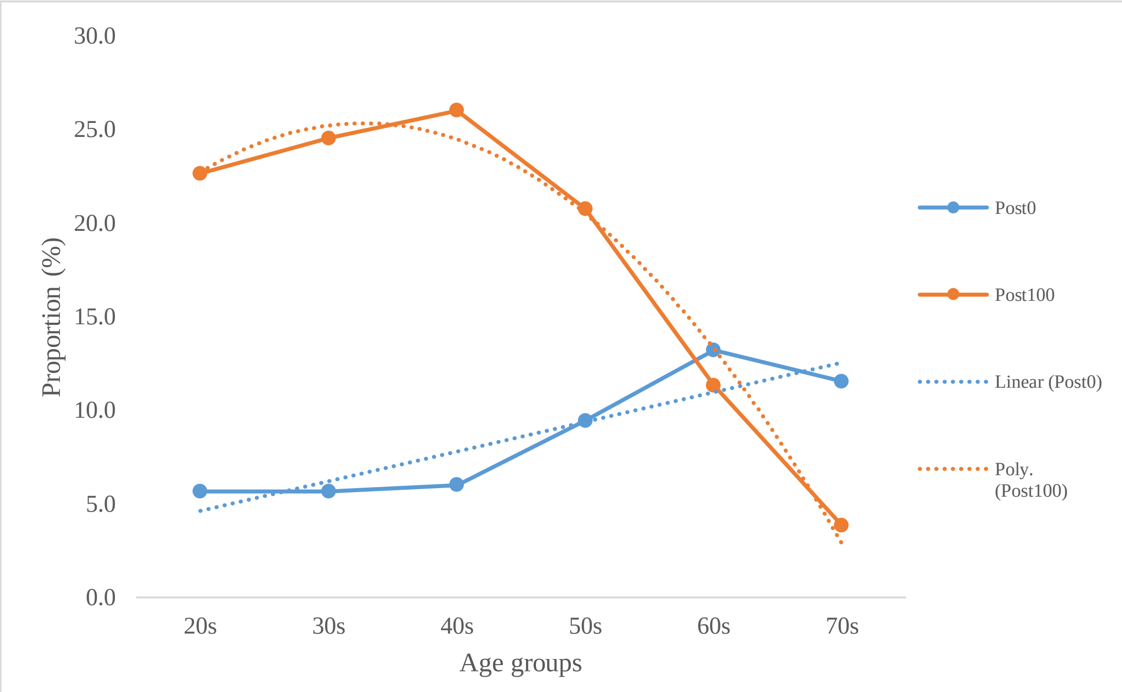


Figure 6.18 Correlations between the proportion of participants with post-rank accuracy (0% and 100%) and different age groups.

Table 6.11 Comparison of the difference of accuracy from post-rank test among different age groups; significant differences are analysed by paired-samples t.test.

Significant difference (*p*-value)	20s	30s	40s	50s	60s	70s
20s	-	0.211	0.028*	0.002*	<0.001*	<0.001*
30s	0.211	-	0.227	<0.001*	<0.001*	<0.001*
40s	0.028*	0.227	-	<0.001*	<0.001*	<0.001*
50s	0.002*	<0.001*	<0.001*	-	<0.001*	<0.001*
60s	<0.001*	<0.001*	<0.001*	<0.001*	-	0.020*
70s	<0.001*	<0.001*	<0.001*	<0.001*	0.020*	-

6.3.5 Comparison of Objective Maximum bite force (MBF) between 20s and 70s

In section 5.3.3, the objective MBF for panellists aged between 20yrs and 30yrs has been illustrated. To explore the influence of ageing on objective masticatory function, the MBF of panellists (*n*= 30) aged above 70yrs was tested by the ELF system. Figure 6.19 shows the distribution of MBF between the youngest and oldest groups. As Figure 6.19(A) shows, the strongest MBF is 607.5 N (from the 20s group), the weakest MBF is 102.8 N (from the 70s group), and the average MBF is 326.1±105.5 N. The majority of participants' MBF from 20s (75%) and 70s (76.6%) age groups is between 200N and 450N, which can be described as normal biters. However, only one 70s age participant's MBF is above 450N as an extraordinary biter, while seven extraordinary biters are found in the 20s group. The stronger MBF of the 70s extraordinary biter suggeststhe lack of uncomfortable feeling during the test, which may relate to a reduced sensitivity to perceive texture (trigeminal sensation). The proportion of weak biters whose MBF is below 200N is 20% in the 70s, but less than 1% is found in the 20s. In addition, there is a significant difference in the mean MBF between the 20s and 70s age group (p=0.03). This evidence that ageing influences the MBF suggests that, as a consequence, a reduction of masticatory function may also be associated with ageing.

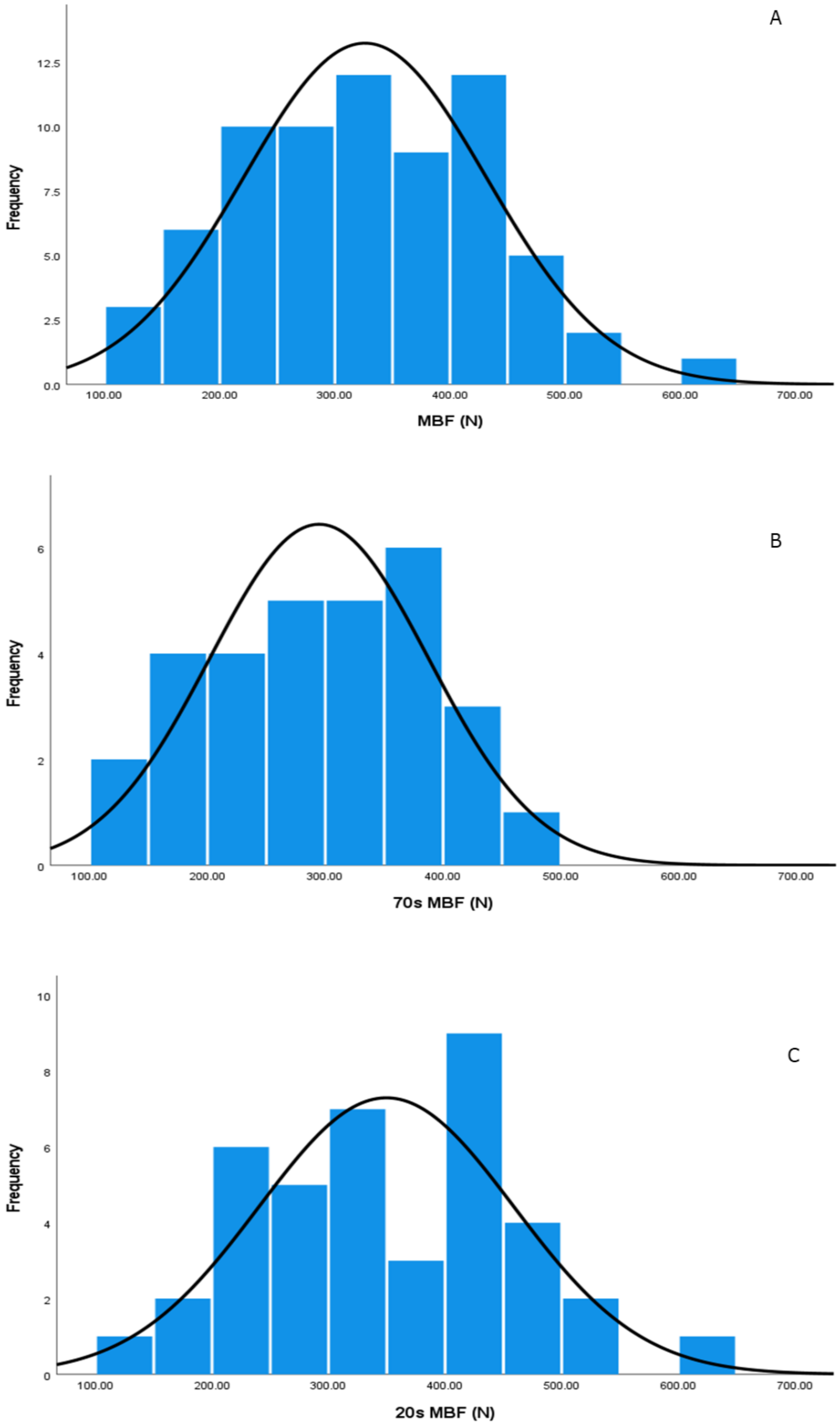


Figure 6.19 Distribution of participants' MBF: A: Combination of 20s and 70s participants (*n*=70); B: 70s (*n*=30); C: 20s (*n*=40).

To investigate the difference in MBF by gender, Figure 6.20 shows that gender, as an independent factor, relates to MBF for the two different ages. As section 5.3.3 discussed, there was no significant difference in MBF between female and male groups in the 20s age groups. However, the MBF of 70s' females is significantly weaker than 70s' males (p=0.002). The average MBF of 70s' females is 245.4 ± 87.3N, while the males' average is 344.1 ± 70.9 N. The maximum MBF of the 70s groups is 463.1 N from the male participants, while the weakest 70s biter was female (102.8 N). When comparing the female participants of different age groups, the difference between 20s' females (Mean= 396.9 ± 97.4 N) and 70s' females is significant (p<0.001). However, there is no difference in MBF between 20s' males (Mean= 329.6 ± 107.5 N) and 70s' males. The significant difference of MBF in females explains that ageing may have a stronger influence on the masticatory function in the MBF domain for females. Ageing will also be associated with other factors to affect masticatory function.

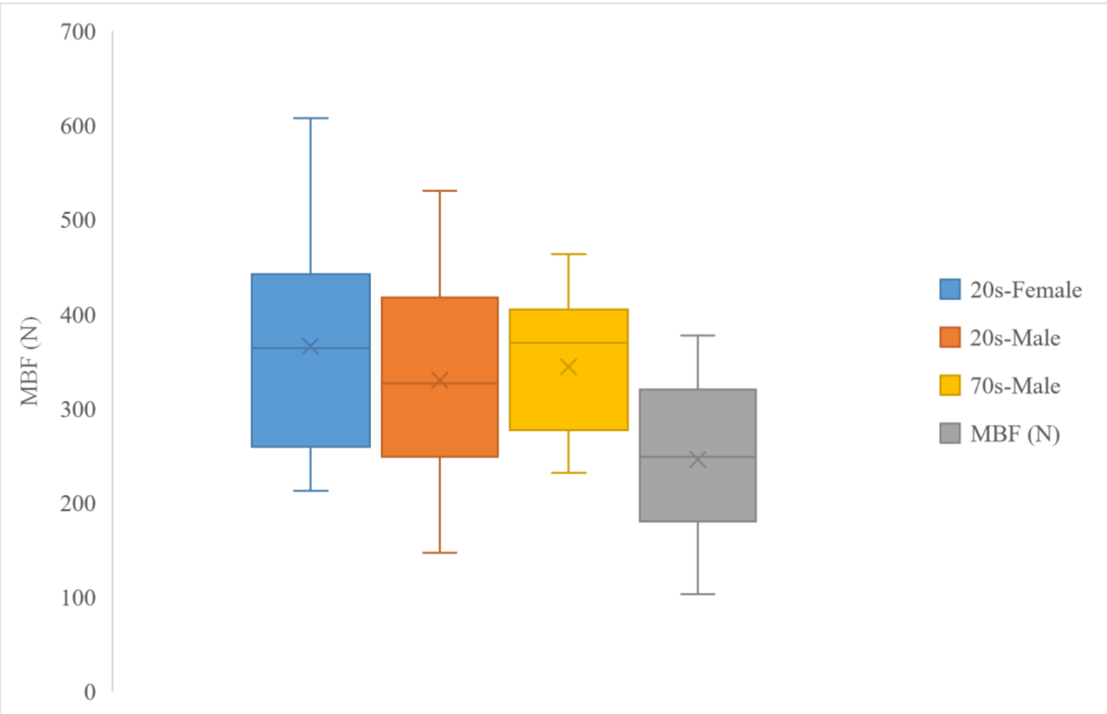


Figure 6.20 Box plots of MBF by gender from the 20s and 70s age groups.

6.3.6 Key indications of Masticatory Function by the New Measurement across lifespan

6.3.6.1 Turning point in masticatory function with age

The project's first aim was to use the new measurement to investigate the turning point of masticatory function across the lifespan in Auckland. From the results of Level 5 biting difficulty of the set of gel-based model foods among the six age groups, the proportion of participants who rated M5 and M4 with Level 5 biting difficulty increased with ageing. The model food-M6, the hardest texture model food, was rated by more than 85% of each age group's participants as a Level 5 and Level 4 difficulty to bite. Although the proportion of participants who rated the three softer model foods (M3, M2 and M1) with a Level 5 biting difficulty was zero in the 20s-60s age groups, a small proportion of 70s participants still reported Level 5 biting difficulty for these samples. The first assumption is that the turning point of masticatory function is the age of 70s based on the rate test. Similar speculation was presented for the rank test, where poor rank accuracy increased in elderly individuals. In the subjective measurement of masticatory function (self-assessed masticatory status questionnaire), the 70s had the worst oral health condition from five domains: the number of natural teeth loss, the condition of teeth (denture condition), the frequency of toothache, the hardness preference and limitation and self-rated levels of bite force. Many studies [1, 23 – 27, 177] found that through other reductions of oral physical and psychological functions, including the number of missing teeth, periodontal disease, degenerated muscle strength and decreased motor skills, ageing leads to a decline of masticatory function in elderly individuals. The quality of the masticatory function questionnaire consists of six dimensions, and three dimensions of the 70s group significantly differ from other age groups, specifically biting meats, raw foods and dried foods. The objective measurement of masticatory function was applied to the 20s and 70s age groups to measure the maximum bite force generated between the molars. The maximum bite force of the 70s is significantly weaker than that of the 20s. Decreased bite force with increasing age has been reported previously [426], which postulated that decreasing masseter muscle size with ageing reduces masticatory function [278]. Feine & Lund (2006) [22] insisted that subjective assessment directly presents the perceptions of patients and reflects their masticatory performance. The measurements can discriminate differences before and after clinical treatments. Very few studies have attempted to explore correlations between masticatory function as assessed by objective and subjective conventional measurements. Two studies show that self-assessed ability of mastication is weakly correlated to objective masticatory function [4, 415]. The validity of the new measurement is proven by objective maximum bite force (MBF) measurement in our study. The result shows that the 70s' MBF is significantly weaker than the 20s; a similar result was found in the new measurement, showing that the 70s' masticatory function differs from younger age groups. Compared with the conventional masticatory function measurement, the new method is more useful for assessing masticatory function with ageing in large populations by linking *hardness* perception with the food mechanical properties. Based on results of rate (biting difficulty of M3) and rank (hardness sensitivity from pre-rank test) test, other assumption is that the 50s age may be the start point of reduced masticatory function.

6.3.6.2 Evaluation of maximum comfortable bite force

The project's second aim was to evaluate the maximum comfortable bite force by the gel-based method, and how it relates to the maximum comfortable hardness texture for an individual based on *hardness* perception. The biting difficulty levels link *hardness* perception from the sensory test to the hardness texture from the compression test. The lower biting difficulty level indicates increased ease and comfort to bite the given hardness texture. Based on the significant relationship between ageing and the proportion of participants who had Level 5 biting difficulty, the model foods with different levels of hardness texture can reflect maximum comfortable hardness texture for different age groups. Figure 6.21 demonstrates the proportion of participants who rated M4, M3 and M2 as Level 5 biting difficulty foods across the different age groups. For a given group, it was assumed that majority of participants are able to comfortably bite the model food texture as long as the proportion of participants who have Level 5 biting difficulty is below 2.5%. A study of texture perception found that the elderly have some difficulty chewing tough food (e.g. meat), which may link to the reduction of jaw muscle activity (EMG) [282]. The biting difficulty level in our study predicts that the maximum comfortable hardness texture would be between M3 and M2 for 98% of the 70s individuals. The proportion of participants who had Level 5 biting difficulty for the three intermediate gel-based model foods (M4, M3 and M2) significantly increased with ageing. As shown in Figure 6.21, 2.5% works well as a threshold for discriminating the majority of participants' maximum comfortable texture.

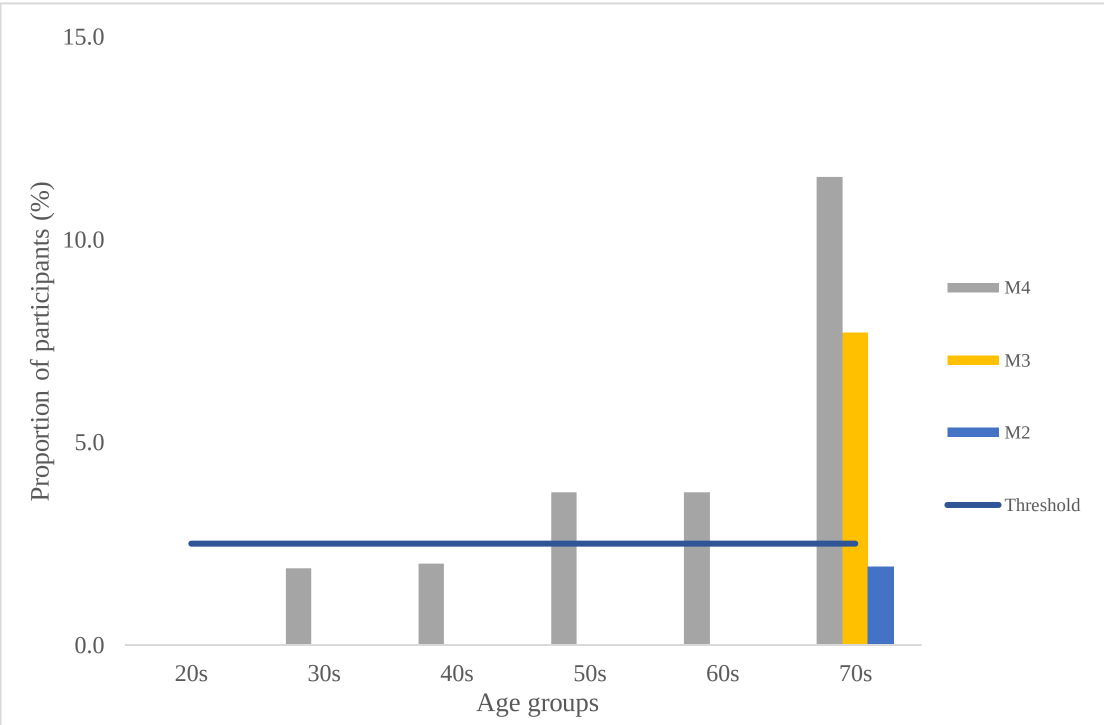


Figure 6.21 Proportion of participants have Level 5 biting difficulty of M4, M3 and M2 among six age groups and threshold of discriminating maximum comfortable bite force.

Combining the hardness of the six gel-based model foods with seven real foods as measured by TPA (refer Section 5.3.1.3.1), the maximum comfortable bite force can be related to food mechanical property by objective measurement (compression test). In the 20s age group, no 20s participants have Level 5 difficulty when biting M4, indicating that the 20s individuals' maximum comfortable texture is above M4 (between M5 and M4). The maximum comfortable bite force of age between 20-30yrs is the strongest and corresponds to a maximum comfortable hardness texture between M5 and M4, which is equal to the hardness texture of hazelnuts. In the 30s and 40s age groups, approximately 2% of the participants have Level 5 biting difficulty for M4, predicting that M4 may be 30s and 40s' maximum comfortable hardness texture. This is equivalent to a real food's texture softer than hazelnuts. In the 50s and 60s age groups, the proportion increased to 3.8%, indicating a softer maximum comfortable texture than the 30s and 40s'. Yet, the 50s and 60s' proportion of biting difficulty for M3 is zero. Hence, the 50s and 60s' maximum comfortable bite force may be between M4 and M3, equal to a similar hardness as M&M chocolates. In the elderly group, the proportion of participants who had Level 5 biting difficulty for M4 and M3 was 26.9% and 11.5%, respectively. With the hardness softening from M3 to M2, the proportion of elderly participants who rated the samples as a Level 5 biting difficulty decreased to below 2.5%. The sensory result from the rate test prove that a significantly higher proportion of elderly individuals aged above 70yrs have difficulty biting foods harder than M2's hardness texture. Hence, the maximum comfortable bite force of healthy elderly aged above 70yrs is linked to a maximum comfortable hardness texture between M3 and M2, which is equivalent to real food textures between milk candy and M&M chocolate.

6.3.7 Assessment of Masticatory Function by establishing a Personal Profile

A personal profile has been established to develop the assessment of masticatory function by the new measurement. The profile consists of ten domains: age, the number of natural teeth loss, the conditions of teeth (replaced teeth/wearing dentures), the frequency of suffering toothaches, the preference and limitation of hardness texture, self-rated levels of bite force, QMFQ total score, the sum of six model foods' biting difficulty levels and pre/post-rank accuracy. Particular requirements can be used to evaluate whether the individual has symptoms of impaired masticatory function in the corresponding domain.

6.3.7.1 Requirement 1: Age

Many studies have revealed a significant difference between old and young individuals in their maximum bite force and jaw muscle activity (masseter and pterygoid muscles) [5, 236, 266, 281]. In the maximum bite force test by ELF system, there is a significant difference in MBF between the 20s groups and 70s groups in our study. The MBF of 70s' participants is significantly weaker than that of 20s', implying that the 70s group may suffer from reduced masticatory function. Osterberg *et al*. (1996) [248] divided the elderly group into three subgroups: young-old subgroup (60-65 years old), middle-old subgroup (70-75 years old) and very-old subgroup (>80 years old). They found that the older subgroup of elderly have significant impairment of chewing ability. In the age domain of the profile, >70yrs is the requirement for increased risk of reduced masticatory function.

6.3.7.2 Requirement 2: Number of natural teeth loss

Most research has found that masticatory ability is strongly correlated to the number of teeth. An individual with less than 20 natural teeth begins to have chewing difficulties [227, 228]. Some studies [15, 39] reported that chewing ability was impaired significantly for individuals missing more than 7 teeth. As Figure 6.1 shows, 92% of 20s participants lose less than two natural teeth while 23% of 70s' number of teeth loss is 0-2. The proportion of participants losing 3-4 teeth increased from 2% (20 yrs) to 23% (70 yrs) with ageing. Similar correlations were found for the proportion of participants losing 5-6 and 6^+ teeth with ageing, respectively. However, the proportion of participants losing 1-2 teeth is not significantly related to ageing. 1-2 natural teeth loss may be common across the lifespan. For many participants of this project, missing 3-4 natural teeth led to wearing a partial denture or implant-supported prostheses. The masticatory performance of individuals with less than three posterior FTUs is reduced, and partial dentures can only compensate for part of the decreased chewing function [244]. In the teeth loss domain of the profile, ⩾3 natural teeth loss is the requirement for increased risk of reduced masticatory function.

6.3.7.3 Requirement 3: Condition of teeth

Many reports have shown that wearing dentures is related to poor oral health [427, 428]. Liang *et al*. (2020) [429] indicated that older individuals with removable dentures have poor chewing ability with worse oral health conditions. Although implant-supported prostheses can significantly rehabilitate the patient's mastication [430], the chewing efficiency of patients wearing this denture might limit the improvement of masticatory function [431]. A strong correlation was observed between the proportion of participants wearing dentures and ageing (Figure 6.4). The proportion of remaining natural teeth decreased with ageing, while the opposite trend was true for the proportion of participants wearing dentures. Since wearing dentures affects masticatory function with ageing, the one requirement of this domain is wearing dentures, including fixed or removable partial dentures, implant-supported dentures and complete dentures. The influence of replacement of natural teeth on masticatory function has found that denture wearers chewed more cycles and finished with a larger median particle size for swallowing than fully dentate individuals in the elderly group [252]. Furthermore, some studies suggested [228, 232] that 21 teeth were the lowest requirement for sufficient masticatory ability. In the condition of teeth domain of the profile, wearing dentures and missing more than three teeth without wearing a denture are the two requirements to evaluate the reduction of masticatory function.

6.3.7.4 Requirement 4: Frequency of toothache

Dental diseases, including periodontitis, dental caries and pericoronitis, cause toothache and lead to tooth loss [432]. Caries commonly occur in the first part of life, but periodontal diseases are a major cause for tooth loss after 50 years old [253, 254]. The reduced tissue of periodontitis has been determined to affect the adjustment of bite force [17]. In the long term, frequent suffering from the diseases impairs oral function, food satisfaction and eventually quality of life [433, 434]. The frequency of toothache has been self-reported by participants, classified into four levels. Level 0 represents the participant who never suffered from toothache, which indicates maintaining good oral health. With increasing level of toothache experiences, the participants more frequently suffered from toothache relating to decreased oral health. As Figure 6.7 shows, the largest proportion of participants' frequency of toothache was Level 1 among each age group (36.5%-60.8%). This suggests that Level 1 (the last toothache occurred more than a year ago) is the most common frequency of toothache for individuals, and does not link to unhealthy oral condition and/or decreased masticatory function. In the 70s participants' distribution of toothache frequency, 28.8% of the participants had a toothache in the last one year (Level 2), while 19.2% have not suffered from toothache (Level 0). Except for the youngest participants (17.0%), less than 10% of the 30s-60s participants' toothache is Level 2. A significantly different proportion of participants have Level 2 of toothache frequency between elderly and younger groups. Due to the progression of disease with time, poor oral health is more prevalent in the elderly [365]. The extent and severity of periodontal diseases that impair oral health increase with ageing [435]. Level 2 can be the turning point of oral health-related deterioration, leading to the reduction of masticatory function. In the condition of frequency of toothache domain of the profile, suffering toothache within the last one year is the requirement to evaluate the reduction of masticatory function.

6.3.7.5 Requirement 5: Texture preference

In the healthy elderly, chewing behaviour changes to compensate for the reduction of masticatory function, leading to dietary changes. In the questionnaire used in this study, the participants self-reported their chewing preference by hardness texture. From Figure 6.9, the percentage of participants who prefer chewing medium texture foods decreased with ageing while the preference for soft texture foods increased with ageing. A study of texture perception assessment in elderly groups hypothesised that denture wearers had higher acceptability of *juiciness* than *tenderness* due to severe masticatory deficiency [436]. Another study found that the reduction and dysfunction of masticatory performance can affect quality of life for individuals who prefer to intake less hard foods [420]. 37% of elderly participants' texture preferences are soft, which link to a decreasing masticatory function. The majority of participants' preference texture is medium regardless of age – medium texture is the most common texture individuals prefer to bite. In the condition of the texture preference domain of profile, soft preference is the requirement for increased risk of reduced masticatory function.

6.3.7.6 Requirement 6: Hardness texture limitation

Hardness texture limitations were self-assessed on a line scale (VAS=10 cm) from the questionnaire, and later converted to a 100 scale. Fontijin-Tekamp *et al*. (2000) [16] and Hatch *et al*. (2001) [130] claimed correlation coefficients between MBF and masticatory function as strong as 0.8. A higher self-perceived *hardness* limitation score reflects that participants can bite harder texture foods, which can relate to a stronger bite force without decreased masticatory function. The highest average score (80.35±17.32) was found in the youngest group, while the average score of the other five groups ranged from 52.79 to 62.43 (Figure 6.10). The difference in score between the youngest age group and the other five age groups were significant ($p< 0.001$). It can infer that 20s participants are the strongest biters and generally feel invincible, leading to the highest self-perceived *hardness* limitation scores. With increased hardness, an increasing trend in chewing duration (time), number of chewing cycles and bite force were found in many research studies using different types of artificial food models: gelatin-based [78, 156], gellan gum [162], tablets with $CaCO_3$ and cellulose [163] and hydrocolloid gels [164]. The first quartile of 20s' *hardness* limitation score is 69.26, which means that 75% of the youngest participants' scores were above approximately 70. The participant whose *hardness* limitation score is over 70 may link to a moderate and above-average condition of masticatory performance. In the condition of hardness texture limitation domain, < 70 hardness limitation score (on a 100 points scale) is the requirement to evaluate the reduction of masticatory function.

6.3.7.7 Requirement 7: Self-rated level of bite force

Bite force is a valuable indicator for assessing the efficacy and function of masticatory performance in dental occlusion [13]. In dental studies, bite force has been used as an essential measure for evaluating the effect of various dental treatments [117] and procedures [169]. In the questionnaire, the participants self-assessed their bite force on a 5-point scale. 3-5 points indicates the participant's self-assessed their bite force is between good and excellent. However, a self-assessed score between 1-2 points reflects their bite force is below average. A significant relationship between bite force and masticatory function was found previously, where lower bite force corresponded to reduced masticatory function [16, 130]. In the condition of self-assessed bite force, < 3 points is the requirement to evaluate the reduction of masticatory function from a subjective aspect.

6.3.7.8 Requirement 8: QMFQ

QMFQ has been proved valid for assessing the quality of masticatory function in participants with or without caries experience [407]. A lower QMFQ score represents lower difficulty in biting food, and thus better subjective masticatory function in this study. In the questionnaire, each dimension's score was between 0 (never) and 4 (always), and the range of overall score was from 0 to 24 for all six dimensions. Significantly higher QMFQ scores were observed between the 70s group and other age groups ($p < 0.001$), which indicates that age above 70yrs may be the threshold for decline in masticatory function. Compared to younger age groups, the median score of the oldest group (70s) was 6.3 higher than other groups' median (1.8-3.1) and the third quartile total scores (4.0-6.1). In the condition of the QMFQ dimension, > 6.3 is the requirement to evaluate the reduction of masticatory function.

6.3.7.9 Requirement 9: Rank accuracy

As presented in Table 6.9, the rank accuracy from pre-rank and post-rank tests is significantly related to ageing (Pearson's correlation). The proportion of participants with higher *hardness* sensitivity, whose pre-rank accuracy was 67% ($p= 0.012$) or 100% ($p= 0.013$), negatively related to ageing. Older participants present a lower rank accuracy in the rank hardness textural test. The negative correlations suggests that ageing affects the oral sensation of *hardness* because of the reduction of masticatory function. In the condition of rank accuracy, < 67% is the requirement to evaluate the reduction of masticatory function.

6.3.7.10 Requirement 10: Sum of biting difficulty levels for six gel-based model foods

Many studies have proven that tougher foods becoming more difficult to chew causes degeneration of chewing function, which along with changes to salivary flow rate, leads to dietary changes [219, 228, 238]. Although the sum of the six model foods' biting difficulty levels as an independent variable does not significantly relate to ageing, the sum of levels as the selection variable enhances the multiple regression model related to ageing (Section 6.3.3). Table 6.12 compares the multiple regression models linking age as an independent variable related to various dependent variables, when associated with or without the sum of biting difficulty levels of model foods as a selection variable.

Based on p-value and R^2 in Table 6.12, using 19 (for sum of biting difficulty levels) as a selection variable improved the prediction of age-related number of teeth loss, condition of teeth and quality of masticatory function in the multiple regression models. Hence, a sum of biting difficulty levels equivalent to 19 may be the threshold for decreased oral health, quality of masticatory function and self-assessed bite force with ageing. In the condition of biting difficulty levels, ⩽ 19 is the requirement to evaluate the reduction of masticatory function.

Table 6.12 Multiple regression models linking age as independent variable related to dependent variable, associated with/without the sum of biting difficulty levels of model foods as a selection variable.

Dependent Variable	Selection Variable	Independent Variable	Standardized β	t	p	Prediction R^2
Number of teeth loss	N.A	Age Constant	0.615 -	13.856 -6.368	<0.001 <0.001	0.379
	Sum ≥19	Age Constant	0.620		<0.001 <0.001	0.385
Condition of teeth	N.A	Age Constant	0.531 -	11.128 -0.224	<0.001 0.823	0.282
	Sum ≤19	Age Constant	0.543		<0.001 <0.001	0.295
QMFQ overall score	N.A	Age Constant	0.232 -	4.233 3.347	<0.001 0.001	0.054
	Sum ≤19	Age Constant	0.215 -		<0.001	0.064

6.3.7.11 Profile scale

Based on the criteria of each domain tested by the new measurement including sensory tests and the questionnaires, the assessment profile of masticatory function can be established as presented in Table 6.13. The assessment score is from 0 to 10, in which a higher score represents worse masticatory function.

Table 6.13 Assessment profile of masticatory function by ten domains with the specified criteria.

Domain	Criteria	Yes	No
1	Age > 70yrs	1	0
2	Number of teeth loss >3	1	0
3	Wearing denture or losing teeth >3	1	0
4	Last toothache ≤ 1yrs	1	0
5	Prefer to biting soft food in daily	1	0
6	Hardness limitation score ≥7.0	1	0
7	Self-assessed bite force ≤2	1	0
8	Total QMFQ score >6.3	1	0
9	Rank accuracy ≤50%	1	0
10	Sum biting difficulty levels ≥19	1	0
Total score		**0-10**	

Based on the assessment profile of masticatory function, the distribution of total scores among different age groups (n = 314) is demonstrated in Figure 6.19. The difference in assessment scores of six age groups is shown in Table 6.14. The 70s groups' assessment scores were significantly higher than that of the five younger age groups, while the 20s groups' scores were significantly lower than those of other older groups. The assessment scores of 30s participants were lower than other age groups, excluding the 20s. The first and third quartiles of each age group's scores are different, as shown in Figure 6.22. The first quartile of the 70s' score is 7 points higher than the third quartile of the other five age groups; suggesting that the assessment profile score of 7-10 points can link to decreasing masticatory function. Except for the third quartile of the 20s' score, other age groups' were above 3 points, assuming 3-6 points can link to moderate masticatory function. A score between 0-2 points links to the excellent condition of mastication. Although there was no significant difference in scores between the 40s, 50s, and 60s age group, the third quartile of 60s participants' scores (5 points) is higher than the 40s and 50s scores. 5-6 points may be the potential scores linked to the onset of reduced masticatory function.

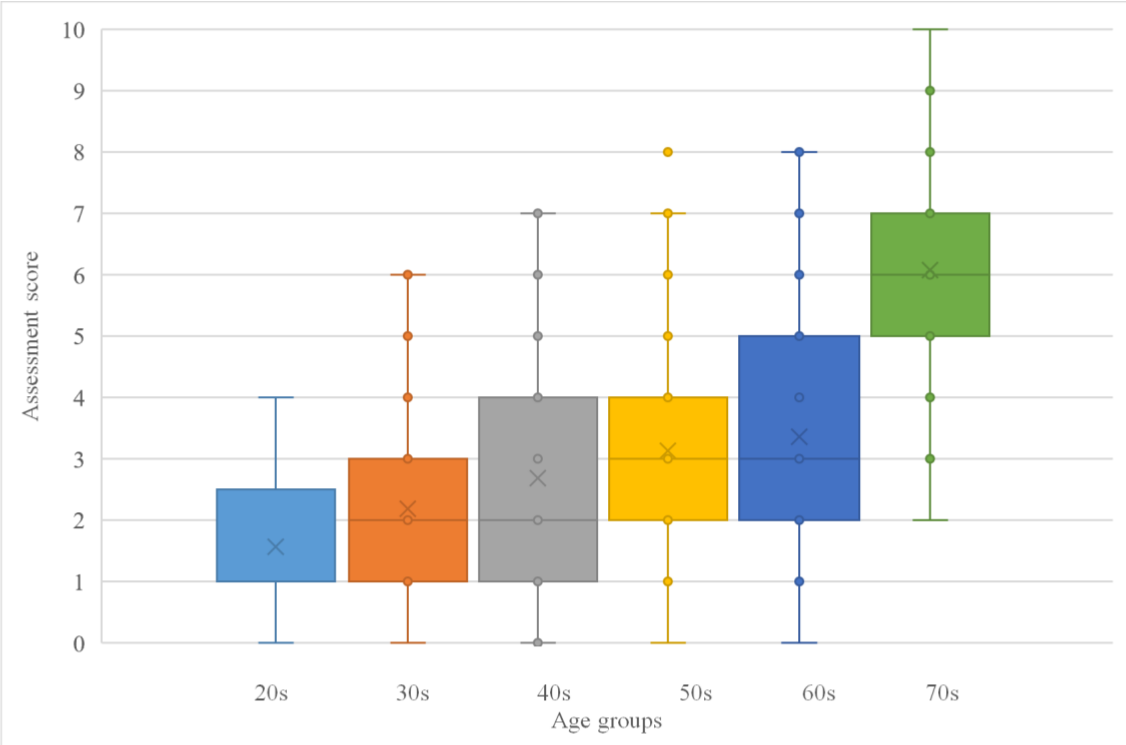


Figure 6.22 Box plot of assessment scores among six different age groups.

Table 6.14 Cross-comparison of the difference of assessment scores among six age groups, analysed by paired sample t.test.

Significant difference (*p*-value)	20s	30s	40s	50s	60s	70s
20s	-	0.008	<0.001*	<0.001*	<0.001*	<0.001*
30s	0.008*	-	0.13	0.003*	<0.001*	<0.001*
40s	<0.001*	0.13	-	0.23	0.08	<0.001*
50s	<0.001*	0.003*	0.23	-	0.55	<0.001*
60s	<0.001*	<0.001*	<0.001*	0.55	-	<0.001*
70s	<0.001*	<0.001*	<0.001*	<0.001*	<0.001*	-

Table 6.15 shows the detailed profile of the 16 participants whose assessment scores are between 8 to 10 points from the ten domains, which can be evaluated as poor masticatory function. The profile shows that the ratio of males and females is 0.45, and 87% of participants are over 70yrs. It suggests that elderly females have a high risk of suffering from masticatory dysfunction. The MBF of males is much greater than that of females [23, 133]. Except for one participant who has not worn a denture, 15

participants wore different types of dentures. 5 out of 7 participants assessed as having the worst masticatory function (score 9-10pts) wear a complete denture, which implies wearing a complete denture has the most significant influence on daily chewing. Complete dentures are described as a poor substitute for the edentulous [237]. 69% of the 16 participants lost more than six natural teeth, indicating that increased natural teeth loss affects masticatory function. 75% of the 16 participants had toothache experience in the last one year, suggesting that a higher frequency of toothache is linked to the reduction of masticatory function. The majority of participants prefer chewing soft food with a low limitation hardness score (< 55.00). Half of the participants experienced a higher difficulty level (⩾19) to bite the set of gel-based model foods. 81% of participants have poor discrimination of hardness texture (Rank accuracy <67%). The majority of the 16 participants self-assessed their quality of masticatory function to be low, and bite force to be fair or poor.

Therefore, a higher assessment score (8-10 pts) is an indicator of worse condition of mastication. The assessment reflects poor oral health status, a higher self-assessed score of QMFQ, softer texture preference, lower limitation of hardness, lower self-assessed bite force, and more difficulty to discriminate and bite through model foods by hardness levels.

Table 6.15 Detailed profile of participants whose assessment scores are 8-10 points, corresponding to poor masticatory function.

Code	Age	Gender	Dental[1]	Missing teeth	Toothache	Texture Preference	Texture Limitation	Self-assess Bite force	QMFQ	Rank %	Difficulty Levels	Total score
1	70	M	7	5-6	≤1yrs	Soft	42.62	Fair	10.2	0.0	28	10
2	70	M	7	>6	≤3M	Soft	73.77	Poor	11.5	16.7	16	9
3	70	F	5	>6	≤1yrs	Soft	24.59	Fair	13.0	50.0	14	9
4	70	F	7	>6	≤1yrs	Soft	50.82	Fair	8.3	33.3	10	9
5	70	F	5	>6	>1yrs	Soft	24.59	Poor	7.6	50.0	19	9
6	70	F	7	>6	Never	Soft	11.48	Fair	8.6	16.7	25	9
7	70	M	7	>6	≤3M	Soft	73.77	Poor	11.5	16.7	28	9
8	70	F	5	>6	>1yrs	Medium	25.41	Fair	6.8	16.7	22	8
9	70	F	4	3-4	≤1yrs	Soft	65.57	Fair	9.0	16.7	16	8
10	70	F	5	>6	≤1yrs	Soft	13.93	Poor	15.0	66.7	23	8
11	70	F	5	5-6	≤1yrs	Soft	77.87	Fair	13.1	66.7	13	8
12	70	F	5	>6	≤3M	Medium	53.28	Fair	7.2	16.7	16	8
13	70	M	3	3-4	≤3M	Soft	70.49	Poor	15.6	50.0	9	8
14	70	F	5	>6	≤1yrs	Soft	0.00	Fair	8.4	0.0	18	8
15	70	M	3	3-4	≤3M	Soft	29.51	Poor	8.1	33.3	12	8
16	70	F	7	>6	>1yrs	Soft	10.66	Fair	11.4	33.3	19	8

Dental[1]: 3: missing several teeth without wearing a denture; 4: wearing a fixed partial denture; 5: wearing a removable partial denture; 6: having the implant-supported prosthesis; 7: wearing a complete denture.

6.4 Conclusions

The gel-based measurement proved useful for assessing masticatory function, linking subjective and objective masticatory function by hardness perception with the mechanical property. It has been efficiently applied to a large population across the lifespan in this chapter at low cost to investigate the influence of ageing on masticatory function and maximum comfortable bite force. The assessment profile can assist in evaluating an individual's masticatory function using ten dimensions.

The correlation between masticatory function and ageing was investigated by the oral health status, self-assess bite force, texture preference and limitation, maximum bite force, the quality of masticatory function, biting difficulty and hardness sensitivity. The turning point of masticatory function appears to be in the age 70yrs, whereas the postulated the onset of reduced masticatory function is 50yrs of age.

The maximum comfortable bite force of different age groups was assessed by the rate test and related to the mechanical property of model and real foods. The 20s individuals had the strongest maximum comfortable bite force, given their maximum comfortable texture was between M5 and M4, which is equal to the hardness of hazelnuts. The 30s and 40s individuals' maximum comfortable bite force relates to the maximum comfortable hardness texture of M4, equalling to a real food texture softer than hazelnuts but harder than M&M chocolates. The 50s and 60s' maximum comfortable bite force is linked to the maximum comfortable hardness texture of M3, similar to the hardness of M&M chocolate. The maximum comfortable bite force of healthy elderly aged above 70yrs is linked to a maximum comfortable hardness texture between M3 and M2, which is equal foods textures between milk candy and M&M chocolates.

Three levels of masticatory function were established based on assessment scores evaluated from the new method, categorised as 'Poor= 7-10 pts", "Moderate=3-6 pts" and “Excellent=0-2 pts”. 5-6 points may be the threshold for the onset of reduced masticatory function. The highest assessment score (8-10 pts) corresponds to the worst condition of mastication, which can be the result of poor oral health status (missing more than six natural teeth, wearing complete dentures, toothache occurred within the last year); a QMFQ score above 8.0; soft texture preference, hardness limitation score below 55.0; self-assessed bite force is fair or poor; rank accuracy is below 50%; and sum of biting difficulty scores is above 19.0. Based on the assessment scores in this category, elderly females have a high risk of suffering from masticatory dysfunction.

In this chapter, the new measurement of maximum comfortable bite force has been proven useful and efficient for application in a large population across lifespan. Based on the results from the new measurement, the assessment profile can quantify an individual’s level of masticatory function, taking into account subjective measures as well as objective measures. In future research, a logistic regression model will be trialled to explore different weights of the ten domains. In addition, different properties of food texture should be considered in the model foods, such as crispness and tenderness, which can investigate the correlation between food texture and masticatory function for different textural preferences outside of hardness.

Chapter 7 Overall Conclusions

This chapter brings together the conclusions of chapter 5 and 6 for the convenience of the readers and also highlights some limitations of the current study.

7.1 Development of a new measurement of masticatory function

A series of gel-based model food with different mechanical properties was established by optimising the shape, size, gel type, and gelatine concentration. The *hardness* perception was assessed by sensory tests (Rank&Rate test and JND test) among 40 young and healthy participant (20-30 yrs). Mechanical properties were measured by instrumental tests including modified TPA test and RE test. The range of hardness level of the main set of gel-based model foods was spread across medium to hard texture. The softest sample was softer than milk candy, and the hardest one was comparable to hard fruit candy. The difference between each model food sample's hardness was confirmed by modified TPA test (objective measurement) and JND test (subjective measurement). The correlation between TPA-measured hardness and subjective *hardness* score is strong and positive, successfully building the relationship between mechanical properties and texture perception. Some of the model food samples make cause difficulty in biting, as designed by thicker dimensions of sample size, more plastic deformation behaviour and harder texture. The uncomfortable feeling caused by biting difficulty may link the texture perception to maximum comfortable bite force.

To compare with the objective of masticatory function, maximum bite force (MBF) of the 20s participants (n=40) and 70s (n=30) were measured by ELF system. For young adults between 20 - 30 years of age, the strongest MBF is 607.5 N, the weakest one is 146.5 N, and the average MBF is 439.6 ± 109.3 N. There is no significant difference in MBF between the male and female groups. 75% of participants' MBF is among the range from 200 N to 450 N. The average MBF of 70s' females was 245.4 ± 87.3 N, while the males' average was 344.1 ± 70.9 N. The maximum MBF of the 70s groups was 463.1 N from the male participants, while the weakest 70s biter was female (102.8 N). When compare the female participants with different age groups, the difference between 20s' females (Mean= 396.9 ± 97.4 N) and 70s' females was significant (p<

0.001). However, there was no difference in MBF between 20s' males (Mean= 329.6 ± 107.5 N) and 70s' males. The validity of the new measurement is proved by objective maximum bite force (MBF) measurement. The result showed that the 70s' MBF was significantly weaker than that of the 20s, the similar result was found in the new measurement showed that 70s' masticatory function differ from younger age groups. Compared with the conventional masticatory function measurement, the new method is available and useful for assessing the masticatory function with ageing in large populations by linking *hardness* perception with the mechanical property.

In the sensory test, a strong positive correlation was found between subjective *hardness* rating score and objective TPA-measured hardness in the six gelatin samples. The accuracy of the post-rank test improving significantly compared to the pre-rank test proves that it is necessary to arrange a trial test to help participants familiarise themselves with the model foods and collect more accurate and reliable results from the sensory test. In the JND test, it was found that a low proportion of panellists (< 30%) -can discriminate small differences of hardness, proving that there is no need to add more hardness levels of samples into the main set of model foods for the large population sensory tests. In general, the correlation between subjective *hardness* perception and objective maximum bite force is not significant. However, by converting the *hardness* rating score to the hardness deviation, we find that participants whose hardness deviation is below 10% had a strong and positive relationship with MBF.

7.2 Applied in a large population across lifespan

The gel-based measurement proved useful for assessing masticatory function, linking subjective and objective masticatory function by hardness perception with the mechanical property. Conducting the gel-based measurement (sensory tests) takes approximately 5-10 minutes with an individual. It has been efficiently applied to a large population across the lifespan at a low cost to investigate the influence of ageing the masticatory function and the maximum comfortable bite force. The assessment profile can assist in evaluating the individual's masticatory function in ten dimensions. In addition, gel-based models can be easily made and packaged in the food-safe lab and stored for more than one week in a standard fridge. The advantage of being able to prepare and store model foods means that the gel-based measurement can be easily applied in a clinical test.

The correlation between masticatory function and ageing was investigated by the oral health status, self-assess bite force, texture preference and limitation, maximum bite force, the quality of masticatory function, biting difficulty and hardness sensitivity. The turning point of masticatory function appears to be in the age 70yrs, whereas the postulated the onset of reduced masticatory function is 50yrs of age.

The maximum comfortable bite force of different age groups was assessed by the rate test and related to the mechanical property of model and real foods. The 20s individuals had the strongest maximum comfortable bite force, given their maximum comfortable texture was between M5 and M4, which is equal to the hardness of hazelnuts. The 30s and 40s individuals' maximum comfortable bite force relates to the maximum comfortable hardness texture of M4, equalling to a real food texture softer than hazelnuts but harder than M&M chocolates. The 50s and 60s' maximum comfortable bite force is linked to the maximum comfortable hardness texture of M3, similar to the hardness of M&M chocolate. The maximum comfortable bite force of healthy elderly aged above 70yrs is linked to a maximum comfortable hardness texture between M3 and M2, which is equal foods textures between milk candy and M&M chocolates.

Three levels of masticatory function were established based on assessment scores evaluated from the new method, categorised as 'Poor= 7-10 pts", "Moderate=3-6 pts" and "Excellent=0-2 pts". 5-6 points may be the threshold for the onset of reduced masticatory function. The highest assessment score (8-10 pts) corresponds to the worst condition of mastication, which can be the result of poor oral health status (missing more than six natural teeth, wearing complete dentures, toothache occurred within the last year); a QMFQ score above 8.0; soft texture preference, hardness limitation score below 55.0; self-assessed bite force is fair or poor; rank accuracy is below 50%; and sum of biting difficulty scores is above 19.0. Based on the assessment scores in this category, elderly females have a high risk of suffering from masticatory dysfunction.

7.3 Limitations

The new measurement of maximum comfortable bite force has been proved useful and efficient to apply in a large population across the lifespan. Based on the results from the new measurement, the profile can quantify the individual's level of masticatory function. However, there are several limitations expect to explore in future work.

1. In this project, the mechanical property of model foods focuses on hardness. The mono-texture is limited to explore the relationship between different texture perceptions and mechanical properties. In the future, create different mechanical properties (e.g. brittleness, tenderness) in model foods with different food ingredients can find a more significant correlation with texture-related masticatory function across the lifespan.
2. Except MBF was measured as an objective masticatory function, other objective factors should be involved to measure. In current studies, the age-related masticatory function has been related to salivary flow [1, 333], dysphagia [345, 350], and chewing efficiency [437]. To investigate the relationship between masticatory ability and masticatory performance, these factors should be considered to measure in future work.
3. To improve measurement of subjective masticatory function, including QMFQ and oral health status, the questionnaire should be expanded (i.e. include

different natural foods associated with chewing difficulties, BMI, swallowing difficulties and mouth behaviour types according to the JBMB model). It will allow the further exploration of multiple domains of masticatory ability.

4. Limited by the submission time, the statistical analysis of the large panel is still being processed. Multiple logistic regression will be involved to explore the different weights of ten domains. The optimised profile will be applied in future work to prove the validity of estimating the masticatory function.
5. A longitudinal study spanning 10 – 50 years can be undertaken, which focuses on measuring the same participant's condition of masticatory function across the lifespan.

Appendix A

Rank & Rate test sheet

This test was reviewed and approved by the University of Auckland Human Ethics Committee (Reference Number: 023536).

Rank & Rate Test

Date:
Session Number:

INSTRUCTIONS OF RANK TEST

1) Put sample into the mouth, then place it between posterior teeth (rear position of the mouth), bite the sample once.
2) Expectorate the sample into a transparent container.
3) Rank the samples' hardness.

Example:

Sample Number: 113; 185; 127

	Draft	Final Result
Hard	***113***	**113**
↓	***185***	**185**
Soft	***127***	**127**

RANK TEST STARTS HERE

Hardness Texture	Take Notes Here	Final Result
Hard		
↓		
Soft		

INSTRUCTIONS OF RATE TEST

1) Put sample into the mouth, then place it between posterior teeth (rear position of the mouth), bite the sample once.
2) Expectorate the sample into a transparent container.
3) Rate sample's hardness based on a line scale.
4) Rinse your mouth with water provided.

Example:

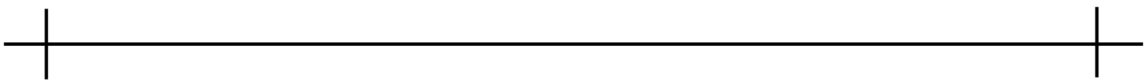
Sample Number:

113

185

127

RATE TEST STARTS HERE



eg.
Raw Tuna
Tofu

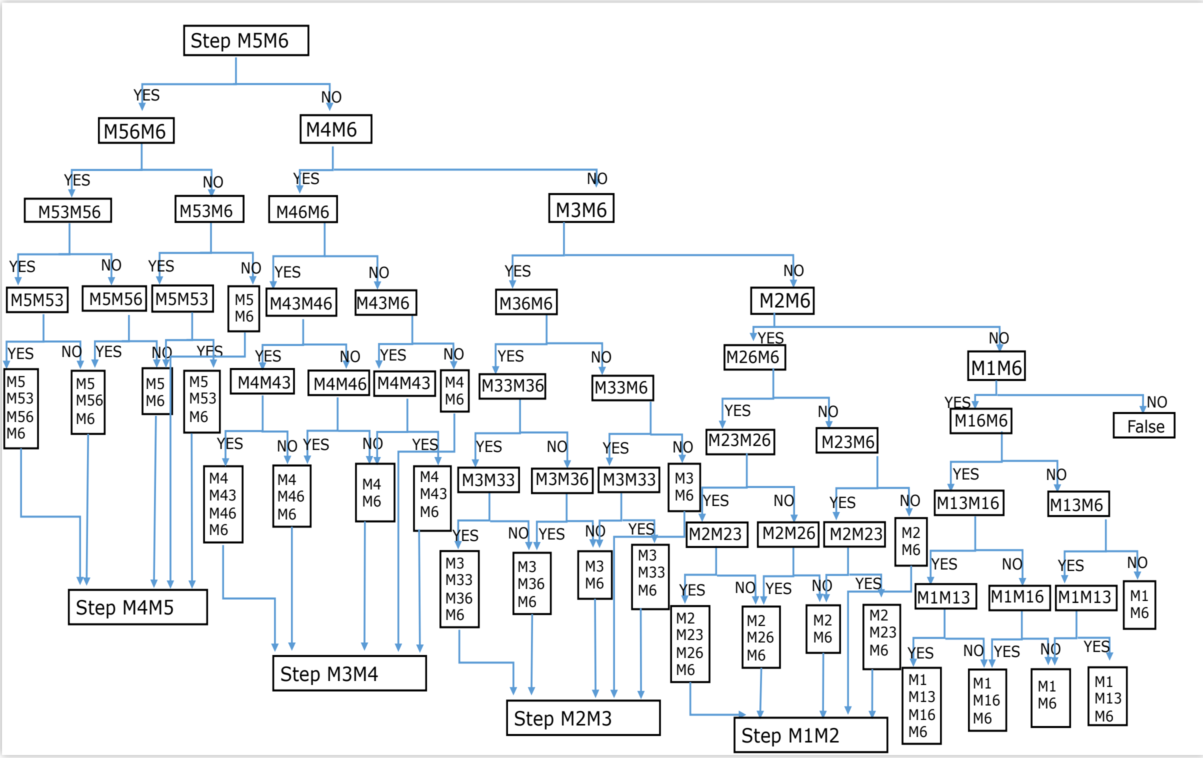
eg.
Hard Candy
Ice Cube

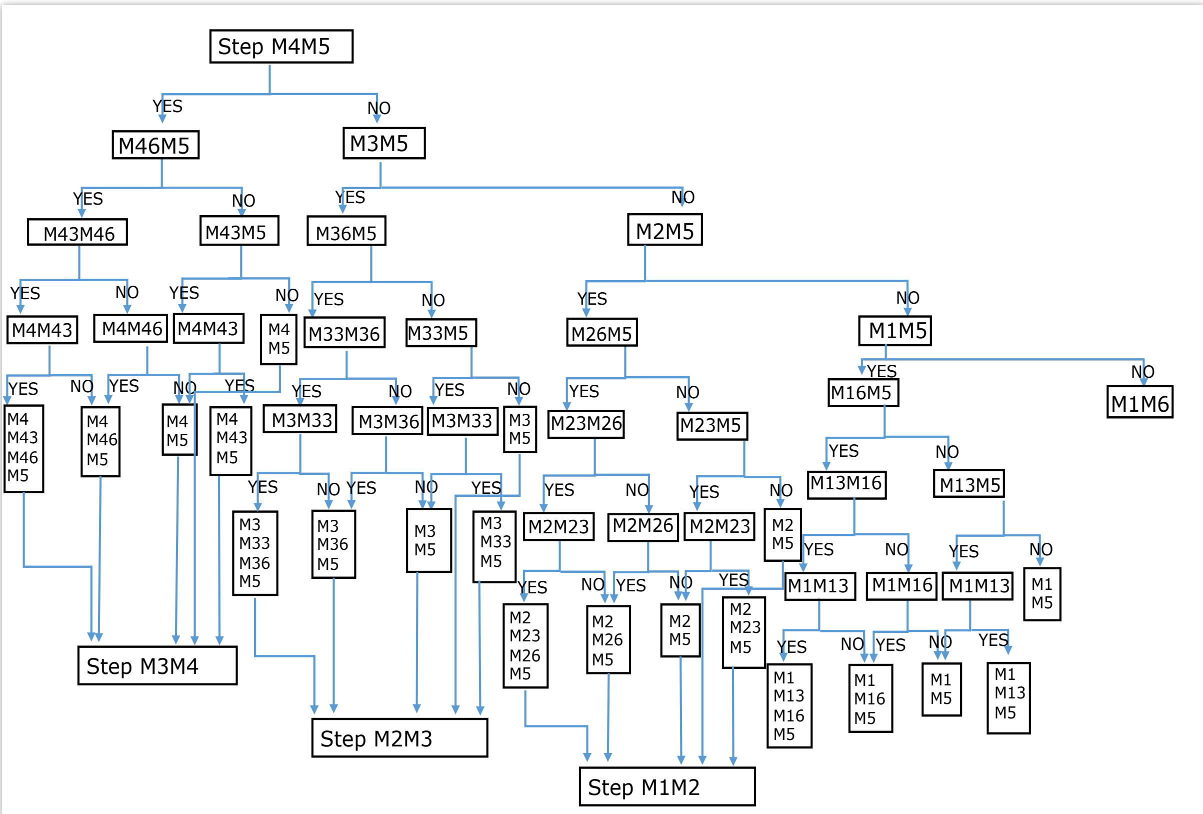
Appendix B

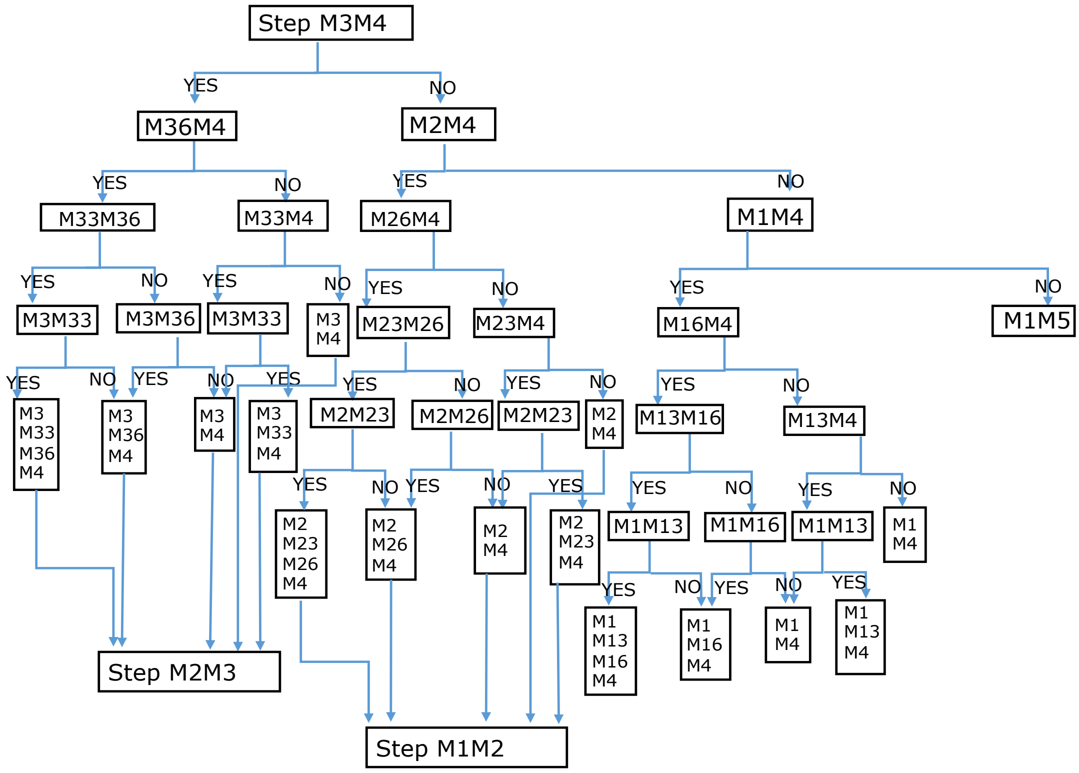
The observation schedules for JND test

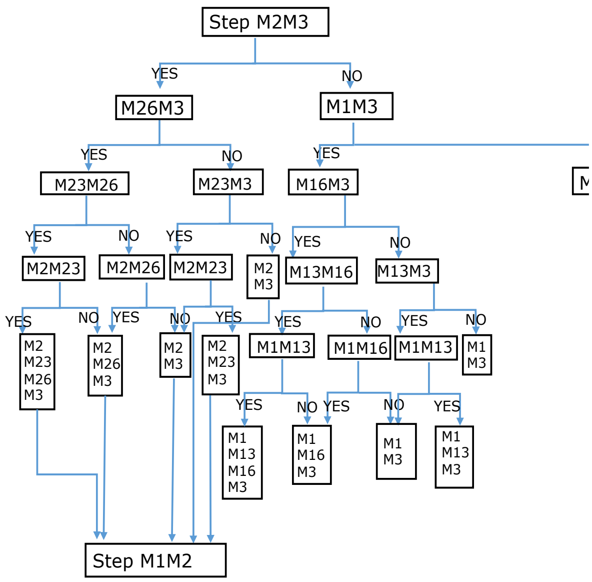
This appendix is the detailed observation schedules for JND test.

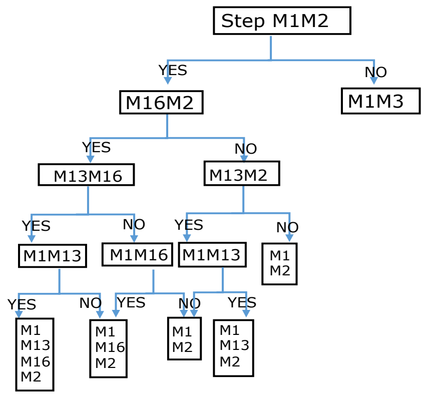
All the JND tests began by comparing M5 and M6 (Step M5M6); participants were required to bite three samples presented in random order and were asked to bite each sample once. After biting, the participant was instructed to identify the odd sample out and record his/her answer. Based on the correctness of the answer (YES/NO), the participant was required to bite different sets of samples (triangle tests) following the process of observation schedules.


Step M5M6
Step M4M5
Step M3M4
Step M2M3
Step M1M2
False


Step M4M5
Step M3M4
Step M2M3
Step M1M2


Step M3M4
M36M4
M2M4
M33M36
M33M4
M26M4
M1M4
M3M33
M3M36
M3M33
M3 M4
M23M26
M23M4
M16M4
M1M5
M3 M33 M36 M4
M3 M36 M4
M3 M4
M3 M33 M4
M2M23
M2M26
M2M23
M2 M4
M13M16
M13M4
M2 M23 M26 M4
M2 M26 M4
M2 M4
M2 M23 M4
M1M13
M1M16
M1M13
M1 M4
M1 M13 M16 M4
M1 M16 M4
M1 M4
M1 M13 M4
Step M2M3
Step M1M2


Step M2M3
M26M3
M1M3
M23M26
M23M3
M16M3
M2M23
M2M26
M2M23
M2 M3
M13M16
M13M3
M2 M23 M26 M3
M2 M26 M3
M2 M3
M2 M23 M3
M1M13
M1M16
M1M13
M1 M3
M1 M13 M16 M3
M1 M16 M3
M1 M3
M1 M13 M3
Step M1M2


Step M1M2
M16M2
M1M3
M13M16
M13M2
M1M13
M1M16
M1M13
M1 M2
M1 M13 M16 M2
M1 M16 M2
M1 M2
M1 M13 M2

Appendix C

Self-assessed masticatory function questionnaire

The questionnaires included QMFQ and the status of oral health to assess the dominant factors of masticatory function, including oral health, gender, age, habits, texture preference, self-assessed the quality of masticatory function. The questionnaires were reviewed and approved by the University of Auckland Human Ethics Committee (Reference Number: 023536).

Self-report Masticatory Status Questionnaire

Date:
Session Number:

1. Age: ☐20-30yrs ☐31-40yrs ☐41-50yrs ☐51-60yrs ☐61-70yrs ☐>70yrs
2. Gender: ☐ Female ☐ Male
3. Condition of teeth: (*Please tick as many as are appropriate. Please note an artificial crown is regarded as a full tooth and wisdom teeth (3rd molars) do not count as teeth missing.*)
   ☐ All of my teeth are remaining (directly go to Q6)
   ☐ I have one or two single teeth missing and not replaced
   ☐ I have several teeth missing, but I do not wear a denture
   ☐ I have a fixed partial denture
   ☐ I wear a removeable partial denture
   ☐ I have an implant-supported prothesis
   ☐ I wear a complete removable denture
4. How many teeth did you lose?
   ☐ 1-2 ☐ 3-4 ☐ 5-6 ☐ >6
5. When did you last experience toothache?
   ☐ Never ☐ >1 year ago ☐ During last year ☐ During last 3 months
6. What the texture of food you prefer to eat?
   ☐ Soft ☐ Medium ☐ Hard
7. How is the hardest of food texture you think you are willing to eat?

Egg pudding | Ice tube

8 ...een prevented from eating foods you would like to eat t... texture is hard to bite?
   ☐ Yes ☐ No (Directly go to Q10)

Named the food you limit or avoid to eat **mentioned in Q8:**

9. Overall, how would you rate the level of your bite force?
   ☐ Excellent ☐ Very good ☐ Good ☐ Fair ☐ Poor

Quality of masticatory function questionnaire (QMFQ)

1. Does it take you longer to finish a meal than other people?
   ☐ Always ☐ Usually ☐ Occasionally ☐ Usually not ☐ Never
2. Do you find your enjoyment of food is less than it used to be?
   ☐ Always ☐ Usually ☐ Occasionally ☐ Usually not ☐ Never
3. Do you avoid eating with other people?
   ☐ Always ☐ Usually ☐ Occasionally ☐ Usually not ☐ Never
4. Do you have difficulty chewing small pieces of beef?
   ☐ Always ☐ Usually ☐ Occasionally ☐ Usually not ☐ Never
5. Do you have difficulty chewing ground beef?
   ☐ Always ☐ Usually ☐ Occasionally ☐ Usually not ☐ Never
6. Do you have difficulty chewing hard, raw vegetables, without cutting them?
   ☐ Always ☐ Usually ☐ Occasionally ☐ Usually not ☐ Never
7. Do you have difficulty chewing hard, raw fruit, without cutting them (e.g.: apples)?
   ☐ Always ☐ Usually ☐ Occasionally ☐ Usually not ☐ Never
8. Do you have difficulty chewing crusted bread?
   ☐ Always ☐ Usually ☐ Occasionally ☐ Usually not ☐ Never
9. Do you have difficulty chewing nuts and grains?
   ☐ Always ☐ Usually ☐ Occasionally ☐ Usually not ☐ Never
10. Do you have difficulty chewing with your prosthesis?
   ☐ Always ☐ Usually ☐ Occasionally ☐ Usually not ☐ Never
11. Do you have to remove one or both of your prostheses in order to eat?
   ☐ Always ☐ Usually ☐ Occasionally ☐ Usually not ☐ Never
12. Do you have to drink while eating to facilitate swallowing?
   ☐ Always ☐ Usually ☐ Occasionally ☐ Usually not ☐ Never
13. Do you have to add sauce to your meal to facilitate swallowing?
   ☐ Always ☐ Usually ☐ Occasionally ☐ Usually not ☐ Never
14. Do you have to soak your food to facilitate chewing and/or swallowing?
   ☐ Always ☐ Usually ☐ Occasionally ☐ Usually not ☐ Never
15. Is your food choice limited because of your prosthesis/chewing ability?
   ☐ Always ☐ Usually ☐ Occasionally ☐ Usually not ☐ Never
16. In general, is the food well chewed before being swallowed?
   ☐ Always ☐ Usually ☐ Occasionally ☐ Usually not ☐ Never
17. Have you eaten beef cut into small pieces?
   ☐ Always ☐ Usually ☐ Occasionally ☐ Usually not ☐ Never
18. Has it been necessary to ground the beef before eating?
   ☐ Always ☐ Usually ☐ Occasionally ☐ Usually not ☐ Never
19. Has it been necessary to convert beef into puree in order to eat?
   ☐ Always ☐ Usually ☐ Occasionally ☐ Usually not ☐ Never

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