Copyright is owned by the Author of the thesis. Permission is given for a copy to be downloaded by an individual for the purpose of research and private study only. The thesis may not be reproduced elsewhere without the permission of the Author.

PHYSIOLOGICAL MEASURES RELATED TO CRISPNESS PERCEPTION OF EXTRUDED SNACKS

A thesis presented in partial fulfilment of the requirements for the degree

of

Doctor of Philosophy
in
Food Technology

At Massey University, Albany,
New Zealand.

Lisa Marjorie Duizer
2003

ABSTRACT

Published research for understanding crispness perception has relied on correlations of sensory results to objective measurements. This research was undertaken to evaluate the contribution of physiological responses to the perception of crispness of corn based puffed snacks.

Predictive models published in literature relate crispness perception to instrumental force and sounds produced during biting and compression. These models were used as the basis for this research. Air-conducted and bone-conducted sounds were measured using both consumer and trained panelists. A novel analysis technique, fractal analysis, was used to analyse the jagged sound wave patterns produced during biting into extruded snacks. A specialised bite force apparatus was designed for measuring bite forces produced by the incisors. All physiological results were then related to panelists' perception of crispness. To minimise sample variability, extruded snack samples were prepared and used throughout the entire trial. A range of crispness levels were achieved by equilibrating the extrudates over various water activities.

Consumer panelists and trained panelists consistently agreed on the relative crispness of the extruded snacks. Air-conducted sounds and bite force showed significant correlations with crispness, while bone-conducted sounds did not. Bite force measures were also shown to relate to instrumental measures of force. For statistical validity, the physiological data from the 39 consumers were used to develop predictive equations for crispness. Analysis of the data showed no significant correlation between the physiological data and crispness. Therefore, it was not possible to develop a predictive equation for crispness based on the physiological measures collected from consumers.

While there are reports linking crispness to various instrumental measures, this is the first time in-vivo physiological measures have been collected from a large group of individuals for development of statistically viable models for crispness. The lack of a relationship between crispness and physiological measures indicates that crispness perception across consumers is complex and not adequately explained by bite force and sounds alone.

ACKNOWLEDGEMENTS

I would like to sincerely acknowledge the support and assistance provided to me by Professor Ray Winger. Without his help, this PhD would never have been completed. I would also like to thank Dr. Osvaldo Campanella, Dr. Geoff Barnes, and Dr. Chris Findlay each of whom provided me with support in different ways throughout the course of this research.

Thanks go to Crop and Food Research Ltd., who provided seed funding for this research, Bluebird Foods Ltd. for the use of their single-screw extruder and HortResearch and Dr. Shafiur Rahman (formerly of HortResearch) for the use of the helium pycnometer. Also, Dr. Patrick Li of Crop and Food Research Ltd. is thanked for assistance with extruding and answering all of my questions about extrudates.

Massey University is gratefully acknowledged for assistance throughout this project. The Institute of Food, Nutrition and Human Health (formerly the Department of Food Technology) provided me with time and support to carry out this research while working as a lecturer. Financial assistance from the Massey University Research Fund helped fund this research. The Academic Women's Award allowed me to take time off from lecturing to start writing this thesis.

I would like to thank Garry Radford and Steve Glasgow for help while extruding and Byron McKillop and Bruce Rapley for building equipment. I would in particular like to thank Kevin Pedley who was a great source of information and assistance with physiological measurements and equipment for measuring bite forces. Dr. Denny Meyer and Duncan Hedderley are gratefully acknowledged for answering all my questions on statistics.

This research was conducted with approval from the Massey University human ethics committee. I'd like to thank all of those panelists who gave up their time to bite samples and make noises during this project. A sensory evaluation research project without panelists would not be possible.

A special thank you to my parents, as well as to friends, Carol and Michael Pound, for support in various ways throughout the years that it took to complete this research. And lastly, I'd like to thank my husband, Shane for his continued patience and encouragement throughout the entire process of completing this research.

TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

LIST OF EQUATIONS

LIST OF ABBREVIATIONS AND SYMBOLS

Abbreviations:

ANOVA	-	analysis of variance
a_w	-	water activity
df	-	degrees of freedom
D_{fk}	-	Kolmogorov fractal dimension
EMG	-	electromyography
F	-	feed rate
FCA	-	factorial correspondence analysis
FFT	-	fast fourier transformation
mhp	-	mean height of peaks
np	-	number of peaks
PCA	-	principal components analysis
PCO	-	principal coordinates analysis
QDA	-	quantitative descriptive analysis
TPA	-	texture profile analysis
TSE	-	twin-screw extrusion
Tukey's HSD	-	Tukey's honestly significant difference
r	-	correlation coefficient
r^2	-	coefficient of determination
RPM	-	rotations per minute
SAS	-	statistical analysis software
SSE	-	single-screw extrusion
vs.	-	versus
W	-	water flow rate
W_f/W_t	-	ratio of work during fracture to total work done
X_f	-	moisture content of the feed
X_p	-	product moisture during extrusion

Symbols:

ε_{app}	-	apparent porosity
ε_{op}	-	open porosity
ε_{cp}	-	closed porosity
ρ_{part}	-	particle density
ρ_s	-	substance density
ρ_{app}	-	apparent density

CHAPTER 1 : INTRODUCTION

Texture is one of the primary contributors to food acceptability (Szczesniak and Kleyn, 1963). If the texture of a food product does not meet consumers' expectations then it is considered to be of poor quality and unacceptable for human consumption (Szczesniak and Kahn, 1971). One textural characteristic for which this is particularly true is that of crispness. Crispness is a complex mixture of the instrumental, microstructural and acoustic characteristics of a food product (Roudaut *et al.,* 1998). Definitions of this characteristic differ depending on product type. Crispness of wet crisp products, such as apples, celery and lettuce has been defined as "...the textural property manifested by a tendency when subjected to an applied force to yield suddenly with a characteristic sound" (Jowitt, 1974). The crispness sensations experienced when biting into porous, dry products such as crackers and potato chips have been defined as "...the textural property manifested by a tendency to crack, fracture, or shatter without substantial prior deformation on the application of force" (Jowitt, 1974). With both definitions, the senses of touch and hearing are important contributors to the perception of crispness.

Structurally, both wet crisp and dry crisp foods have a tendency to be cellular (Brennan *et al.,* 1974). When a force is applied to such a cellular product, each cell ruptures, creating a sound. The overall rupture pattern produces an irregular frequency and amplitude sound signature (Vickers and Bourne, 1976; Vickers and Christensen, 1980; Vickers, 1981; Vickers, 1987). The frequencies of sounds generated by biting crisp foods have been shown to fall within the 3 to 12.8kHz range (Lee *et al.,* 1988; Dacremont, 1995). In comparison, a "crunchy" food is one that has a lower frequency of sound produced during biting (1.25 to 2 kHz) (Dacremont, 1995).

Acoustic signatures of bite noises have been analysed by numerous methods. Early researchers used Fourier transformation of the data to identify frequencies of particular importance that could be associated with a characteristic texture attribute (Vickers and Christensen, 1980; Edmister and Vickers, 1985; Vickers, 1985; Seymour and Hamann, 1988; Dacremont, 1995). Sound waves have also been characterised using measures such as mean height of the peaks in the sound wave, the number of peaks in the sound wave and duration of the sound waves (Edmister and Vickers, 1985; Vickers, 1987).

However, more recently, sound waves have been characterised using fractal analysis. Fractal analysis has been used to quantitatively describe the degree of jaggedness of stress-strain relationships and is a reproducible method for monitoring changes in the texture of food products (Peleg, 1993).

An individual's tactile (touch) response to crispness is one that has largely been ignored during research into crispness perception. The vibratory element of crispness is manifested in two ways; through bone-conduction which transmits vibrations to the ears causing the ear drum to vibrate, and secondly, through bite forces produced during consumption of the food. During biting, mechanoreceptors located within the mouth gauge the muscle's responses to biting the food and relay vibratory information to the brain to assist in perception of the texture of the food product. In most research the sensation of crispness has been predicted from the acoustic component and instrumental measures of force. However, no work has been conducted to explore the intra-oral responses of biting of crisp foods and their relationship to sensory responses.

The vibrations produced during compression of crisp products not only contribute to the auditory component of crispness but also to the touch-pressure sensation of crispness. These oral-tactile cues provide critical sensory indicators for the perception of crispness (Christensen and Vickers, 1981). The touch-pressure contribution to crispness perception has been thoroughly studied using instrumental compression of crisp products (Iles and Elson, 1972) and combined with acoustics to produce regression equations for prediction of crispness (Mohamed *et al.*, 1982; Vickers, 1987; Seymour and Hamann, 1988). Based on the results of research into potato chip crispness, Vickers (1987) concluded that sensory crispness is positively related to acoustical measurements of compressive brittleness and inversely related to other force-deformation measurements such as work and force during shearing. This suggests that sensory hardness may be detracting from the perception of crispness. This conclusion has only been drawn based on instrumental testing. The direct contribution of intra-oral forces to the perception of crispness has not previously been studied. It is important that the intra-oral bite forces produced while biting into crisp products be measured and correlated with sensory hardness scores in order to fully understand crispness perception as it occurs within an individual.

The overall aim of this research was to further develop the understanding of an individual's perception of crispness. More specifically, this research was completed with the following objectives in mind:

1) To determine the effectiveness of fractal analysis of acoustic signatures to predict the perception of crispness.

2) To determine the relative contribution of bone-conducted and air-conducted sound to the perception of crispness.

3) To compare intra-oral bite forces to instrumental testing of crisp products.

4) To determine the relative importance of intra-oral bite force, bone-conducted and air-conducted sounds as predictors of perceived crispness.

5) To explore, briefly, the relationship between the structural properties of extruded snacks and perceived crispness.

CHAPTER 2 : LITERATURE REVIEW

Texture has been defined as "all rheological and structural (geometric and surface) attributes of a product perceptible by means of mechanical, tactile and where appropriate, visual and auditory receptors" (ISO, 1981). It is a sensory property which can only be described and perceived by a human subject (or an animal) (Szczesniak, 2002). Because an action is required for sensations to be produced, texture perception has been described as active perception (Christensen, 1984). During consumption of a food, texture perception is the result of various inputs from the action of mandibular muscles, and from pressure on the oral mucosa as well as from the sounds produced as the food is eaten. The contribution of each input to the perception of texture varies, depending on the textural characteristic of interest. For crispness perception, the sound and bite forces produced during biting appear to be the most important characteristics. In order to understand the perception of crispness, an appreciation of the physiology and anatomy of both the human mouth and auditory system is required.

2.1 The anatomy and physiology of the human mouth

The mouth is comprised of the lips, the teeth, the gums (gingiva), the tongue, and the jaw. In addition to these structures, within the mouth are mechanoreceptors and muscles that are required for texture detection. All of these structures in the mouth are well adapted to detect many properties of food, including shape, size, and mechanical properties (Harker *et al.*, 1997). The anatomy of these structures is detailed in Figure 2.1.

There are two jaw bones found in the mouth. The upper jaw bone is known as the maxilla and the lower jaw bone is the mandible. The mandible is attached to the temporal bones of the head by the temporomandibular joint (labelled in Figure 2.1c as point C - TMJ). It is through this joint that the mandible moves against the maxilla to bring the teeth together for the grinding and chewing of food (Boyar and Kilcast, 1986).

Each of the jaws is covered with bone forming fibrous tissue known as the periosteum and, in normally dentate individuals, on both the upper and the lower jaw surface are teeth. The roots of the teeth are attached to the bone by the periodontal membrane. The function of this membrane is two-fold. First, it is required for support and positional

Figure 2.1: Anatomy of the human jaw (Harker *et al.*,1997)

(a) The surface of the teeth
- each jaw contains 4 incisor and 2 canine teeth in the anterior region and 2 premolar and 3 molar teeth per side of the posterior region

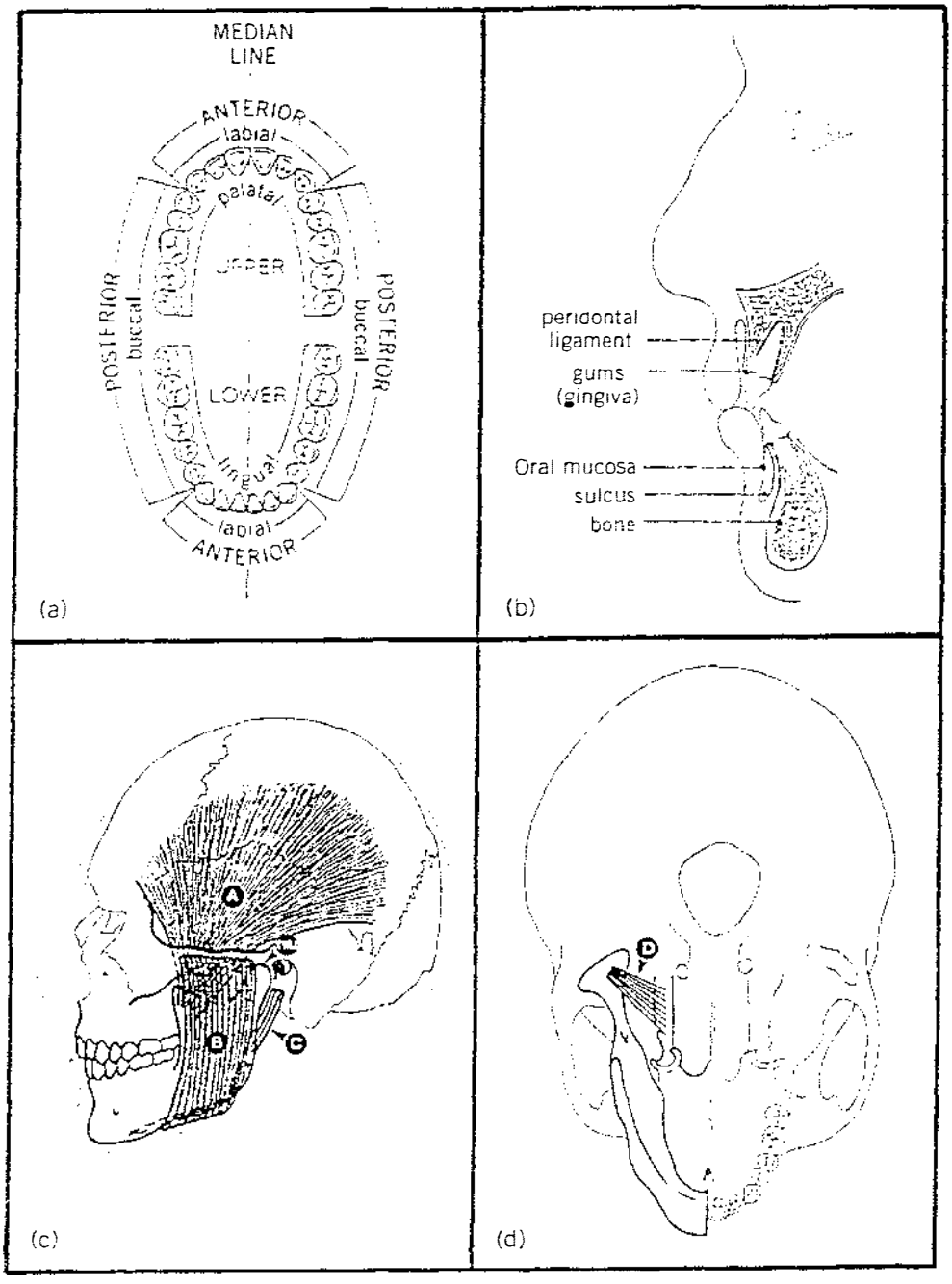
(b) Structure of the teeth within the maxilla (upper jaw) and mandible (lower jaw)

(c) and (d) Muscles of mastication

A. Temporalis
B. Masseter
C. Digastric
D. Lateral pterygoid

TMJ Temporomandibular joint

A and B are used for jaw closing and C and D are used for jaw opening and protrusion



adjustment of the teeth. The second function is for sensory perception while chewing (Boyar and Kilcast, 1986). At the front of each of the jaws are four incisors and two canine teeth (labelled in Figure 2.1a as anterior) and at the posterior region of each jaw there are two premolar and three molar teeth on each side (Figure 2.1a).

A number of muscle groups are required to move the mandible during mastication. The locations of these muscles are outlined in Figure 2.1c. The masseter, internal pterygoid and temporalis muscles are responsible for elevation of the mandible (Agrawal *et al.,* 1998); while the external pterygoid muscle is responsible for the depression of the mandible (Boyar and Kilcast, 1986). When the mandible is depressed, the temporalis muscle becomes elongated and the masseter and pterygoid muscles stretch to allow the mouth to open. During elevation of the mandible, these muscles then contract and the mouth closes.

Muscles work in combination with mechanoreceptors during mastication to detect the position of the jaw as well as to detect items within the mouth (van der Bilt *et al.,* 1995). Mechanoreceptors are cells that can detect pressure and frequencies of vibration and convert the pressure and vibratory stimulation into an electrical signal (Gillespie and Walker, 2001). Within the mouth, mechanoreceptors are present in oral mucosa, the periosteum, the salivary duct, the periodontal membrane, the temporomandibular joint capsule, and the bony structures of the jaw (Sakada, 1983; Harker *et al.,* 1997). There are two classifications of mechanoreceptors, differing in the types of frequencies they detect. Slowly adapting mechanoreceptors act as low frequency vibration detectors, while rapidly adapting mechanoreceptors detect high frequency vibrations (Sakada, 1983).

Upon closure of the jaw during chewing, the electrical signal that is generated by the mechanoreceptors and the muscle spindles travels to the brain via neural pathways. Once the signal has been received by the brain, the information is then processed and the texture of the product in the mouth can be identified.

2.1.1 Mastication

Mastication is the process of manipulating food between the upper and lower teeth in preparation for swallowing (Boyar and Kilcast, 1986). There are three stages of the mastication process; an initial ingestion phase, a cyclical chewing phase and a swallowing or deglutition phase (Heath and Lucas, 1988). During the initial stage, the food is introduced into the mouth. It is typically grasped between the upper and lower incisors, with these teeth in an edge-to-edge position. This is followed by an initial bite and subsequent chews. During the initial bite, after the teeth make contact with the food, the movement of the jaw depends on the texture of the food being consumed. If the food is soft, the mandible moves forward slightly in order to bring the cutting edges of the incisors near to one another. This movement is required to separate the food for further chewing (Jenkins, 1978). Tougher foods need to be separated by a tearing action. Tearing is accomplished by bringing the edges of the incisors together through the food by a lateral forward and backward movement of the jaw which is followed by an increase in muscle activity. The mandibular movement changes from a lateral movement to a side to side oscillatory movement that continues until the food breaks (Jenkins, 1978).

Following separation of the food, the mandible drops and the lips guide the bolus toward the tongue and cheeks, with the tongue placing the food between the opposing posterior teeth for further chewing (Thexton, 1992). Sensory endings on the tongue and in the posterior part of the mouth aid in the selection of parts of the bolus which are ready for swallowing. These parts are separated from the rest of the food and are moved by the tongue to the pharynx and oesophagus and swallowing occurs. The remaining bolus requires further mastication and subsequent separation before swallowing. This process of mastication and swallowing continues until the mouth is empty (Jenkins, 1978).

Although research has been conducted looking at crispness perception during the entire chewing process (Lee *et al.*,1988), the majority of the sensations required for the perception of crispness occur during fracture of the food at the initial mastication stage (Sherman and Deghaidy, 1978; Christensen and Vickers, 1981).

2.1.2 Bite forces produced during mastication

The forces that are produced during the breakdown of a product in the mouth are a result of the activity of the masseter, temporalis and pterygoid muscles. Electromyographic recordings of the activity of these muscles, combined with polygraphic tracings of bite forces during biting of food products have been used to determine that maximum bite force is achieved as the teeth come together during the initial stages of the biting process (Ahlgren and Öwall, 1970).

The forces produced by an individual during chewing of food are, in general, lower than the individual's maximal bite force (Carlsson, 1974). Normal chewing forces rarely exceed between 44N to 66N (Bourne, 1994), however some individuals chew with forces close to their maximal force which, for Europeans and Americans, can average between 588N and 735N (Gibbs *et al.*, 1981). This results in fatigue during chewing for such individuals.

There are many factors which affect the strength of an individual's maximum bite force and chewing forces. Physiological factors include the state of dentition of the individual, the dental area where the biting takes place within the oral cavity, gender and chewing habits.

The state of dentition is one of the major physiological factors affecting bite forces. Individuals who wear dentures have a lower bite force than those who have normal dentition. Complete denture wearers typically have bite forces of one-third to one-quarter less force than individuals who have normal dentition (Carlsson, 1974). One hypothesis for this decrease in force is the fear of dentures slipping during biting of the food (Jenkins, 1978). Another possible reason is the lack of mechanoreceptors required for sensorimotor regulation of bite force (Trulsson and Johansson, 1996a). Mechanoreceptors are found in the periodontal ligament in the anterior portion of the mouth (Trulsson and Johansson, 1996b; Trulsson and Gunne, 1998). If the mechanoreceptors are absent or impaired, which occurs with individuals with dentures or orthodontic implants, then forces for holding and manipulating food are more variable and the movement of the jaw is less controlled, meaning that mastication is more variable (Jenkins, 1978; Trulsson and Gunne, 1998).

The greatest bite forces occur in the region of the first molars (Carlsson, 1974; Helkimo *et al.,*1977; Paphangkorakit and Osborn, 1998; Spencer, 1998). Bite force at the incisors is approximately one-third to one-quarter that of the molars (Carlsson, 1974). The most frequently suggested reason for the higher bite force occurring at the molars is because of the position of the molars in relation to the masticatory muscles (Carlsson, 1974). From Figure 2.1c, it can be seen that the molars are in close proximity to the masseter muscle, which is the muscle used for crushing food products. In addition to the proximity to the muscles, the molars have a larger supportive area for biting. Beam (1973) evaluated the effects of different bite areas on bite force values. Three different removable occlusal tables were created; a broad area such as occurs with molars, a narrow edge such as occurs with premolars and a knife edge such as occurs with incisors. Bite force measures from each of the occlusal edges showed that the greatest bite force occurs with a broad area. Bite force was significantly less for the narrow edge as well as for the knife edge, supporting the theory that the larger supportive structure of the molars is responsible for the greater bite force produced by such teeth.

Bite forces have been shown to vary between males and females, with men having a greater bite force than females (Waltimo and Könönen, 1993; Fontijn-Tekamp *et al.,*1998). This is considered to be due to the length of the mandible, with men having a longer mandible than women, rather than the muscle structure (Linderholm and Wennström, 1970).

Individuals who exhibit bruxism (teeth clenching) behaviour are also known to have much greater bite forces than those with normal jaw clenching behaviour (Gibbs *et al.,*1986). It has been suggested that this is due to hypertrophy of the masseter muscles (Carlsson, 1974).

It has also been shown that with practice, individuals can increase their bite force capacity. It is thought that this is not only due to improved muscle function, but because of a decreased sensitivity in the mechanoreceptors within the periodontal ligament (Carlsson, 1974).

There are also non-physiological factors which affect bite forces. An individual exhibits large differences in bite forces depending on the type of food consumed. In general, a harder food, such as a nut, requires a higher bite force than a softer product like bread (De Boever *et al.*,1978). It is clear that an individual is capable of adjusting their bite force to suit the food being consumed, based on prior experience biting similar food products and expectations of the food's texture.

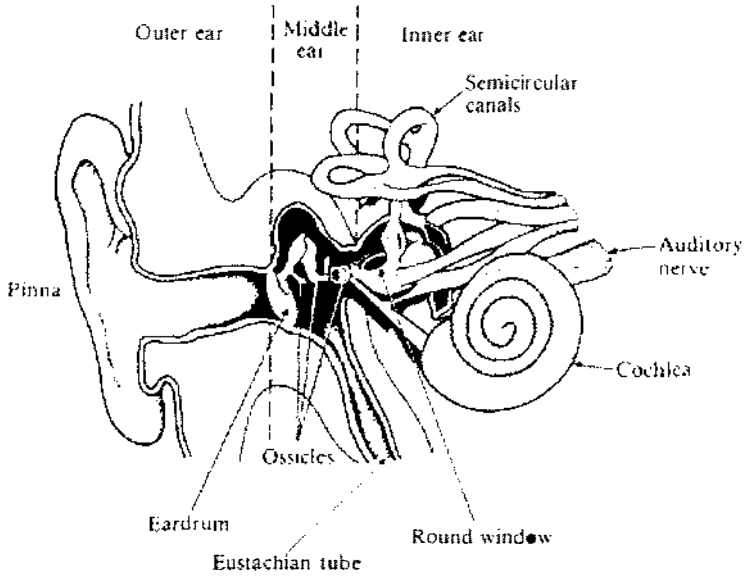
When measuring bite forces, variability within the same individuals on different days is often observed (De Boever *et al.*,1978; Paphankorakit and Osborn, 1998). De Boever *et al.*, (1978) observed significant day-to-day variability in forces required for chewing different food products. For this reason, it has been concluded that absolute bite force values are unobtainable because of the uncontrollable factors which occur during biting (Marklund and Wennström, 1972). These uncontrollable factors can include motivation, tooth status, muscle health and fatigue (Marklund and Wennström, 1972; Paphankorakit and Osborn, 1998).

In addition to large day-to-day variability, large inter-subject variability has also been reported. De Boever *et al.*, (1978) showed bite forces ranging from 0.78N to 10.49N between partially dentate individuals biting the same foods. The differences in the forces were mainly attributable to changes in the texture of the food products tested.

2.2 Anatomy and physiology of the human auditory system

The auditory system is divided into three sections; the outer ear, the middle ear and the inner ear (Figure 2.2). The outer ear is composed of the pinna (the visible part of the ear) and the auditory canal. The pinna aids in localization of sounds (Moore, 1982) while the auditory canal functions as a funnel for incoming sound waves (Stevens and Davis, 1938). The tympanic membrane, or eardrum, is located at the end of the outer ear.

Figure 2.2: Structure of the auditory system (Rossing, 1990)



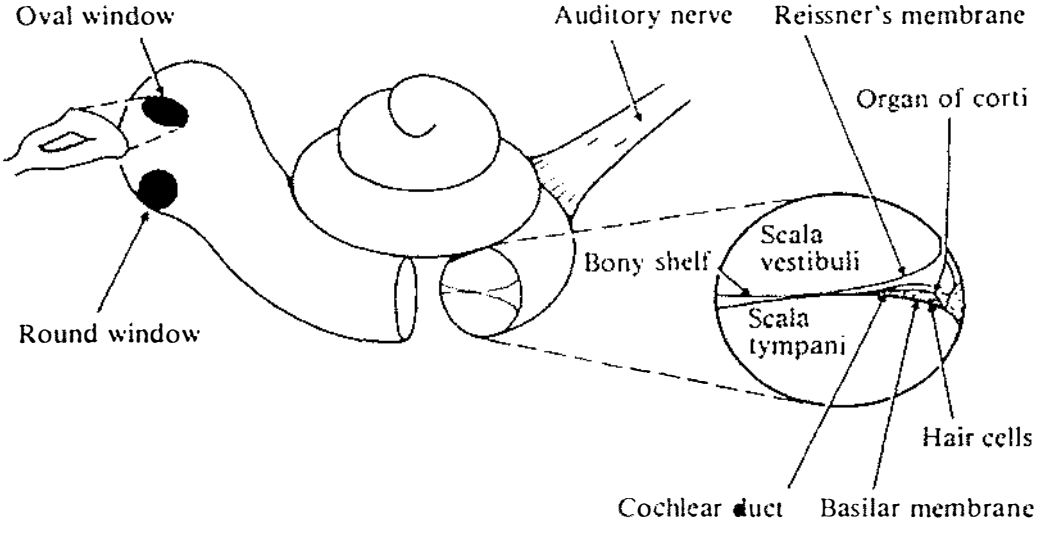
Internal to the tympanic membrane is the middle ear. This portion of the auditory system contains the ossicles which are three small bones called the malleus, incus and stapes (commonly referred to as the hammer, the anvil and the stirrups)(Kiang and Peake, 1988). The major function of the middle ear is to ensure the efficient transfer of sound from the air to the fluid in the cochlea within the inner ear (Moore, 1982).

The last section of the auditory system, the inner ear, lies within the temporal bone of the skull. Located within the inner ear, the cochlea is the most important part of the auditory system. It is here that the sound pressure variations are transformed into neural impulses (Rossing, 1990). The cochlea has three distinct chambers; the scala vestibuli, the scala tympani and the cochlear duct (Figure 2.3). Each of these chambers contain fluid; perilymph in the scala and endolymph in the duct. These fluids are separated by the Reissner's membrane and the basilar membrane. The basilar membrane stops short of the end of the cochlea to allow the fluid to flow between the scala vestibuli and scala tympani via a small opening known as the helicotrema. Two membrane covered windows, the round window and the oval window are located on the cochlea on

opposite sides of the basilar membrane (Figure 2.3). Resting on the membrane of the oval window is the foot-plate of the stapes.

During the conduction of sound down the auditory canal, sound waves enter the auditory canal and cause the tympanic membrane (eardrum) to vibrate. The ossicles pick up the vibrations and transmit them through the middle ear. The movement of the foot-plate of the stapes vibrates the membranous covering of the oval window, causing pressure changes in the cochlear fluids. The inward movement of the oval window causes a flow of fluid around the helicotrema and an outward movement of the round window. This flow of fluid causes the basilar membrane to move in waves from the base of the cochlea toward the apex or end of the cochlea. The waves build slowly, increasing in amplitude as they move down the cochlea. Upon reaching maximum amplitude, the magnitude of the waves decreases abruptly.

Figure 2.3: Structure of the cochlea (Rossing, 1990)



Sounds of different frequencies produce maximum amplitude at different places along the basilar membrane. High frequency sounds produce maximum intensity displacement near the oval window with little activity further along the membrane. Low frequency sounds produce vibrations along the entire membrane, with maximum amplitude near the end of the cochlea (Moore, 1982).

Resting on the basilar membrane is the organ of corti (Figure 2.3). This organ is responsible for converting mechanical activity into neural activity. Hair cells within the organ of corti translate the wave motions of the basilar membrane into nerve impulses. The hair cells are composed of three rows of outer hair cells and one row of inner hair cells, separated by an arch known as the tunnel of corti. There are approximately 25,000 outer hair cells, each with about 140 hairs protruding and there are approximately 3500 inner hair cells, each with about 40 hairs (Moore, 1982). Located above the hair cells is the tectorial membrane. The hairs of the outer cells touch this gelatinous membrane. As the basilar membrane moves up and down, a shearing motion is created between the basilar membrane and the tectorial membrane. The hairs at the top of the outer hair cells are bent which leads to the generation of action potentials in the auditory nerve (Moore, 1982).

Sound waves are transmitted not only through air-conduction but also through bone-conduction. For bone-conduction, the sound waves do not have to enter via the auditory canal. The sound energy is transmitted to the inner ear through the bones of the skull around the middle ear. The transmission of sound by bone-conduction produces similar movements of the endolymphatic fluid and the basilar membrane as those produced by air-conduction (Stevens and Davis, 1938).

2.3 Measurements of texture

2.3.1 Sensory evaluation of texture

As texture is a combination of perceptions unique to humans and animals, sensory techniques have been developed to aid in classification, identification and quantification of these perceptions. These techniques may take on the form of descriptive analysis, consumer testing or laboratory testing.

There is a variety of different descriptive analysis techniques that have been developed for quantifying attribute perceptions. These include; Flavour Profile Analysis (Cairncross and Sjöstrom, 1950), Quantitative Descriptive Analysis (QDA)(Stone *et al.,* 1974), Texture Profile Analysis (TPA)(Brandt *et al.,* 1963), Spectrum Analysis (Meilgaard *et al.,* 1991) and generic descriptive analysis (Lawless and Heymann, 1998; Murray *et al.,* 2001). Of these descriptive techniques, QDA, TPA and generic descriptive analysis have been employed for evaluating textural properties of food products. Each of these techniques requires that panelists have some level of sensory acuity and a level of interest and motivation to be part of an ongoing panel. The first stage in the development of these descriptive panels is the screening of the panelists. The key to screening is to select panelists who are able to reliably discriminate between products for the attributes selected. Various researchers have published guidelines for selection and training of panelists for various types of descriptive panels (Civille and Szczesniak, 1973; Zook and Wessman, 1977; Rutledge and Hudson, 1990). Screening tasks typically include triangle and ranking tests to select panelists with the best discriminative ability (Zook and Wessman, 1977; Meilgaard *et al.,* 1991). Based on the results of the screening tests, panelists are then selected for further training. Opinion varies on techniques for selecting panelists. Meilgaard *et al.,* (1991) recommend selecting panelists based on success at discrimination and ranking tests. Sinesio *et al.,* (1991/2) suggest using multivariate analysis techniques such as Principal Components Analysis and cluster analysis to evaluate the homogeneity of panelists' performance.

Cluster analysis is a multivariate technique which groups objects based on similarity in their characteristics. These groupings have high internal homogeneity and high external heterogeneity, meaning that the objects within the group are similar yet different to those in other groupings (Hair, *et al.,* 1998). During cluster analysis, clusters are formed using either hierarchical or nonhierarchical techniques. Hierarchical procedures classify the objects into clusters based on the number of original objects. If there are five objects to be clustered, the procedure starts with five objects and will classify them into firstly, four clusters, then three clusters, continuing through to one cluster. Objects are grouped within a cluster based on how close they are to other objects. Objects with small differences separating them are clustered together.

Nonhierarchical clustering groups objects based on a specified number. The initial cluster centre must be selected. This will act as the seed cluster and selection of the objects to fall in clusters is based on their distance from the seed cluster.

Within each clustering type there are various algorithms which can be used to determine the clusters. Hierarchical algorithms include single-linkage, complete linkage, average linkage, ward's method and centroid method. The nonhierarchical methods include sequential threshold, parallel threshold, optimization and selecting seed points (Hair *et al.,* 1998). The selection of the algorithm to use depends on which clustering type is to be used (hierarchical or nonhierarchical). One advantage of the hierarchical technique is that it is faster to compute and requires less computing power than nonhierarchical (Hair *et al.,* 1998).

No matter how selection of the panelists is made, individuals who show consistency of responses and a continued interest in the project should be retained (Meilgaard *et al.,* 1991). The selected panelists then undergo training. During training the panelists are required to develop their own terminology for characterising their perceptions of the product attributes. This is done through repeated exposure to a wide range of products within the product category to be tested under the guidance of a panel leader. Terminology development involves defining and describing the characteristics present in the product. Although each panelist initially develops their own terminology, final descriptors and definitions are generated through round table discussion and panel consensus, with the panel leader acting as a facilitator throughout the process. This leads to precisely defined characteristics which adequately describe the products being evaluated. Standardized procedures for evaluation of the samples are established, discussed and agreed upon. This includes ensuring that the position of the sample in the mouth during testing as well as the number of chews to be made before evaluating each characteristic are identical for each panelist.

Once the final descriptor list has been developed, the panel must be trained to use a "common frame of reference" for evaluation of the products (Murray *et al.,* 2001). As all panelists use their own past experience and descriptors to evaluate products, training must occur to ensure all panelists evaluate intensities of product attributes in a similar

fashion. This is often accomplished through the use of reference standards (Civille and Lawless, 1986; Rainey, 1986; Nielson and Zannoni, 1998). These standards aid in the alignment of concepts for each panelist, which can therefore improve panel performance.

Panelist performance should be carefully monitored throughout training and prior to beginning testing; the panelists should be pre-tested to ensure consistency of responses and discrimination of differences (Powers, 1984). Once the panel leader is confident of the panel's ability to evaluate the samples, testing can begin. Testing involves evaluating samples using a category scale or a linear scaling technique.

Although this is a general overview of panel training, each type of descriptive analysis panel has specific aspects of training which are unique to the type of panel selected for use. The following is a more detailed outline of each type of descriptive panel which could be use for texture research; QDA, TPA and Generic Descriptive Analysis.

Quantitative Descriptive Analysis was developed by Stone *et al.,* (1974) to use qualified subjects to quantify all perceived characteristics present in a product in the order in which the characteristics appeared during consumption. This technique addressed various issues which were not addressed in earlier descriptive analysis techniques, namely Flavour Profile Analysis. These issues included the selection of the panelists, the development of a language appropriate for characterising perceptions of the food products, the quantification of the perceptions and the design of the experiment and analysis of the data (Stone and Sidel, 1998). Firstly, panelists for the QDA panel are recruited from within local communities, having no knowledge of the technologies used to develop the products. Stone and Sidel (1998) state that these individuals have no personal involvement in the products; therefore, they have no biases regarding the products. In order to qualify for the panel, individuals are screened with regard to product usage and their ability to discriminate. Discrimination tests are conducted over a series of sessions to select those individuals who can discriminate at better than chance. A typical QDA panel has between 10-12 individuals selected from the screening process to then move on to language development. In this stage, the individuals are required to develop an agreed upon terminology, definitions for these

words and an agreed upon process for evaluating the products. It is suggested that five, 90 minute sessions are required to complete the language development task (Stone and Sidel, 1998). Although Stone *et al.,* (1974) state that all sensory characteristics perceived in the products must be evaluated, Lawless and Heymann (1998) state that this technique can be used to evaluate a narrow range of properties within a product, such as texture, as long as the "dumping" bias is avoided. "Dumping" is classified as an "attribute response restriction effect" where responses relating to one sensation are "dumped" into another sensation because the first sensation does not have an intensity scale present on the evaluation sheet (Lawless and Heymann, 1998). In order to avoid dumping, all important attributes must be included in the test.

Prior to testing of the products, panelist performance is evaluated. This is done by collecting replicated data on a selected number of samples during training. Performance is monitored through statistical analysis of the data.

With QDA, once the language has been developed responses are input onto a line scale by each panelist in order to quantify the perceptions of the products. The panelists must evaluate the products numerous times and an experimental design is used to ensure that all sources of variability are taken into consideration. This includes variability within panelists, products, attributes and the testing process (Stone and Sidel, 1998). Analysis of the data is conducted through analysis of variance and multiple comparison tests.

Analysis of variance (ANOVA) tests whether there is a significant difference between the means of the independent variables being studied. In descriptive analysis testing, independent variables include the samples or treatments being tested, the panelists and the replicates of testing.

The ANOVA test is based on two assumptions; homoscedasticity or equal variances and normal distribution of the data (O'Mahony, 1982). ANOVA compares the variation between treatments with the variation within treatments. The variation within treatments is known as experimental error and is attributable to variability in the population as well as any uncontrolled experimental variability. If the variability between treatments is greater than the variability within treatments, then the means are significantly different.

No significant difference in means exists if the variability between treatments is the same or less than the variability within treatments. This significance is determined by calculating the F-value. The F-value is a ratio of the variance between treatments to the variance within treatments. A larger F-value indicates that the differences between treatments are due to more than just error, therefore, the treatment means are significantly different. ANOVA, however, only indicates if means of treatments are different. It does not indicate which means are different. For that, a multiple comparison test must be used to find out which pairs of mean scores are significantly different. To determine differences, a range value is calculated. The formula used for this range value is based on the error mean square from the ANOVA and the number of scores in each treatment sample. If the calculated range value is larger than the differences between the means of each sample then there is no significant difference between the samples. If the range value is smaller, then the means are significantly different (O'Mahony, 1986).

There are various multiple comparison tests which have been used to analyse sensory data. Commonly applied to sensory data are the Sheffé, Tukey's Honestly Significant Difference (HSD), Newman-Keuls, Duncans and Fisher's Least Significant Difference (LSD) tests (Lawless and Heymann, 1998). O'Mahony (1986) has categorised these tests according to their ability to detect differences between treatment means. A powerful test is one that has a smaller range value which means that it is easier to find two means to be significantly different. A conservative test has a larger range value, making it more difficult to find two means which are significantly different. The Sheffé test is the most conservative and least powerful test, while the Fisher's test is the most powerful and least conservative test (O'Mahony, 1986).

A second type of descriptive analysis panel which can be used to evaluate texture is the General Foods Texture Profile Analysis (TPA). Preceding the development of the TPA as a sensory technique, a classification of textural characteristics was published based on the premise that texture is a multi-parameter sensory property. Based on this classification, texture is divided into three categories; mechanical, geometrical and other characteristics (Brandt *et al.,* 1963; Szczesniak *et al., 1*963; Civille and Szczesniak, 1973; Civille and Liska, 1975). Mechanical characteristics are related to the reaction of the food to stress. Within this class are the textural properties of hardness, fracturability,

chewiness, gumminess, adhesiveness and viscosity. Geometrical characteristics are related to the arrangement of the physical constituents within the food product, which can be further subdivided into those constituents relating to particle size and shape (such as powdery, chalky, grainy) and those related to particle shape and orientation (such as flaky, fibrous, pulpy) (Brandt *et al.,* 1963). The "other" characteristic classification includes properties related to moisture and fat within the food product such as the wetness, oiliness and mouthfeel of the products. Properties within each of the three classifications have been carefully defined and reference standards (commercial products exhibiting ranges of each characteristic) have been identified in order to have a standardized approach to texture testing. These reference standards are not to be used as a basis of comparison in order to evaluate the sample, but instead are to serve as examples of the range of the specific characteristics being evaluated (Civille and Liska, 1975). Standardised procedures for preparation of the reference standards, such as serving size and temperature for serving, are published with the references. An example of the reference standards originally published for hardness is shown in Table 2.1.

Various modifications have been made to the originally developed texture standards (Civille and Szczesniak, 1973; Civille and Liska, 1975; Muňoz, 1986). However, one limitation of the TPA is that products used as reference standards may have changed through reformulation of the products, or they may not be available outside the United States. Another limitation is that textural characteristics of interest may not be present in the TPA standardised scales. For instance, crispness is not in the TPA lexicon. Therefore, more generic descriptive analysis approaches must be adopted for evaluation of such characteristics.

Table 2.1: Original hardness scale for TPA (Szczesniak *et al.*, 1963)

Panel rating	Product	Brand or type	Manufacturer	Sample size	Temperature
1	Cream cheese	Philadelphia	Kraft Foods	12.7mm	7.2-12.7°C
2	Egg white	Hard cooked 5 min.	---	12.7mm tip	room
3	Frankfurters	Large, uncooked, skinless	Mogen David Kosher Meat Products Corp.	12.7mm	10-18.3°C
4	Cheese	Yellow, American pasteurised	Kraft Foods	12.7mm	10-18.3°C
5	Olives	Exquisite giant size, stuffed	Cresca Co.	1 olive	10-18.3°C
6	Peanuts	Cocktail type in vacuum tin	Planters Peanuts	1 nut	room
7	Carrots	Uncooked, fresh	---	12.7mm	room
8	Peanut brittle	Candy part	Kraft Foods	---	room
9	Rock candy	---	Dryden & Palmer	---	room

Lawless and Heymann (1998) have described how to conduct generic descriptive analysis in "three easy steps". In the first step, panelists are trained through the provision of a wide range of products in the specific category of interest using either consensus training or ballot training. In consensus training, the panelists produce descriptors and reference standards to differentiate between the samples. Alternatively with ballot training, the panelists are provided with a list of descriptors and references to describe the products. Sometimes, the two approaches are combined and the panel leader provides some descriptors and the panelists indicate other characteristics which they feel are important in the products. During the initial stages of training, potential reference standards are provided for each of the attributes suggested for the products.

The panelists are encouraged to try them and suggest those which would be possible references for the samples being evaluated. The descriptors, standards and references are refined during the course of training to ensure that the panelists are comfortable with the terminology and reference standards being used for each characteristic. After the development of the questionnaire (completed with the assistance of the panelists), the reproducibility of the panelists is determined. Samples to be used during data collection are presented to the panelists to evaluate in three replicates and the collected data are analysed to determine if significant panelist interactions exist. It is essential that the panelists are consistent in their evaluations of the characteristics; therefore, the panelists responsible for these interactions are identified and retrained. The last stage is evaluation of the samples. Proper sensory techniques, such as labelling all samples with three digit codes, randomizing sample presentation and controlled temperature of testing should be employed so that potential errors are minimised, or at least kept constant. Analysis of the data is carried out using analysis of variance and a multiple comparison test to test for differences amongst samples. Generic descriptive analysis is often used when adaptations to a test methodology, such as QDA, invalidates its trademarked name (Lawless and Heymann, 1998).

Other, less objective sensory research techniques have also been used to evaluate the perception of texture by consumers. In-depth interviews with consumers have been conducted to conclude that texture is a subconscious sensation which plays a role in determining an individual's feelings toward a food product (Szczesniak and Kahn, 1971). Word association interviews have been conducted to measure which textural properties feature prominently in specific food products (Szczesniak and Kleyn, 1963; Yoshikawa *et al.,* 1970; Szczesniak, 1971) and consumer surveys have tested which products display various sensory characteristics, such as crispness (Szczesniak, 1988; Dacremont *et al.,* 1991). Results from the consumer surveys can be analysed by calculating frequencies of responses and by conducting Factorial Correspondence Analysis (FCA) on these frequencies. The frequencies are placed into a frequency or contingency table, with the food products studied in columns and the textural properties in rows. With FCA, the frequency data are first normalised by dividing each frequency by the square root of the grand total of the rows and columns. These normalised data are then analysed using Principal Components Analysis (PCA) and Principal Coordinates

Analysis (PCO) (Piggott and Sharman, 1986). These two techniques are multivariate analysis techniques for providing a description of the objects in the data set using a reduced set of factors. PCA is used to indicate a relationship between the groups of textural variables being studied while PCO is used to indicate the relationship between the samples. Because the data have been normalised, the plots of PCO and PCA data can be overlaid to show which food products are described by which textural property. To analyse data using FCA, consumers must assign one attribute to one food product. An individual cannot allocate the same attribute to two products during testing.

Laboratory tests have been used to obtain a more thorough understanding of various textural attributes by studying the sounds made while biting and/or chewing food products (Vickers and Wasserman, 1979; Vickers, 1980; Christensen and Vickers, 1981; Vickers, 1981; Vickers, 1984a; Vickers, 1984b; Vickers, 1985; Vickers, 1987). Individuals are placed in a controlled environment and asked to respond to various questions relating to a specific task. Through this technique, associations of crispness to acoustic loudness and pitch as well as to hardness have been established. Additionally, the effect of biting with the front teeth and chewing with the molars on the perception of texture has been assessed through laboratory testing.

2.3.2 Instrumental testing of texture

There are numerous tests which can be used to objectively evaluate texture. Scott Blair (1958) first classified texture tests under headings of fundamental, empirical and imitative. Fundamental tests measure well-defined rheological properties and may not represent what is actually occurring in the mouth. For this reason, results from fundamental tests do not necessarily correlate well with sensory evaluation (Bourne, 2002). Conversely, empirical tests measure parameters that are not well-defined and the tests are simple to perform, rapidly providing answers. They are, however, arbitrary and do not provide a complete specification of the food. The third test, imitative testing, imitates conditions which the food undergoes during chewing. Results from imitative tests are most often highly correlated to the results from sensory panels (Bourne, 1994). Other means of classifying texture tests have been published and combine the fundamental, empirical and imitative tests based on the principle of the test (Bourne, 1966). Within this classification system are methods for measuring force (puncture,

extrusion, cutting-shear, crushing, tensile, torque, snapping and deformation), distance measures (length, area and volume) as well as methods for measuring time and energy. Tests most often used for testing the texture of dry extrudates are the force measuring tests and include compression tests, snap tests and shear/compression tests.

Compression testing is a crushing test which involves applying a force to a sample with a compression probe which travels into the sample at a constant rate. This causes the sample to deform and eventually shatter. The instrument most often used for this test is an Instron universal testing machine which consists of a fixed base and a compression probe attached to a moving cross-head. The force exerted on the sample is recorded as a force-deformation curve.

The snap test involves placing a sample onto two parallel horizontal bars. A third horizontal bar, attached to the cross-head of an instrument such as the Instron universal testing machine, moves onto the sample between the two horizontal bars, bending the food until it snaps. The force-deformation curve provides the same parameters as for compression testing (Vickers and Christensen, 1980).

The shear/compression test is reportedly a better imitation of the human bite than other tests (Seymour and Hamann, 1988). The sample is placed within a box and a probe with multiple blunt blades moves through the sample, first compressing it, then extruding it and finally shearing it.

All of these instrumental tests are based on a constant deformation of the sample at a constant rate of movement of the probe. However, it has been suggested that a constant rate of deformation is not an adequate method for characterizing the texture of crisp products because most crisp products undergo sudden failure to an applied force. This makes it difficult to follow the pattern of deformation of the sample (Mohamed *et al.,*1982). It has been suggested that it is better to use a technique which applies a steadily increasing compression force to the sample (Jowitt and Mohamed, 1980). A constant loading rate texture testing instrument consists of a hydraulic cylinder and piston to which a compression head is attached. Water is added to the cylinder, which then moves a piston, causing the compression head to move onto the sample. The

progressive increase in the amount of water in the cylinder means that the compression head moves at a constant rate while increasing the load on the sample. Under these standardized loading conditions, the sample breaks freely at its own rate, mimicking the human bite (Mohamed *et al.*,1982). With a constant rate of loading, the sudden structural collapse of the crisp food products, the collapse rate of the cells and the work done during the crushing of the samples can be measured.

2.4 Measurement of bite forces

One of the reasons for the large differences in reported bite force measurements is the diverse range of methodologies used to measure bite force. These are listed in Table 2.2.

The technique most often used to measure bite has been the implantation of a strain gauge within an artificial tooth, or strain gauges within teeth or complete dentures inside individuals' mouths (Anderson, 1956; Atkinson and Shepherd, 1967; Beam, 1973; De Boever *et al.*,1978). Such a technique is invasive, with wires being attached to the strain gauges within the mouth. In addition, individuals with natural dentition cannot be used for such testing. As it is known that there are significant differences in bite forces between individuals with natural and artificial dentition (Jenkins, 1978), it is difficult to draw conclusions which relate to the bite forces of individuals with natural dentition.

To overcome the limitation based on dental state, Mioche and Peyron (1995) developed a system where three small (13mm diameter and 2.5mm thick) load cells were placed in the mouths of individuals with normal dentition. The load cells were placed between a sample and the maxillary incisors and were bitten onto by the incisors. This allowed for measurement of bite forces of fully dentate individuals, without having to implant strain gauges into teeth. However, this technique was still invasive.

Table 2.2: Intra-oral bite force measurements in food research

Methodology used	Foods bitten	Recorded force (N)	Researcher
Strain gauge in artificial tooth – individuals with total or partial dentures	Bread	10.76	Yurkstas and Curby, (1953)
	French roll	17.70	
	Boiled beets	2.93	
Strain gauges in molar tooth – individuals with natural teeth	Biscuit	6.5 - 16.3	Anderson, (1956)
	Raw carrot	6.4 - 17.2	
	Cooked meat	3.9 - 15.7	
Electromyographic recordings	Gum Peanut	Not reported	Ahlgren and Öwall, (1970)
Strain gauges in knife edge, narrow edge and wide edge teeth mounted in dentures	Biscuit	5.88 - 23.2	Bearn, (1973)
	Apple	5.88 - 13.2	
	Chewing gum	3.92 - 11.9	
Electromyographic recordings and radio transmission in molars – individuals with natural teeth	Bread	2.71 - 8.9	De Boever *et al.*,(1978)
	Peanuts	5.33 - 10.1	
	Gum	2.75 - 10.8	
	Paraffin wax	4.89 - 18.9	
Sound transmission – individuals with natural teeth	Cheese Raisins Bread Beef Peanuts Carrots Gum	261.9 (averaged across products)	Gibbs *et al.*,(1981)
10 strain gauges in maxillary bridge – one partially dentate individual	Meat Meat products	Measured strain	Tornberg *et al.*,(1985)
3 load cells placed under sample and bitten with maxillary incisors	Pharmaceutical tablets	60 - 70 (estimated from graph)	Mioche and Peyron, (1995)
	Silicone elastomers	30 (estimated from graph)	
	Dental waxes	50 (estimated from graph)	
Strain gauge on plate between incisors	Biscuit	7.8 - 10.3	Trulsson and Johansson, (1996a and 1996b)
	Peanut	16 - 19	

To overcome the limitations of intra-oral interference due to wires, Gibbs *et al.,* (1981) developed the "sound transmission system" for bite force measurements. In this system, an accelerometer laced on the chin of the individual detected vibrations produced during biting as they were transmitted through the teeth to the chin. The greater the force produced between the mandible and maxillae, the greater the vibration detected by the accelerometer (Gibbs *et al.,* 1981). These authors reported that such a technique avoided the use of intra-oral devices for force measurements; however the subjects were constrained by the accelerometer attached to their chin.

Another technique which is used to measure maximum bite forces (when no food is present) is that of a strain gauge dynamometer or bite fork (Fløystrand *et al.,* 1982; Gibbs *et al.,*1986; Fontijn-Tekamp *et al.,* 1998). Typically, the strain gauge transducer is placed between two plates. The plates are compressed and the strain gauge registers the load applied to compress the plates between the teeth.

Some researchers have recorded electromyographic (EMG) measurements of muscle activity during chewing and related those with bite force readings from dynamometers. EMG does not interfere with chewing as it involves electrodes on the skin above the muscle of interest and the electrical potential underneath the electrode is recorded. EMG patterns produced during chewing of soft foods shows spikes with higher frequencies and amplitudes than EMG patterns produced during chewing of hard foods (Steiner *et al.,* 1974). When integrated, EMG patterns are strongly correlated with strain gauge dynamometer results (Garrett *et al.,* 1964).

2.5 Measurement and analysis of sound

Sounds produced during the biting of crisp products travel to the ear through the air or via bone and tissue of the mouth. Air molecules vibrate at the same frequency as that of the sound source and the properties of the sound source dictate the vibrational frequency (Speaks, 1999). For bone-conducted sounds, the surrounding medium of bone and tissue will vibrate at different frequencies. Vibration transmission increases when biting with an open jaw, when the teeth come into contact with each other during recording and if the surrounding muscles are stiff during biting (Hashimoto and Clark, 2001).

The sound wave produced during the biting of a crisp product travels through the surrounding medium as a pattern of pressure changes (Moore, 1982). For air-conducted sounds, air molecules vibrate which results in periods of compression (increased density of air due to compression into a smaller volume) and rarefaction (decreased density of air as the force is released and molecules return to their original position). The frequency of this vibratory motion is the rate at which the source of the sound vibrates (in Hz) (Speaks, 1999). These molecular movements are plotted as a waveform of pressure variation against time. The simplest type of waveform from an acoustic point of view is the sine wave. However, the waveforms produced during biting of crisp products are more complex than a sine wave with many jagged, irregular peaks (Vickers and Bourne, 1976)

Sound pressure, sound pressure level, and frequencies of the sound can all be determined from the sound waves. Sound pressure is the amount of force per unit area of a sound wave (measured in $N.m^{-2}$) (Speaks, 1999) and is used in the calculation of sound pressure level. Sound pressure level is a measure of the magnitude of a sound on a decibel (dB) scale. It is the ratio between actual sound pressure and a reference sound pressure (2×10^{-5} $N.m^{-2}$). This reference sound pressure value is the threshold of hearing. Based on this ratio, a sound pressure at the threshold of hearing would have a sound pressure level of 0dB (Rossing, 1990).

Frequencies of the sound are determined using Fourier analysis. During Fourier analysis, the original data points are transformed into underlying frequencies. These data are then plotted as amplitude versus frequency. From the plot it is possible to identify special or important frequencies as these are characterised by higher amplitude on the plot.

To obtain a quantitative measure of the sound wave, Edmister and Vickers (1985) and Vickers (1987) counted the number of peaks on the sound wave, the mean height of the peaks and the duration of the sound wave. Another means of characterizing the sound waves is through fractal analysis. Fractal analysis is a technique for assessing the overall ruggedness or jaggedness of irregular objects (Barrett *et al.*, 1992). Mathematical

algorithms are used to determine the degree of jaggedness of the line and the outcome is a fractal dimension of the line.

Although there are many different algorithms which can be used for fractal analysis, the algorithm most often used for acoustic research is the Kolmogorov algorithm. This algorithm is a box counting technique that involves dividing the signature into a grid and counting the number of squares which contain a part of the object. The size of the boxes of the grid is halved and again the occupied squares are counted. This process continues for numerous iterations. The size of the boxes cannot be smaller than the resolution of the object (Russ, 1994). The slope of a log: log plot of the number of filled boxes versus the size of the box is drawn and gives the Kolmogorov fractal dimension (D_{fk}).

For an object to be truly fractal, it must be self-similar. This means that any part of the object cannot be distinguished from the whole object or another part of the object (i.e., it has the same scaling factor in all directions). In the case of a sound wave, it is not possible to achieve self-similarity due to restrictions in sampling rate. Despite this, Barrett *et al.*,(1992) and Tesch *et al.*,(1995) concluded that it was possible to use fractal analysis as an objective measure of the degree of jaggedness of the sound waves. In this instance, the fractal dimension must be termed "apparent" rather than "true".

Fractal analysis has proven useful for measuring the jaggedness of acoustic signatures recorded during instrumental compression of products that make noise when fractured (Tesch *et al.*, 1995; Tesch *et al.*, 1996). However it has never been used for the analysis of sound waves produced while individuals bite into crisp food products.

2.6 Crispness

2.6.1 Sensory measurements of crispness

Sensory crispness gives the perception of freshness. Consumer research shows that crispness is a stimulus for active eating and is a tooth-oriented activity (Szczesniak and Kahn, 1971). Laboratory testing indicates that the perception of crispness has an auditory component (Vickers and Bourne, 1976) and a non-auditory component

(Christensen and Vickers, 1981). Acoustically, a crisp food is loud. The more crisp the food product, the louder the sound (Vickers, 1985). Additionally, a crisp food produces a high pitched sound when bitten (Vickers, 1984b; Vickers, 1985; Dacremont, 1995). A crisp food can also be positively (Vickers and Christensen, 1980) or negatively (Mohamed *et al.,* 1982; Vickers, 1987) related to hardness or firmness. Roudaut *et al.,* (1998) summarised the perception of crispness by stating that crisp products have a low density, cellular structure. They are brittle and generate a loud, high pitched sound when fractured.

Descriptive analysis using trained panelists has been used to quantify the degree of crispness of food products including; potato chips (Vickers, 1987; Lee *et al.,* 1988; Seymour and Hamann, 1988; Lee *et al.,* 1990), tortilla chips (Lee *et al.,* 1990), cereals (Liu and Tan, 1999), extruded snacks (Barrett *et al.,* 1994; Faller and Heymann, 1996) and dry bread (Roudaut *et al.,* 1998). In some instances many of the products have been commercial products purchased from local stores and the history of the product is not known (Vickers, 1987; Seymour and Hamann, 1988; Lee *et al.,* 1988; Lee *et al.,* 1990). In other instances, products have been processed by the researchers and stored under various conditions (Chen *et al.,* 1991; Sauvageot and Blond, 1991; Onwulata *et al.,* 1992; Roudaut *et al.,* 1998). However in these cases, the objective of the research was to study the product and the effect that changing processing and storage conditions had on the final product rather than the sensation of crispness. In research conducted to understand the sensation of crispness (Lee *et al.,* 1988; Seymour and Hamann, 1988; Lee *et al.,* 1990), commercial products have been modified by altering the water activity (a_w) of the samples. Water activity is a measure of the unbound or free water available to support biological and chemical reactions within a food. It is defined as the ratio of the partial water vapour pressure of pure water and a solution at the same temperature and pressure (Troller, 1989).

In the studies where texture was evaluated when water activity was modified, the structure of the samples was not altered to study the effect that structure had on the texture of the product. Only one paper has been published (Barrett *et al.,* 1994) where the structure of extrudates has been altered to study this effect. However this research addressed the breakdown of the products during instrumental compression and not the

acoustic component of crispness. Research needs to be conducted combining acoustics, force, and structure and how it affects the crispness of products.

2.6.2 Instrumental measures of crisp textures

A variety of instrumental tests have been used to assess the crispness of products. A list of these tests and the parameters measured from each of them are shown in Table 2.3. The most common tests are compression tests (Iles and Elson, 1972; Andersson *et al.,* 1973; Barrett *et al.,* 1994), snap tests (Iles and Elson, 1972; Andersson *et al.,* 1973; Vickers and Christensen, 1980; Vickers, 1987) and shear/compression tests (Seymour and Hamann, 1988).

Various curve parameters from compression testing have been used to describe crispness, including the peak force required to compress the sample, the slope of the deformation curve before and after fracture and the area under the force-deformation curve (a measure of the work of fracture)(Andersson *et al.,* 1973).

Shear/compression testing was used to show that the maximum force at failure and the work done to failure were inversely related to crispness (Seymour and Hamann, 1988).

Results from the Instron compression and snap tests were different to the constant loading rate instrument results. Mohamed *et al.,*(1982) found that crispness was not significantly correlated to fracture force using the constant rate loading instrument during crushing of various crisp products (sponge fingers, wafer biscuits, Dutch crisbakes, ice cream wafers, Maltesers). On the other hand, Vickers (1987) and Seymour and Hamann (1988) found that the maximum shear/compression force of potato chips was significantly related to crispness.

Table 2.3: Instrumental measures used for evaluating crisp products

Instrumental test	Parameters measured	Food tested	Author
Compression and snap test	Deformation before breakdown Force at breakdown Slope	Various wet and dry crisp products	Iles and Elson, (1972)
Compression and snap test	Slope of curve before fracture Fracture force Work of fracture Fracture modulus Compression modulus and flex modulus	Crisp breads	Andersson *et al.*,(1973)
Snap test	Peak force Slope Deformation to fracture Young's modulus	Various wet and dry crisp foods	Vickers and Christensen, (1980)

Table 2.3 cont'd...

Instrumental test	Parameters measured	Food tested	Author
Constant rate-loading instrument	Force of rupture (N) Work done before fracture Work done during fracture Total work done until complete compression Ratio of work done before fracture to total work done Fracture or collapse rate	Various friable foods	Mohamed *et al.*,(1982)
Snap test	Peak force Slope of the force-deformation curve at its steepest point Area under the force-deformation curve	Potato chips	Vickers (1987)
Shear/compression	Maximum force at failure Work done to failure	Dry crisp products	Seymour and Hamann (1988)
Compression	Stress Peak stress Young's modulus	Extruded snacks	Barrett *et al.*,(1994)

It has been postulated that because the relationship between instrumental measures and crispness differs for various food products, that perhaps the force required for mastication differs when biting into these foods (Vickers, 1988). Mioche and Peyron, (1995) have suggested that instrumental measures of force are an overestimation of intra-oral bite forces. Care must be taken when relating instrumental techniques to perception of textural properties based on physiological responses.

2.6.3 Bite force measurements of food products

Although the relationship between instrumental force measurements and crispness has been examined, little published research exists which explores the relationship between physiological bite forces measured intra-orally and the perception of the texture of food products. Tornberg *et al.,* (1985) compared the bite force measures collected using strain gauges implanted in the upper dentures of one individual to sensory results collected from that same individual. The resistance to chew, elasticity, chewiness, ease of disintegration, amount of residue and juiciness of meat samples were evaluated using a 3-point category scale. The maximum load on the strain gauge did not have a significant relationship with the perceived textural properties of the meat samples.

More recently, Mioche and Peyron, (1995) measured occlusal forces during biting of elastic, plastic and brittle non-food products (silicone elastomers, waxes and pharmaceutical pills) and related the measured forces to hardness threshold levels determined by paired comparison testing. Miniature load cells were placed in the mouth so that the maxillary incisors were in contact with the flat side of the load cell. A sample was placed on the surface of the load cell and in contact with the mandibular incisors. During biting, the subjects were instructed to place their incisors edge to edge so that the forces developed were perpendicular to the flat surface of the sample. Force results were correlated to the hardness threshold results, as well as to instrumental compression testing results. For brittle products, the bite forces were highly correlated with the hardness of the product ($r=0.99$). It was concluded that the force to bite into the brittle product was the sensory cue required to assist in the assessment of a product's hardness.

2.6.4 The contribution of air-conduction and bone-conduction to the perception of crispness

Many researchers have studied either air-conducted sounds (Edmister and Vickers, 1985; Vickers, 1985; Lee *et al.,* 1988) or bone-conducted sounds (Kapur, 1971) and their contribution to crispness perception. Although both types of conduction have been deemed important for the perception of crispness, only one researcher has assessed the contribution of both air-conduction and bone-conduction to crispness perception (Dacremont *et al.,* 1991). Various crisp, crunchy and crackly foods were bitten into and the air-conducted and bone-conducted sounds were recorded for these foods. When the air-conducted and bone-conducted sounds were mixed and attenuated (decreased) to provide an indication of the contribution of each sound to the overall food sound, air-conducted sounds were always attenuated in the same proportion for all foods studied (regardless of the textural property of the food). The bone-conducted sound of crisp food products showed an 8dB difference in the amount of attenuation of the sounds between the two crisp food products studied. This difference, however, was not significant, indicating that it was not possible to distinguish between the kinds of food studied using bone-conducted sound measurements (Dacremont *et al.,* 1991). Later research showed that crisp food products generated high pitched sounds, especially by air-conduction. Biting into crunchy and crackly products produced sounds of lower frequency with differences between crunchy and crackly apparent only in the bone-conducted sound (Dacremont, 1995).

It has been stated that recording the sounds produced during instrumental breakage of crisp samples is a good method for obtaining objective acoustic information with many sources of variability eliminated (Mohamed *et al.,* 1982; Seymour and Hamann, 1988). However, recordings of sounds produced by instrumental crushing or breaking do not provide valuable bone-conducted information which may be required for discriminating between different textures which have similar air-conducted sensations.

Various acoustic measures have been correlated to sensory crispness scores (Table 2.4). Sound pressure level is a factor in the psychophysical perception of loudness of crisp samples (Rossing, 1990). When assessed with regard to the crispness of potato chips stored at different water activities, the sound pressure levels decreased as the water activity of storage of the potato chips increased (Seymour and Hamann, 1988).

Table 2.4: Acoustic parameters used to define crisp products

Author	Parameter	
Drake, (1965)	Mean frequency Bite time Sound level at 1200 c/s	
Mohamed *et al.*,(1982)	Equivalent continuous sound level	
Edmister and Vickers, (1985); Vickers (1987)	Mean height of the peaks (mhp) Duration of sound Number of peaks (np)	
Seymour and Hamann, (1988)	Mean sound pressure (N/m^2)	Averaged over frequency ranges of: 0.5-3.3 0.5-1.9 1.9-3.3 0.5-1.2 1.2-1.9 1.9-2.6 2.6-3.3
	Mean sound pressure level (dB)	Averaged over frequency ranges of: 0.5-3.3 0.5-1.9 1.9-3.3 0.5-1.2 1.2-1.9 1.9-2.6 2.6-3.3
	Acoustic intensity ($watts/m^2$)	Sum over frequency ranges of: 0.5-3.3 0.5-1.9 1.9-3.3 0.5-1.2 1.2-1.9 1.9-2.6 2.6-3.3

The sound pressure plots have been analysed to quantify the waves by counting the number of peaks on the amplitude-time curve, assessing the duration of the sound and calculating the mean height of the peaks. Vickers (1987) counted the number of the peaks, and calculated the mean height of the peaks and the duration of the sound from sound waves produced during biting of crisp potato chips. The number of the peaks produced while biting a potato chip was found to be the best predictor of chip crispness (r=0.92), followed by the duration of the sound (r=0.87). Mean height of the peaks did not correlate well to crispness of potato chips.

Using Fourier analysis, the predominant frequencies produced while eating potato chips were found to be 3 to 4kHz and 6 kHz (Lee *et al.,* 1988) and for other noisy foods between 5 to 12.8kHz (Dacremont, 1995). Predominant frequencies produced during instrumental crushing of various noisy products were 1.9 to 3.3kHz (Seymour and Hamann, 1988). In this latter research, frequencies greater than 3.3kHz were not detected as the maximum analysed frequency was 3.3kHz.

2.6.5 Measures of association

Relationships between sensory measures of crispness and instrumental and acoustic measures have been explored through simple correlation analysis and linear regression techniques. Both correlation analysis and regression analysis are measures of association between sets of variables. The Pearson product moment correlation analysis is the simplest correlation approach. This analysis is a measure of the linearity of the data and shows how two data sets are associated. Prior to calculating the correlation coefficient (r), the data are plotted in an x, y scatter plot to check for linearity. If the data fall in a perfectly straight line, then this is a perfect correlation or relationship. If, upon calculating the coefficients, a negative value is obtained, then an increase in one variable is followed by a linear decrease in the second variable. If a positive value is obtained, then an increase in one variable is followed by a linear increase in the second variable. A coefficient of zero denotes no correlation between the two variables (O'Mahony, 1986). From the correlation coefficient (r), the coefficient of determination (r^2) can be determined. This is a measure of the proportion of variation in y which can be explained by x. For instance, if r=0.5, then r^2=0.25 which means that 25% of the variation in y is attributable to a change in x.

While correlation analysis provides an indication of linear association between two variables, linear regression is used to fit the best straight line through the data which leads to the prediction of y based on changes in x. Simple linear regression is used to predict one variable based on one other variable, while multiple linear regression is used to predict one variable based on multiple variables. Like correlation analysis, the data must be plotted first to ensure linearity. A line of best fit is then determined through the data points. This line is based on least squares criteria (Snedecor and Cochran, 1989). For this, the distance of each data point from the drawn line is calculated. The sum of the squared distances from the line is the measure of degree of fit of the line. The line which provides the least sum of the squared distance has the best fit to the data.

With multiple linear regression, there are numerous approaches to selecting the variables which should be used in the predictive model. Sequential search methods such as forward or backward regression or stepwise regression will select variables with the best regression estimates. A combination approach involves analysing all possible subsets of the data for determining which combination provides the best regression estimates (Hair *et al.,* 1998). The criteria used for determining the best regression model involves looking at the r^2 value and the size of the residual mean square from the ANOVA (Meilgaard *et al.,* 1991). A large r^2 value is preferred when selecting appropriate models. The residual mean square is the estimated residual variance around the predicted line. A small residual mean square means that the variability of the dependent variable is small, therefore, resulting in a good fit of the line. A small residual mean square indicates that the model is a better prediction of y than if the residual mean square is large.

Correlation analysis and regression analysis have often been used to develop an understanding of crispness and associated variables. Correlation coefficients have been calculated to explore the relationship between crispness and many individual acoustic and instrumental measures (Vickers and Christensen, 1980; Vickers, 1981; Edmister and Vickers, 1985; Vickers, 1987).

Regression analysis has been used to predict crispness and four different models for predicting sensory crispness have been published (Table 2.5). Each is based on an

Table 2.5: Models for predicting crispness

Author	Foods tested	Methods used: Instrumental	Methods used: Acoustic	Methods used: Sensory	Equation	r^2
Mohamed *et al.*,(1982)	Sponge fingers, wafer biscuits, dutch crisbakes, ice cream wafers, maltesers stored at 5 water	Constant Loading Rate Texture Test	Recorded during instrumental compression	12-17 panelists	*Log Crispness* = $0.59 + 0.49\log(L_{eq}^{1}) + 0.50(W_F/W_T^{2})$	0.85
Vickers, (1987)	Various potato chip brands stored at water activities of 0.11 and 0.44	Instron bite cell	Recorded from 4 individuals	20 panelists	*Oral crispness*[3] = $-15.6 + 5.35(np^{4}) + 133(mhp^{5}) - 6.21(\text{peak force}^{6})$	0.98
Seymour and Hamann, (1988)	Pringles™ potato chips stored at 3 water activities	Instron compression	Recorded during instrumental compression	6-7 trained panelists	*Crispness*= 9.904 - 0.134(work[7]) + 0.025(mean sound pressure 2.6 - 3.3kHz[8])	0.95
	Crunch twists stored at 3 water activities				*Crispness*= 16.47 - 0.064(force[7]) - 0.11(sound pressure level 0.5 - 1.2kHz[8])	0.95

[1] L_{eq} = equivalent sound level recorded during instrumental compression of the samples.
[2] W_F/W_T = ratio of work during fracture to total work during instrumental compression.
[3] Oral crispness is crispness perceived while biting samples.
[4] np =number of peaks of sounds produced while biting.
[5] mhp = mean height of peaks of sounds produced while biting.
[6] Peak force as measured using an instrumental bite test.
[7] Work and force measured using a shear/compression cell mounted on an Instron.
[8] Mean sound pressure and sound pressure level were evaluated from recordings of sounds produced during shear/compression using the Instron.

instrumental measure as well as an acoustic measure relating to the perceived crispness of dry crisp products. For each of the models, the water activity of dry crisp products was modified in order to obtain different levels of crispness.

Mohamed *et al.,* (1982) studied five different products at five different water activities. A panel of 12-17 panelists evaluated each treatment for crispness, sound intensity, rate of breakdown and hardness. Instrumental compression using the constant loading rate texture testing instrument was conducted and the noises produced during this test were recorded. Force, total work done, work done before fracture, work done during fracture and fracture rate were all removed from the deformation-time curves and the equivalent sound level (a measure of the average sound intensity over a given period of time) was determined for the recorded sound waves. All data were combined for the five brands and five water activities and regression analysis was conducted using the equivalent sound level, fracture rate and ratio of work during fracture to total work done (W_F/W_T) to predict perceived crispness. Regression equations were produced using various combinations of these variables and although a number of these equations were almost similar in their ability to predict crispness, the researchers selected the model which had the instrumental fracture (W_F/W_T) as the dominant criterion for predicting crispness followed by the equivalent sound level as the second dominant variable. This equation had an r^2 value of 0.84.

Vickers (1987) modified the crispness of various potato chip brands by storing them at water activities of 0.11 and 0.44. These chips were tested instrumentally using a bite cell attached to an Instron and the slope, area and peak force required to break the chips were reported. Bite sounds from four individuals were recorded and these were analysed for the number of peaks, mean height of the peaks and duration of sound. Twenty sensory panelists were asked to evaluate the recorded bite sounds for crispness (a measure of auditory crispness) as well as to bite the samples and evaluate their perception of crispness while biting (a measure of oral crispness). Auditory crispness was not highly correlated with oral crispness indicating that oral crispness judgments required some form of tactile input as well as the auditory input. This was confirmed by the regression analysis which showed that combinations of the number of sounds, the mean height of the peaks of the sound and the peak instrumental force produced the

highest correlation with oral crispness (r^2=0.98). When the instrumental peak force was replaced with another instrumental measure, the correlation dropped slightly to 0.96, indicating that any instrumental measure of force combined with acoustic measures could adequately predict crispness.

Seymour and Hamann (1988) studied the crispness of crunch twists, saltine crackers and various brands of potato chips stored at different water activities and developed individual regression equations for each product. Similar to Mohamed *et al.,* (1982) the acoustic measures were recorded from instrumental compression. The sound waves were characterised by calculating the sound pressure, sound pressure level and acoustic intensity for a range of frequencies. These measures were then combined with instrumental measures of force at failure and work at failure to determine the combination of measures which could be related to perceived crispness. These researchers used a trained panel of up to seven panelists to evaluate crispness, crunchiness and hardness of the samples. Crispness of potato chips was best explained by instrumental work and mean sound pressure of 2.6 - 3.3kHz (r^2=0.95) while crispness of crunch twists was best explained by instrumental force and sound pressure levels of 1.2 - 1.9kHz (r^2=0.95).

Acoustically, all regression equations in Table 2.5 except for the equation developed for crunch twists showed positive input from the acoustic measures, indicating that as the crispness increased, so too did the acoustic measure studied. In the case of the crunch twists, the sound pressure level at 0.5 - 1.2kHz decreased as crispness increased. The sound pressure level at 0.5 - 1.2kHz is a measure of the magnitude of the sound at the frequencies within this range. Sounds produced in this range are low frequency sounds and a decrease in sound pressure level at those frequencies as the crispness increases indicates that the loudness of the low frequency sounds decreases as the crispness increases. As crispness has been related to higher frequency sounds (Dacremont, 1995), this result is not surprising. The predictive ability of the models in Table 2.5 is typically high (r^2 = 0.85-0.98), however, in all cases, these models have been based on instrumental techniques for the force/work measures and in some cases for the acoustic reading as well (Mohamed *et al.,* 1982; Seymour and Hamann, 1988). Additionally, the acoustic recordings have been made from few individuals biting into the sample

(Vickers, 1987) and the sensory crispness scores were often collected from a small population of untrained individuals differing from those used for acoustic recordings (Vickers, 1987).

Although these models show appropriate trends, they are not true reflections of how physiological sensations contribute to the perception of crispness. No measures of intra-oral bite forces and bone-conducted sound have been used in these models. In order to get an actual measure of the physiological inputs into perceived crispness, these physiological measures must be collected.

2.7 Extrudates and design of extruders

An extrudate is a product which has been shaped by pressure and cooked by heating using an extruder. Food extruders can be divided into two general categories; single-screw extruders and twin-screw extruders. The basic difference between the two types is in the number of screws used to convey the material. All extruders have three sections; the feeder/preconditioner, the screw and the die (Harper, 1986). In the feeder/preconditioner, feed moisture is controlled so that pre-treated ingredients are delivered uniformly to the feed section of the extruder. Although preconditioners are necessary for single-screw extruders, they are not crucial for twin-screw extruders, where water can be metered directly into the extruder barrel and the twin-screw design will evenly distribute the water.

During processing, the material travels from the feeder/preconditioner to the screw section of the extruder. In the screw section, the raw material is transformed into a viscous dough-like mass. Within both single-screw and twin-screw extruders, the processing zones of the screw section can be subdivided into conveying, kneading and final cooking zones. As the raw material moves through these zones toward the die, it is compressed, heated and sheared. Water is added in the conveying zone to enhance conductive heat transfer as well as for texture and viscosity development (Huber and Rokey, 1990). In the kneading zone the raw material is transformed from discrete particles to a viscous dough-like mass due to shear, pressure and heat. In the final cooking zone, temperature and pressure increase rapidly and the material becomes a

homogenous dough. Typically for corn based snacks, the extruder barrel temperature is between 120°C - 160°C and barrel pressures of up to 7093kPa can be achieved depending on the extruder type (Huber and Rokey, 1990). Heating of the product is done through external heating sources around the barrel of the machine or by steam injection into the extruder. Additionally, heat is produced by friction as the product travels through the rotating screws.

After travelling through the screw, the heated material eventually reaches the die, which is the point at which the product exits the extruder. The die has one or more small holes of varying shapes through which the product is forced (extruded). The product is shaped as it passes through the holes to atmospheric pressure (101.3kPa) and temperature on the other side. Because there is a dramatic difference in pressure and temperature either side of the die, water (superheated on the screw side) is flashed off and the product expands. Cooling of the product is mainly due to evaporative cooling as well as the convection transfer of heat to the atmosphere.

The main differences between the single-screw and twin-screw extruders occur in the screw section. The single-screw extruder has one screw surrounded by a heated barrel. The channel between the screw and the barrel wall gradually becomes smaller toward the end of the extruder, increasing the pressure on the material travelling through the barrel. The increased pressure and heating occurring in the barrel allows the product to travel through to the end of the extruder by frictional forces. Conversely, the twin-screw extruder has two intermeshing, counter rotating screws configured to convey, knead and shear the material. Within single-screw extruders, slip is less likely to occur where the product will not move while within the twin-screw extruder slip can be avoided by suitable configuration of the screw elements.

2.8 Physical properties of extrudates

Due to the nature of the extrusion process, all extruded snacks have a dry porous structure. It is this porosity which contributes to the production of sounds during biting or crushing of the extrudates and the textural characteristics of the product. Porosity is defined as the fraction of the bulk volume of the sample which has void or open space

(Dullien, 1979). In general, starch based extruded products have a pore volume of between 60 and 90% (Barrett and Ross, 1990).

Porosity is produced by the expansion of the extrudate caused by the instantaneous decrease in pressure which occurs as the starch melt leaves the die (Barrett and Ross, 1990). Void spaces are produced during the expansion process and are usually due to overstretching of the cell wall film (Barrett and Ross, 1990). In extrudates, the pores that are formed are mostly open with intracellular channels (Hiçşaşmaz and Clayton, 1992). This type of pore is classified as an interconnected void space, meaning that is accessible from both sides. Closed pores, which have solid material forming every face of the cells (Ashby, 1983) are isolated and totally inaccessible.

The mechanism behind pore formation during the extrusion process has not been identified. Hiçşaşmaz and Clayton (1992) suggested that the degree of formation of closed pores is a random event and that further work needs to be done to understand pore formation mechanisms. The ingredients used have an effect on porosity. Ghorpade *et al.,* (1997) studied the effect of protein on microstructural and chemical properties of extruded starch based products. In general, the degree of open pore structure increased with increasing protein content. In addition, as amylose content increased from 0 to 25%, the total porosity decreased.

2.9 Instrumental measures of physical properties of extrudates

The simplest measure of the structure of an extrudate is a density measure (Barrett and Peleg, 1992a). Bulk density (also known as apparent density) is a measure of the density of a material including all pores remaining in the material (Rahman, 1995). It can be measured using solid displacement of rapeseeds (Hiçşaşmaz and Clayton, 1992), glass beads (Moore *et al.,* 1990; Ryu *et al.,* 1993; Ghorpade *et al.,* 1997) or sand (Hsieh *et al.,* 1990). Bulk density can also be determined by weighing samples of the same length and measuring the diameter (Barrett and Peleg, 1992b). Two products may have the same density, yet differ in other characteristics such as cell size, wall thickness and porosity. It is therefore, important to measure these parameters to have a thorough understanding of the physical properties of extrudates.

Methods of evaluating extrudates for these parameters have included optical methods such as image analysis (Barrett and Ross, 1990; Moore *et al.,* 1990; Barrett and Peleg, 1992a) or by instrumental methods such as porosimetry (Hiçşaşmaz and Clayton, 1992).

2.9.1 Optical measurements

Microscopy is a valuable tool in defining the physical changes in extrudates (Cohen and Voyle, 1987). Photomicroscopy involves taking a two dimensional picture of a three-dimensional sample. Wax can be injected into the porous sample prior to obtaining the image to ensure that in the image, the cellular spaces within the sample are observed as a different colour than the cell walls. Often samples are sectioned in order to observe their internal structure.

Various measures can be made from the image including a measure of the volume of the sample and its particle size. However photomicroscopy is only reliable if the observed two-dimensional porosity is the same as the bulk or three-dimensional porosity of the actual sample (Rahman, 1995). Additionally, it may sometimes give inconsistent results due to human error in the measurement or if a sectioned sample which is not representative of the entire sample is evaluated (Dullien and Mehta, 1971/2). This has been improved through the use of three-dimensional imaging of samples. Scanning electron microscopy (SEM) and transmission electron microscopy (TEM) can be used to obtain three-dimensional images of the structure of samples. Image analysis using video captures of samples can also be used.

With computerised image analysis, images are processed and displayed to quantify grey levels into discrete intervals. An image is scanned and stored as a matrix of pixels with number grey levels. This image is then analysed by searching the contrast between dark and white areas of the image in order to obtain the contour of the sample as well as the contour of the cells within the sample. From this analysis, various structural parameters can be calculated including, perimeter, area, and porosity (Smolarz *et al.,* 1989) as well as cell size distributions and cell size area (Barrett and Ross, 1990).

2.9.2 Instrumental measurements of structure

Instrumental techniques for the assessment of pore structure and porosity and density typically involve a gas expansion method such as pycnometry, an imbibition test or an infusion method such as mercury porosimetry.

Pycnometry is the measurement of volume through the displacement of a gas. A sample is enclosed in a container of known volume under a known gas pressure. The sample chamber is connected to a second chamber (of known volume) and when the valve separating the two is opened, gas from the first chamber expands into the second chamber. Using the ideal gas law (equation 2.1), the volume of solids in the sample chamber can be calculated.

Equation 2.1:

$$V_p = V_B - V_a - V_b[P_2/(P_2 - P_1)]$$

Where:
V_p is the pore volume
V_B is the bulk volume of the sample (m^3)
V_a is the volume of the sample chamber (m^3)
V_b is the volume of the evacuated chamber (m^3)
P_1 is the initial pressure (Pa)
P_2 is the final pressure (Pa)

Once the volume has been determined, various measures of density can be calculated. Apparent density (ρ_{app}), also known as bulk density, is a measure of all pores (open and closed) present in the product (Rahman, 1995). It is calculated from volume and weight measurements of whole intact samples.

Particle density (ρ_{part}), a measure of the density of a product including all closed pores but excluding those pores open to the surface (Rahman, 1995), is calculated by determining the volume of a sample coated in wax. The wax coating penetrates the open pores. Upon cooling, the wax sets, and the closed pores are the only voids left remaining in the sample. The volume of wax on each sample is determined from the weight difference of the sample before and after the wax coating and knowledge of the density of the wax ($0.9107 g.cm^{-3}$). After waxing, the sample is placed in the pycnometer to

obtain the total volume of the waxed sample. The sample volume is determined by subtracting the volume of the wax from the total volume of the wax coated sample.

The substance density (ρ_s) is the density of a product which has been thoroughly broken down to remove all pores. Substance density is determined by measuring the volume of the a known mass of crushed sample in the pycnometer.

These three density measures are then used to calculate porosity. Apparent porosity is a measure of the total porosity of the extrudate, including both the open and closed pores within the product (Rahman, 1995) and can be calculated using Equation 2.2.

Equation 2.2:

$$\varepsilon_{app} = 1 - \frac{\rho_{app}}{\rho_s}$$

where:
ρ_{app} is apparent density
ρ_s is substance density

Open porosity, is the ratio of apparent density and particle density subtracted from one as shown in Equation 2.3.

Equation 2.3:

$$\varepsilon_{op} = 1 - \frac{\rho_{app}}{\rho_{part}}$$

where:
ρ_{app} is apparent density
ρ_{part} is substance density

Closed porosity can be calculated knowing the particle density and the substance density as shown in Equation 2.4.

Equation 2.4:

$$\varepsilon_{cp} = 1 - \frac{\rho_{part}}{\rho_s}$$

where:
ρ_{part} is apparent density
ρ_s is substance density

Imbibition testing involves immersing the sample in a perfectly wetting fluid so that it moves into all pore spaces within the sample. Pore volume is calculated based on the density of the liquid and knowing the sample weight before and after wetting. The bulk volume is determined by volumetric displacement when the samples are completely saturated in the wetting fluid. From the pore volume and the bulk volume the porosity is calculated (Dullien, 1979). This technique is useful for products which do not break down upon wetting. Extrudates will lose all of their porosity when wetted and therefore this technique is not a valid technique for determining porosity of extruded snacks.

Pore volume and pore size can be measured using mercury porosimetry (Dullien, 1979). Mercury will not spontaneously flow into the pores of most samples. Pressure is used to force it into the pore spaces. Knowing the amount of applied pressure, the pore diameter can be determined. The volume of imbibed mercury gives the pore volume and pore volume distribution. For testing, the sample is placed into a chamber containing mercury. As the pressure on the mercury increases, it moves into the pores of the sample. The size of the pore which mercury will move into is dependent on the amount of pressure within the chamber. This method is based on the assumption that the pore channels within the products are straight and does not account for the fact that during extrusion, pore formation is a random event and pores are neither evenly sized nor shaped. Therefore, one disadvantage of this technique is that not all pores will be filled as mercury is unable to move into the edges and corners of all pores (Dullien, 1979). For this reason, it has been suggested that mercury porosimetry should be used in combination with pore size distributions collected by optical methods in order to account for the randomness of pore cell size (Dullien, 1979).

2.9.3 Measures of the physical properties of extrudates

Both optical methods and instrumental methods have been used to characterise the physical properties of extrudates. Some authors have used image analysis to report qualitative information regarding cell wall thickness and size of pores, but have not quantified the information (Gomez and Aguilera, 1984; Owusu-Ansah *et al.,* 1984; Bhattacharya *et al.,* 1986). Ryu *et al.,* (1993) used SEM as well as photocopies of cross-sections of the extrudates to determine cell wall thickness and the number of air cells per unit area of extrudates. Barrett and Ross (1990) used image analysis of sectioned extrudates to determine the cell size distributions and cell size uniformity. In addition to cell size, image analysis has been used to determine cell elongation, cell orientation and the number of cells per pixel area of extruded snack products (Moore *et al.,* 1990).

Pycnometry has been used to characterise cereal products (Climas, 1987), grain kernels (Chang, 1988) and extrudates (Ghorpade *et al.,* 1997) in terms of open and closed pores.

Some researchers have combined optical and instrumental methods. Hiçşaşmaz and Clayton (1992) used both SEM and mercury porosimetry to determine the pore diameter, pore size distribution and orientation of pore structure of the highly expanded and compact food materials. Combining an optical technique with an instrumental technique provided more information regarding the microstructure of the product than one technique alone.

Although the effect of cellularity and density on the sensory properties of extrudates is important, few studies have been published discussing the relationship between structure and perceived sensory properties (Barrett *et al.,* 1994; Guraya and Toledo, 1996). It has been shown that porosity and bulk density affect the instrumental strength and fracturability of extruded products (Barrett *et al.,* 1994). The work that has been conducted has shown that cellularity influences product failure using instrumental measurements. These failure characteristics are a reflection of the perceived texture of the products (Barrett *et al.,* 1994). However no other research has been published relating physical properties to the perceived textural properties of extrudates measured by a sensory panel.

2.10 Conclusions

Crispness perception requires input from both sound and force. Sounds produced during biting occur through air-conduction (movement through the air to the auditory canal) and also bone-conduction (movement through the bones to trigger movement of the eardrum). Previous research has studied air-conducted sounds and their contribution to crispness; however, bone-conduction has not received a great deal of attention. It is important to understand the relative contribution of air-conducted and bone-conducted sounds to the perception of crispness.

Instrumental measures related to perceived crispness of dry crisp snacks have shown that tactile force is required for perception of crispness. Hardness detracts from the perception of crispness, as shown by a negative contribution to crispness of instrumental force and work measures in regression equations. However, there have been no direct measurements of the contribution of intra-oral forces to sensory crispness measurements. The true link between perceived crispness and the various physiological parameters experienced by the panelist is yet to be measured and defined. The development of a model composed of air-conducted sounds, bone-conducted sounds and intra-oral force will provide greater understanding of the physiological sensations occurring during mastication of a crisp product.

The relationship between structure and sensory properties of extruded products has not been well researched. Understanding the physical properties of extrudates and their effects of structure on the sensory properties of these products will further enhance the understanding of crispness of extruded snacks.

CHAPTER 3 : ACOUSTICS, STRUCTURE AND THEIR RELATIONSHIP WITH CRISPNESS

Analysis of sound wave data collected during biting or crushing of crisp products has involved quantifying the jaggedness of a curve by counting the number of peaks and calculating the mean height of the peaks and the duration of the sound (Edmister and Vickers, 1985; Vickers, 1987). However, fractal analysis is another method for quantifying jagged signatures which has been used in food science research (Barrett *et al.,* 1994), but never for the quantification of acoustic signatures produced during biting. Fractal analysis is a quantitative measure of the jaggedness of a curve and is similar to the determination of parameters such as number of peaks and size of the peaks. This research was conducted to assess the use of fractal analysis for characterising the sound waves produced during biting of crisp extrudates. Results from the fractal analysis were correlated to the perceived sensory properties of the crisp products.

Preliminary research into the understanding of some of the structural properties of extrudates and how these properties relate to crispness was also undertaken.

3.1 Experimental methods

For this research, extrudates were produced using both twin-screw and single-screw extruders. The extrudates produced using the twin-screw extruder varied in processing moisture content and in final water activity. In this chapter, these extrudates will be termed TSE, for twin-screw extrusion. The single-screw extrudates varied in levels of ingredients used in the formulation. In this chapter, these extrudates will be termed SSE, for single-screw extrusion.

3.1.1 Twin-screw extruder overview

Puffed, dry crisp corn extrudates were produced using a twin-screw co-rotating extruder with intermeshing screws (Clextral model BC21; Clextral, Firminy Cedex, France) located in the Food Pilot Plant, Massey University, Palmerston North. The Clextral model BC21 has a screw diameter of 25mm, a barrel length of 400mm and 5.5kW motor power.

The same screw configuration was used for all extrusion trials and it is shown in Figure 3.1. It was comprised of a combination of forward screw elements, decreasing in pitch from the inlet end to the discharge end of the forward kneading disks and a pair of reverse element screws. Located at the discharge end of the screws was a solid stainless steel plate with two 3mm die holes drilled directly into the plate (Figure 3.2).

Figure 3.1: Screw configuration for Clextral BC21 twin-screw extruder

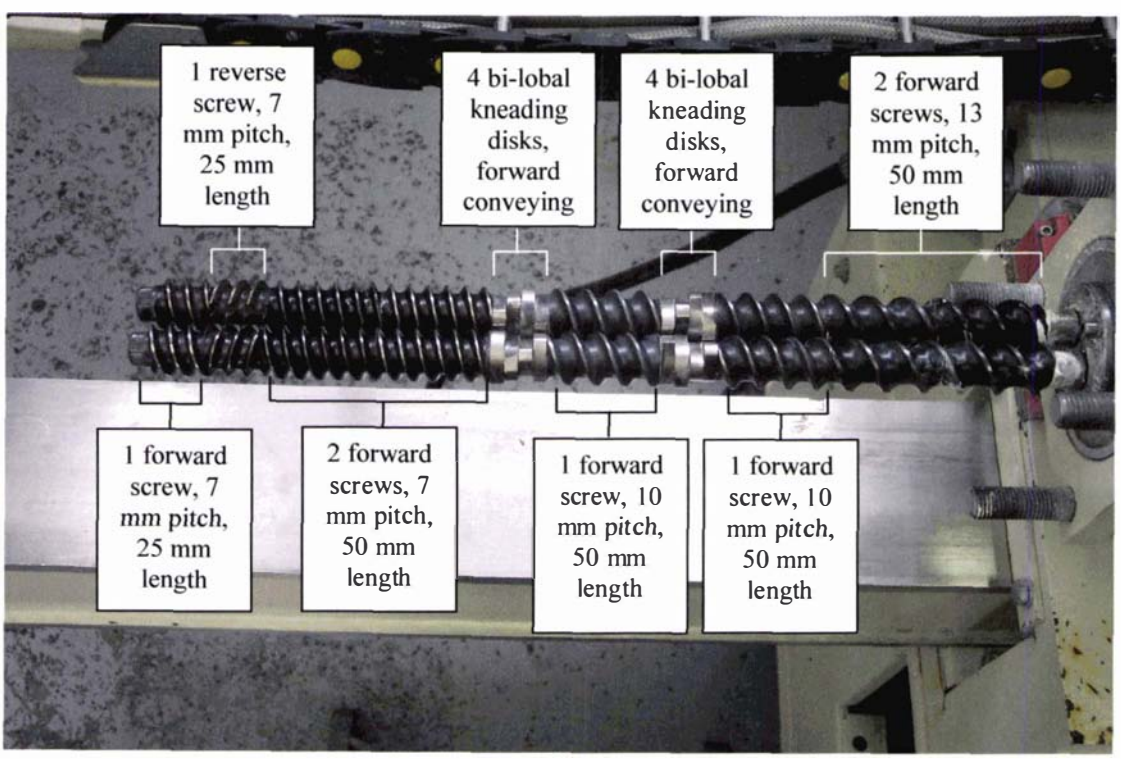
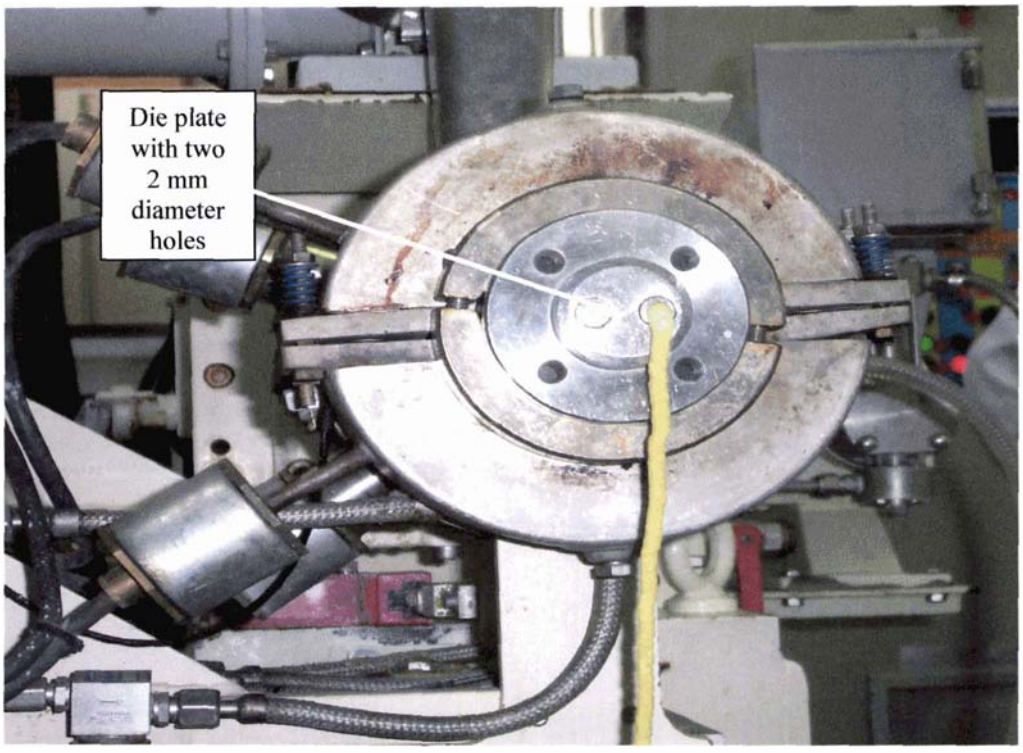


Figure 3.2: Die configuration used for Clextral BC21 extruder



During processing, corn grits were fed from the raw material hopper into the inlet end of the extruder via the raw material feeder. The feed rate was controlled by a variable-speed feed pump (Figure 3.3). Water was pumped into the extruder using a variable-speed water pump and was mixed with the corn grits at the front set of the bi-lobal kneading disks (Figure 3.1). As the product moved through the forward kneading elements, it was mixed and kneaded by rotation of the screws. During this time, the product was heated by both the friction produced as it moved through the screws and external electrical heating in the barrels. The temperature was maintained at a constant set value by the external heating/cooling chambers (Figure 3.4) thermostatically controlled via an electronic control panel.

At the discharge end of the extruder, the product was forced through the die. At this point, the pressure was approximately 500-600kPa. As it exited the extruder to the atmosphere (101.3kPa), the product expanded because of the pressure drop across the die which allowed water to flash off as steam.

Figure 3.3: Overview of Clextral BC21 twin-screw extruder ready for operation

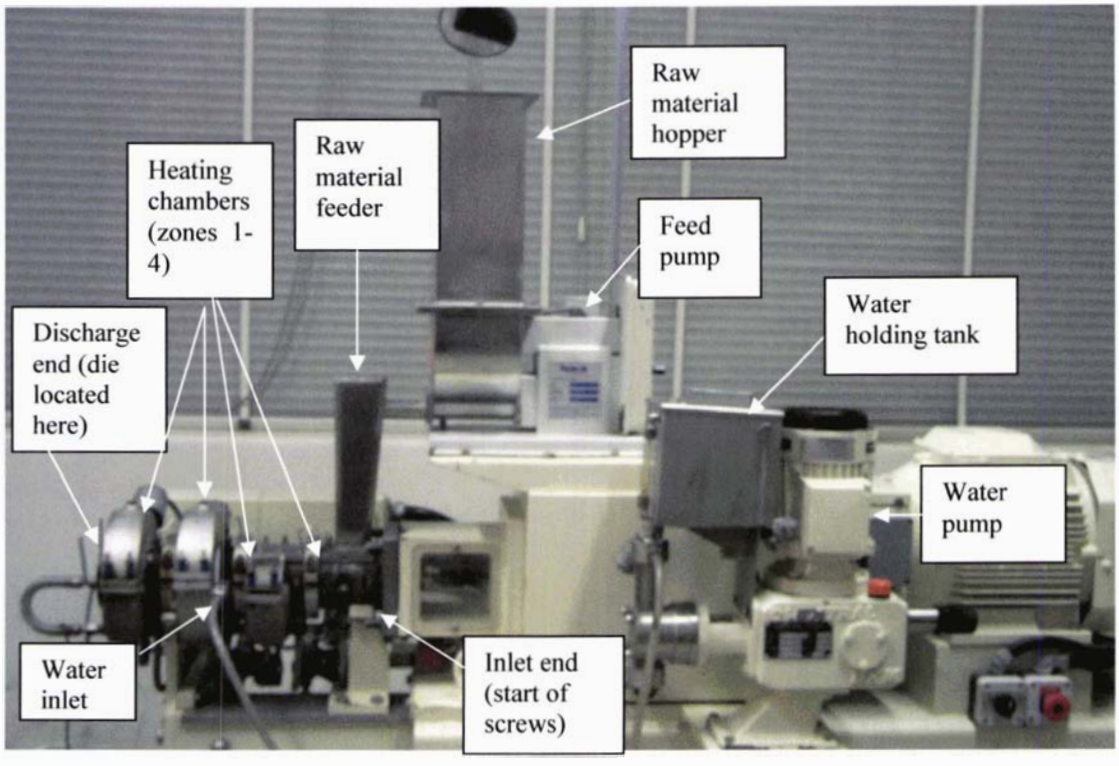
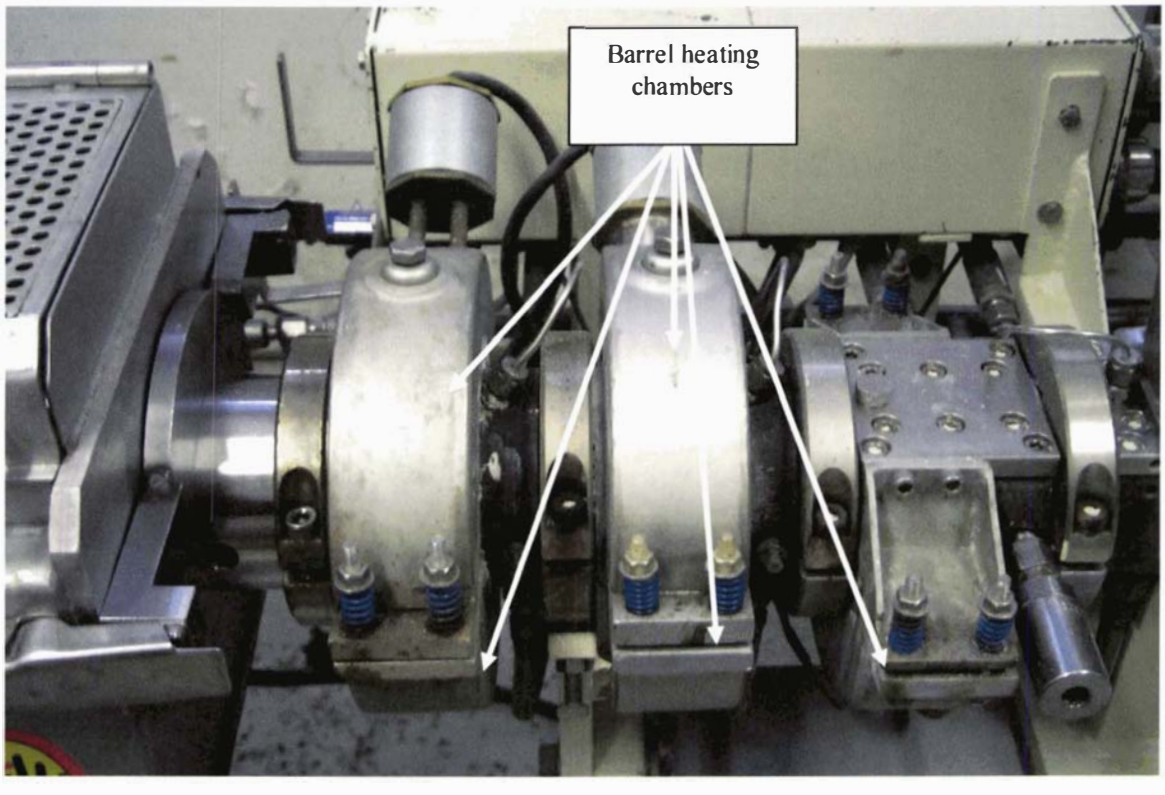


Figure 3.4: Barrel heating elements on the Clextral BC21 twin-screw extruder



3.1.2 Twin-screw extruder Start-up

The screw elements were fitted to the extruder shafts in the desired screw configuration. The extruder barrel was closed and the die plate attached. The heating chamber temperatures were set on the control panel and the chambers were heated prior to beginning the extrusion process. The raw material hopper and the water chamber were filled with corn grits and water, respectively. The screw speed was set to the desired speed (in this instance 400 RPM) and the water pump was set to pump at a rapid water feed rate of $3.88 \times 10^{-4} kg.s^{-1}$. Once steam exited the die, the corn grits were fed slowly into the extruder at a rate of $1.45 \times 10^{-5} kg.s^{-1}$. When the product began to exit the die, the water feed rate was reduced and the corn grit feed rate was slowly adjusted to the level which optimised the final product characteristics. During this time, the torque was always kept under 30Nm so that the screws did not become blocked with product. When the corn grits and water feed rates were finally established, the extruder was run for a further 15 minutes to ensure that a steady torque had been reached before extrudates were collected.

3.1.3 Twin-screw extrusion experiment

Twin-screw extrusion extrudates (TSE) were produced using ultrafine corn grits (Seedbank, New Zealand). The corn grits had a moisture content of 12 ± 1% moisture and a sauter mean diameter of 355.87 ± 1.4 μm. During the extrusion experiment, the corn grits were fed into the extruder using a feed rate of $2.06 \times 10^{-3} kg.s^{-1}$. The screw speed was set to 400 RPM and the barrel temperature for zones 1 to 4 (from feed to die) were respectively, 30°C, 60°C, 130°C, 180°C. Extrudates were cut to a uniform size (20 mm in length) using a cutter blade speed set to 49 RPM.

The moisture content of the product during extrusion prior to expansion was controlled using a control pump. The product moisture content was calculated using equation 3.1.

Equation 3.1:

$$X_p = \frac{FX_F + W}{W + F}$$

where:
X_p is the product moisture during extrusion
F the feed rate ($kg.s^{-1}$)
W the water flow rate ($kg.s^{-1}$) dosed to the extruder
X_F the moisture content of the feed

The value of X_F was taken as an average of the batches used and was 0.12 ± 0.01 g/100g corn grits. In this experiment three water flow rates were used; $8.33x10^{-5}kg.s^{-1}$, $1.66x10^{-4}kg.s^{-1}$, and $1.25x10^{-4}kg.s^{-1}$. This equated to processing moisture contents of 15.6%, 17.2% and 18.9%.

Following extrusion, the extrudates were placed on racks and dried for two hours in a forced-air oven (95 ± 2°C). They were cooled at room temperature and transferred to high-density polyethylene bags (thickness 195μm). Final moisture contents were 3 ± 0.1%, 8 ± 0.1% and 10 ± 0.1%, corresponding to extruder moisture contents of 15.6%, 17.2% and 18.9%, respectively.

Moisture contents of the cooled, dried samples were determined using a forced-air oven (110 ± 3°C). For each extrusion treatment, approximately 2g of crushed sample was placed in aluminium moisture dishes within the oven. Drying was carried out for five hours until the weight was constant (±0.001g). Moisture contents were determined in triplicate.

After drying and cooling, products from each of the three extrusion conditions were stored in sealed containers at 20°C at different water activities (a_w). Defined water activities were achieved by using saturated salt solutions of lithium chloride (a_w = 0.11), potassium acetate (a_w = 0.22), magnesium chloride (a_w = 0.33) and potassium carbonate (a_w = 0.44) (Greenspan, 1977). Equilibrium was assumed when the weight change was constant (±0.001g) over 24 hours. The extrudates were then placed into high-density polyethylene bags (thickness 195μm) and vacuum-sealed until required (approximately

one week). The water activity of the extrudates was verified directly using a water activity meter (Decagon CX2).

3.1.4 Single-screw extruder overview and start-up

The extrudates for this experiment were produced using a Maddox single-screw extruder (MX 350, Maddox Metal Works Ltd, Texas) located at Bluebird Foods Ltd., (Auckland, New Zealand). The single-screw extruder had a short barrel length (approximately 300mm) and a fixed screw configuration with a screw diameter of 68mm. The single-screw extruder had also an increasing root diameter, meaning a decreasing flow channel size through the length of the screw. The die, located at the end of the screw, was an 8mm hole inserted with a 4.8mm pin. This formed a ring shape when the extrudates exited the die. Prior to the experiments, the processing conditions were set and the extruder was run for 15 minutes to stabilize the temperature and the motor current. During this time, standard corn grits for commercial production were used to warm up the machine.

3.1.5 Single-screw extrusion experiment

To produce the single-screw extrusion (SSE) extrudates, three treatment factors were used. These were moisture content, monoglyceride content and rice bran content. Corn grits were obtained from Corson Grains Ltd (Gisborne, New Zealand) with an original moisture content of 14 ± 2%. Powdered monoglyceride and finely ground rice bran were obtained from Bluebird Foods Ltd. The following levels of each of the three ingredients (factors) were used:

Monoglyceride content: 0%, 0.5% and 1.0%

Rice bran content: 0%, 0.5% and 1%

Moisture content: 13%, 14%, 15% and 16%

These factors were combined into a central composite design, producing 36 different extrudates. A copy of the experimental design is shown in Appendix A.

The ingredients were preconditioned prior to extruding to set the moisture content levels to the range of 13% to 16%. To do this, all ingredients were mixed for 5 minutes in a

Hobart mixer and water was added to bring the moisture content to the desired level. The preconditioned ingredients were then stored in high-density polyethylene bags (thickness 195μm) for 18 hours.

All extruding using the single-screw extruder was conducted at Bluebird Foods Ltd (Auckland, New Zealand). The barrel temperature was 160°C. A feed rate of 100kg.h^{-1} and a screw speed of 224 RPM were used. These settings were standard for commercial production of extruded snacks. During the extruding experiments, the preconditioned formulations were fed into the extruder, one at a time, through its feeding hopper (located at the top of the extruder). Extrudates exited the die and were stored in high density polyethylene bags (thickness 195μm) and vacuum-sealed for transport to Massey University, Albany Campus. Each formulation was produced in a randomised order. When ingredients for a new formulation were added to the extruder, extrudates produced during the first minute were discarded to ensure that the products did not contain ingredients from the previous formulation.

Upon arrival at Massey University, all extrudates were dried at 90 ± 2°C in a conventional oven until a final moisture content of 1.6 ± 0.1% was reached.

3.2 Trained panel sensory evaluation

Trained panels were used to assess the textural properties of the extrudates. Panelists were recruited and selected based on availability and interest in the project. During training, panelists were presented with samples of extrudates which were representative of those to be tested. The panelists were instructed to bite the extruded products and individually record the characteristics that described the texture of the products and to record how they would define each characteristic. These terms and definitions were then discussed as a group. Redundant characteristics and those which the panelists did not agree on were discarded. These remaining characteristics were then combined with those that the panel leader had compiled and a final list of characteristics agreed upon. For the TSE panel, these characteristics were; crispness, pitch, loudness, crumbliness, toughness and density. For the SSE panel, the characteristics were; crispness, loudness, fracturability, hardness and denseness. Under the guidance of the panel leader,

definitions for each characteristic were discussed and formalized for each characteristic so that all panelists were evaluating the products in a similar manner.

Subsequent training sessions were used to train the panelists in the evaluation of each characteristic. The sessions were used to train panelists to consistently evaluate each characteristic using a 10cm line scale as well as to introduce the panelists to the range of extrudates they would ultimately be testing. Each training session followed a similar format. At each session, panelists were trained to evaluate two or three characteristics only. Characteristics were chosen by the panel leader prior to the start of training. At the start of each training session, the panel was instructed as to which characteristics would be evaluated in a given session and the definitions of the characteristics were written on a whiteboard. Panelists were presented with samples which displayed extremes of each characteristic to be used as references for anchoring their evaluations on the line. Where possible, these were typically extrudates that had been modified to exhibit extremes of the characteristic. However, for characteristics of fracturability and denseness other samples were used. For fracturability, samples of pita crisps (Pita Bread Ltd, New Zealand) were used as extremely fracturable. For denseness, cream cheese (Philadelphia Brand, Kraft Foods, Australia) was used as the most dense sample.

To ensure that panelists understood each characteristic and could discriminate between extrudates displaying a range of each characteristic, panelists were provided with four extrudates with a wide spread of the intensity of that characteristic. All extrudates were labelled with three digit codes and presentation to the panelists was randomized so that all panelists received the extrudates in a different order. The panelists were then asked to rank, from one to four (where 1 was most and 4 was least for the characteristic), the four extrudates exhibiting the characteristic. Following the ranking test, results of the test were discussed with the panelists. If problems were encountered with understanding the characteristic or ranking of the extrudates, then further extrudates were presented to the panelists and the definition was discussed until everyone was able to agree on the characteristic and could adequately evaluate extrudates for that characteristic.

Following the ranking test, panelists were then asked to evaluate the same extrudates (labelled with different three digit codes) using a 10cm unstructured line scale anchored

and labelled with appropriate end points. Each panelist measured their responses and results were discussed. This discussion highlighted panelists who were having difficulties evaluating extrudates for the characteristic and also showed panelists how their results compared to the others. If there were large discrepancies in placement of responses on the line scale, panelists were encouraged to move their responses to better align with the others.

This format was repeated for each characteristic. During the last part of each training session, the panelists evaluated four extrudates for all of the characteristics that they had been trained on in the current training session, as well as any characteristics that they had been trained for in previous training sessions. Results from these evaluations were shown to the panelists at the beginning of the next training session. At that time, discussions were held regarding the results and problem areas were highlighted. If the panel leader felt that further training was required for a particular characteristic then it was held at that point.

Once all the characteristics had been introduced and the panelists were able to adequately evaluate extrudates for all of the characteristics, the last two training sessions were used as practice for the panelists. During these practice sessions, two sets of six extrudates (labelled with a three digit code) were presented to the panelists in a randomised order and the extrudates were evaluated for all characteristics using a 10cm unstructured line scale labelled with appropriate anchors. Results were discussed and panelists were given an opportunity to have further training on any characteristic. Within the six extrudates presented during the practice sessions, at least two extrudates were duplicated in order to determine the discriminative ability of the panelists. Results were analysed by ANOVA to ensure that the panel could discriminate between extrudates and that all panelists were reproducible in their responses.

Once the panel leader was happy with the panel's performance, testing was conducted. Two distinct panels were used during testing. The first panel evaluated the extrudates produced using the twin-screw extruder (as described in section 3.1.3). For this panel, 7 experienced panelists were recruited. Training of these panelists occurred over 10 days using techniques previously discussed in order to orient the panelists to the test to be

completed and the extrudates to be evaluated. All training and evaluations took place in the sensory evaluation room of the Mary Earle House, Turitea Campus, Massey University.

During each testing session, panelists were presented with six extrudates to evaluate. The six extrudates were selected from the twelve treatments (four water activities x three moisture contents as described in section 3.1.3). Each panelist assessed four replicates of each extrudate. A total of eight sessions was required to complete testing.

All testing was conducted in individual testing booths illuminated with fluorescent lighting. One half-hour prior to each testing session, extrudates were removed from the storage bag and placed in low-density polyethylene zip lock bags (40μm thick). All bags were labelled with a 3-digit code corresponding to the extrudate treatments. Each bag contained five pieces of the extrudate treatments. Panelists were instructed to eat as many of the pieces as were required to complete their evaluations. Each extrudate piece was approximately 20mm in length and 6-7mm in diameter. Presentation of the extrudates was randomized among the panelists to prevent order effects from occurring. Filtered water was used to cleanse the palate between each sample. All evaluations were made on questionnaires with 10cm unstructured line scales labelled with each characteristic and appropriate anchors for each characteristic. A definition sheet was provided with each questionnaire in case the panelists wanted to refresh their memory on the definitions established for the characteristics. Panelists evaluated each extrudate for the characteristics of crispness, pitch, loudness, crumbliness, toughness and density. A copy of the questionnaire used by the panelists is shown in Appendix B.

Once testing was completed, all line scales were measured from 0 using a ruler and responses were recorded in centimeters to one decimal place. Data were then saved as a text file for analysis in SAS.

The sensory data were analysed to determine if significant differences existed amongst extrudates (based on moisture content and water activity), panelists and replicates using a program written in SAS (Version 6.4 and 8.1, SAS Institute, North Carolina). Significant differences were determined by ANOVA using SAS. A Tukey's Honestly

Significant Difference (HSD) test was used to indicate the differences between the extrudates (for both moisture content and water activity), panelists and replicates. All results were significant at 95% confidence.

The second trained panel evaluated the extrudates produced by the single-screw extruder (section 3.1.5). Ten experienced panelists were recruited from the Albany area. Training was conducted over six sessions using the format described earlier in this section. All training and testing was conducted in the sensory evaluation laboratory on the Albany Campus of Massey University. At each testing session, panelists were presented with 6 different extrudates for evaluation. Sample presentation to the panelists was randomized across the 36 extrudates so that one replication of testing required 6 sessions to complete. A total of 3 replicates of testing were conducted, for a total of 18 testing sessions. Sample presentation within each replication of testing was randomized so that each panelist received the 36 extrudates in a different order. Testing was carried out in individual booths illuminated with fluorescent lighting. All extrudates were served in low-density polyethylene zip lock bags (40μm thick). All bags were labelled with a three digit code corresponding with each extrudate treatment. Three extrudates from each treatment were placed in the bag and the panelists were instructed to hold the sample with the hole perpendicular to the upper and lower jaw and then bite the sample in half. Filtered water was used to cleanse the palate.

The extrudates were evaluated for characteristics of crispness, loudness, fracturability, hardness, and density. All responses were recorded onto 10cm unstructured line scales labelled with appropriate anchors for each characteristic. A copy of the questionnaire used by the panelists is shown in Appendix C.

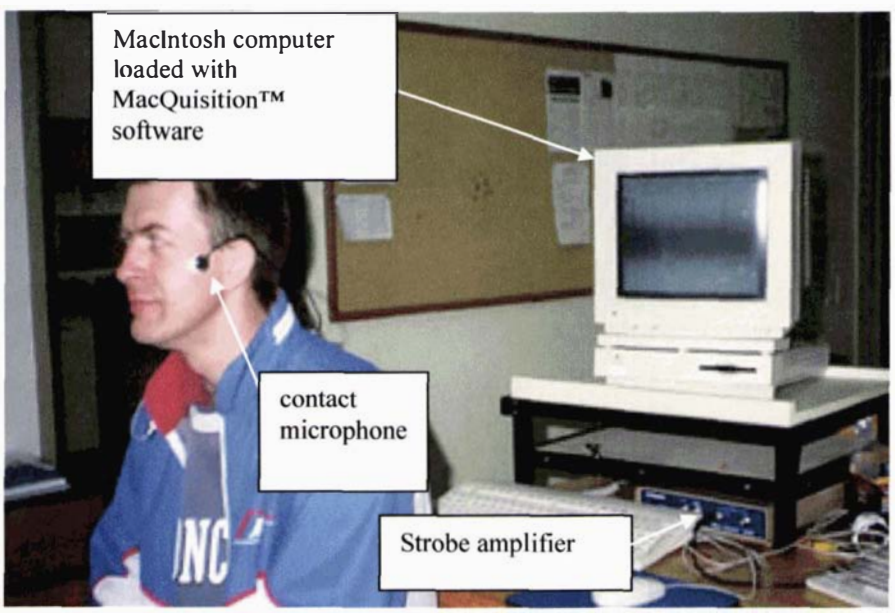
The sensory data from the second panel were analysed using the average linkage algorithm of cluster analysis in SAS (Version 6.4, SAS Institute, North Carolina) to classify the 36 extrudates into a smaller subset of samples for instrumental testing. Mean scores of the sensory properties were calculated for each cluster using SAS (Version 6.4, SAS Institute, North Carolina).

3.3 Recording acoustic sounds

For recording of sounds produced during biting of the TSE samples, a contact microphone (Shadow, Germany, frequency range 1Hz-20kHz) was attached to the skin on top of the mandibular bone close to the condoyle arch on the dominant chewing side of each subject using adhesive tape placed over the microphone. The microphone was interfaced to a Strobe amplifier (Strobe Industries, Wellington) and MacQuisition™ software loaded onto a MacIntosh computer (Figure 3.5).

Prior to collecting acoustic recordings, the microphone and data acquisition unit were tested to ensure that the microphone was detecting sounds at appropriate frequencies and the data acquisition unit was correctly recording these frequencies. A frequency generator was used to produce specific sound frequencies. The microphone was attached to the frequency generator and the software recorded a sequence of defined frequencies played into the microphone. The recorded data were exported from the MacQuisition™ program and opened in SigmaPlot. A spectral analysis of the voltage-time data was conducted using SigmaPlot to verify that all desired frequencies were recorded by the software.

Figure 3.5: MacQuisition data acquisition equipment



The MacQuisition™ system converted the sound waves picked up by the microphone into digital voltage readings which were processed and stored by the MacQuisition™ software. In addition, all data recording parameters were defined and controlled using the software. For all recordings, the "sampling rate" was set at 20,000 recordings per second. This was the rate at which the input sound waves were sampled to create the voltage reading.

Following standardization of the system, the sound data were collected. The panelists were instructed to place the sample between the back molars on the dominant chewing side of the mouth and bite through the sample once the software began recording. Data were collected for three seconds from the start of the bite. Once collected, the data were plotted as voltage versus time and these data were exported and stored as a data file for further analysis.

3.3.1 Characterisation and analysis of sound waves

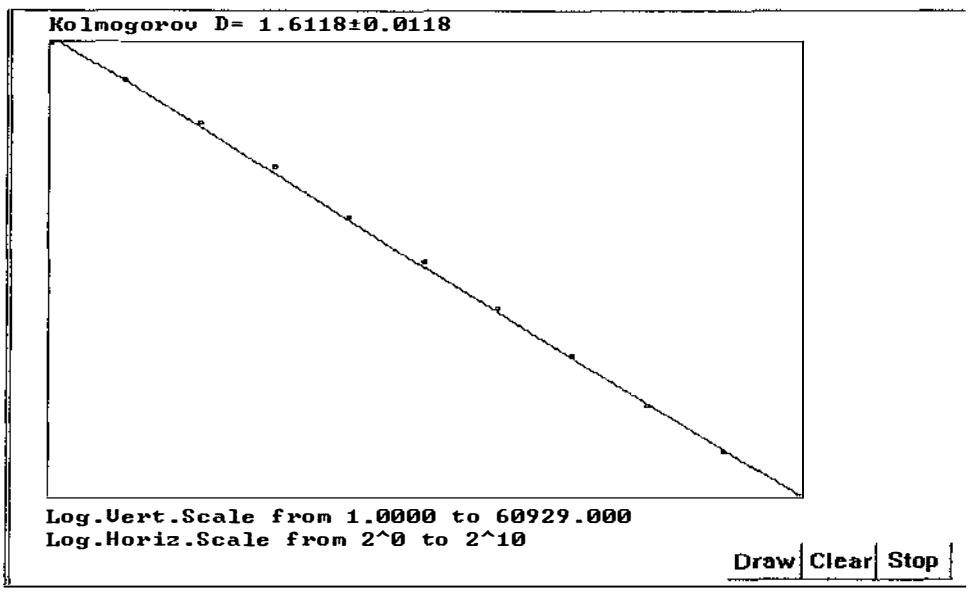
For analysis, the collected voltage-time data from the MacQuisition™ software were exported as a text file and imported into SigmaPlot.

The data were then analysed using a macro written in SigmaPlot to calculate the mean height of the peaks, the number of peaks and the duration of the sound. Duration was calculated from the start of the bite to the point at which the extrudate broke. The number of peaks was determined by counting each peak greater than 0.02 volts. The mean height of the peaks was determined by summing the height of each peak in the sound wave and dividing by the number of peaks.

The jaggedness of the sound waves was determined by calculating their fractal dimension. Using SigmaPlot, the headers were removed from the file and the voltage data were saved as a text file. The text file was imported into the fractal analysis program (Fractals for Windows; version 1.0b designed by Russ, copyright 1991-1993) and the data were analysed using the Kolmogorov algorithm. This algorithm is explained in section 2.5. Figure 3.6 contains an example of a plot obtained during analysis of a sound wave using the Fractal analysis program.

Figure 3.6: Typical fractal analysis plot of bite sounds from extruded snacks

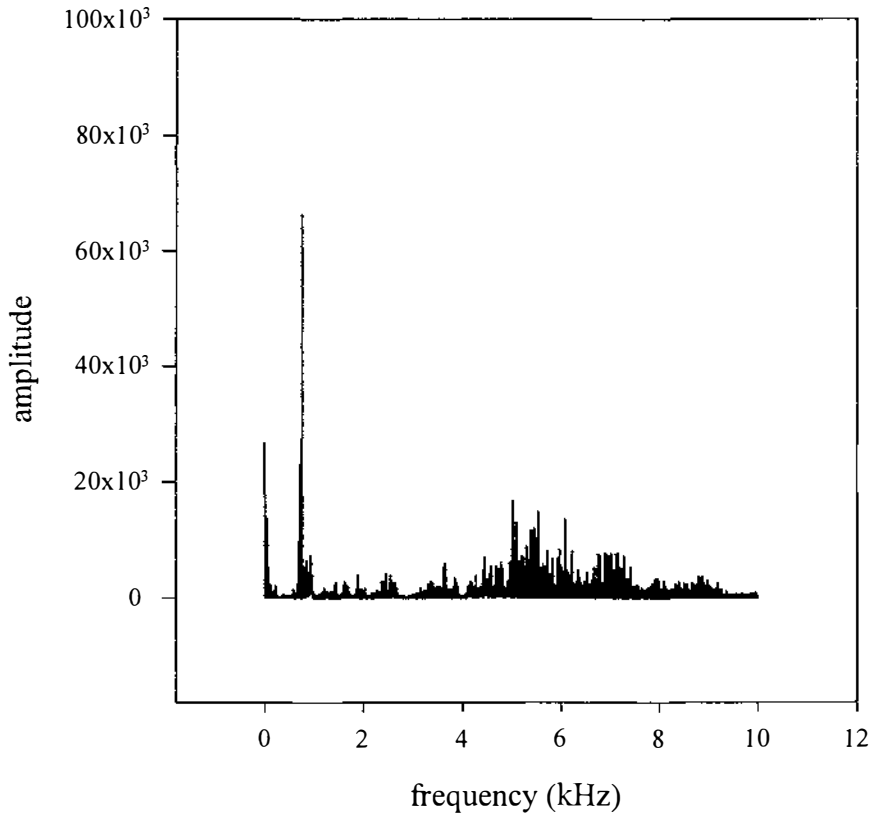
- Y axis is Log number of occupied boxes
- X axis is Log size of box
- The kolmogorov D_{fk} is the fractal dimension calculated as the slope of the line.



Acoustic signatures were analysed using Fast Fourier Transform (FFT) by using the power spectral density transform in Sigmaplot. The power spectral density transform calculated the FFT of the voltage-time data in order to observe the amplitudes of the frequencies produced when biting into crisp products. A typical frequency–amplitude curve developed by the FFT in SigmaPlot is shown in Figure 3.7. In order to provide a clearer picture of the main frequencies produced during biting of the snack products, the resulting FFT data from each extrudate were divided into 1 kHz segments and the results averaged and plotted.

Figure 3.7: Typical power spectrum analysis of a bite sound from extruded snacks

- The power spectrum was calculated using the power spectral density transform in SigmaPlot and the amplitude vs. frequency plotted.
- The amplitude refers to the level of sound at each frequency noted. In this curve, amplitudes were highest for sounds between 1-2kHz and again between 5-8kHz.



The number of peaks, mean height of the peaks, duration of the sound and fractal dimensions for the extrudates (both moisture content and water activity) and for panelists were analysed in SAS (Version 8.1, SAS Institute, North Carolina) by a 2-way Analysis of Variance (ANOVA). A Tukey's Honestly Significant Difference test was used to indicate where differences existed.

To look at the relationships between the perceived textural properties of the extruded snacks and the sound properties of the products, the acoustic parameters were correlated to sensory measures of texture using Pearson Product Moment Correlation analysis in SAS (SAS V8.1, SAS Institute, North Carolina) The data used from the descriptive

analysis and the sound measurements were collected from identical panelists. Although it was assumed that the extrudates were homogenous, mean scores were calculated based on the fact that the data collection for the sensory panel and the sound measurements were conducted in different sessions using different extrudates from the same treatments.

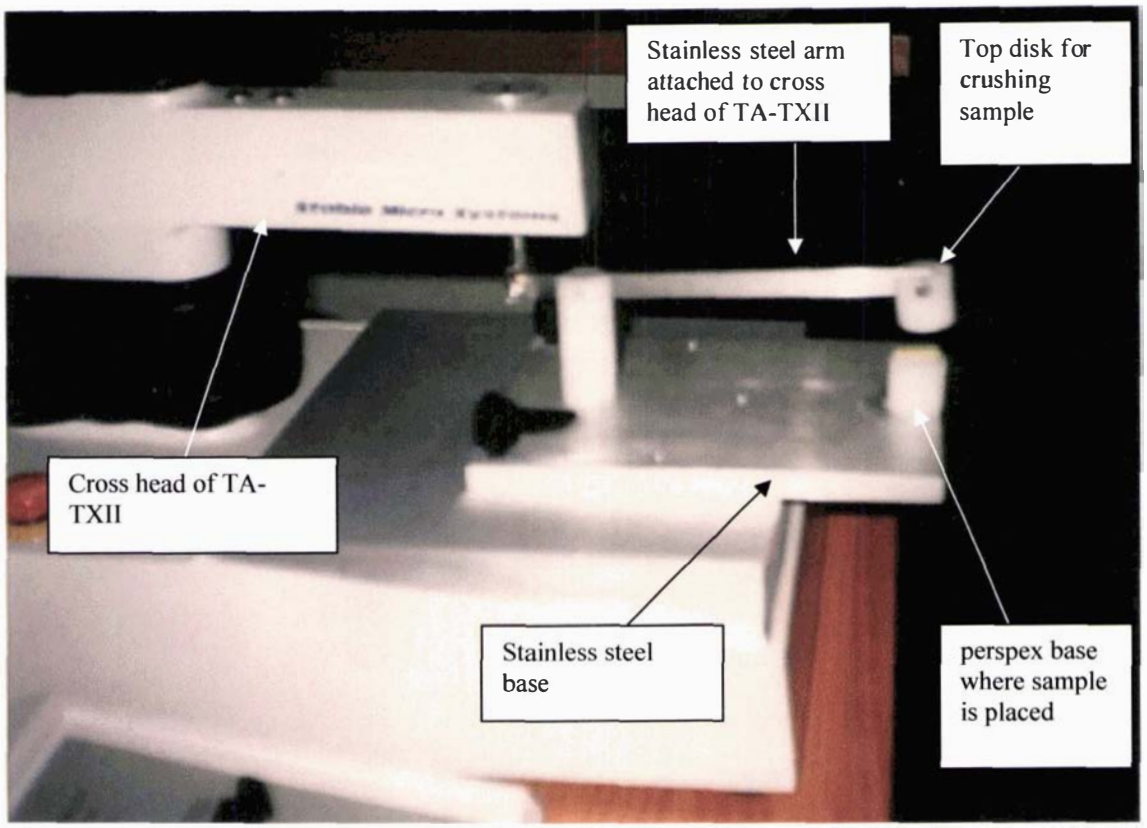
3.4 Instrumental testing of crisp products

A TA-XTII texture analyser (Stable Micro Systems, UK) was used to compress the TSE extrudates. The TA-XTII consisted of a vertically moving arm to which a compression probe was attached. Located on the arm was a 25kg load cell, interfaced to a computer loaded with Texture Expert software (Stable Micro Systems, UK). This software was used for programming the instrument and for recording and analysis of the force-time data.

The probe attached to the TA-XTII was designed to produce compression speeds similar to that used during chewing. The probe consisted of a perspex base 250mm in diameter and 250mm high. A second perspex disk with the same dimensions was fixed to a stainless steel arm (190mm in length) which was attached at one end to the moving arm of the texture analyser (Figure 3.8). The point of contact between the stainless steel arm and the moving arm of the texture analyser acted as a pivot point, allowing for a faster speed of movement of the perspex probe into the sample. When the arm was lowered the top disk came into contact with the bottom disk and thus the sample was compressed. The probe moved into the sample at a speed of $50mm.s^{-1}$.

For compression testing, a 20mm length of the extrudate was placed on the bottom perspex base. The probe crushed the extrudate lengthwise and the continuous force-time curve recorded. The texture analyser was set so that the top probe compressed the extrudate by 67% of the original diameter. However, as the extrudates were brittle, all shattered when the disk came into contact with them. Four replicates of compression of each treatment were made.

Figure 3.8: Probe designed for instrumental measuring using the TA-TXII



From the force-time curves, the maximum force and the time to reach maximum force were measured for each extrudate using the Texture Expert software. The extrudates had a circular shape and the accurate contact area of the probe was impossible to calculate. Thus, it was not possible to calculate stress for this analytical method.

The data were then analysed by a 2-way ANOVA using SAS (SAS 8.1, SAS Institute, North Carolina) to determine differences amongst extrudates (both moisture content and water activity) and replicates of testing. A Tukey's HSD test was used to indicate where differences existed.

3.4.1 Measurement of acoustic sounds produced during instrumental testing

To record the sounds produced during compression of the extrudates, the acoustic equipment outlined in section 3.3 was used. The Shadow microphone was attached to

the bottom perspex disk of the probe and the vibrations produced during compression of the extrudate were recorded. Four replicates of each treatment were recorded.

The jaggedness of the compression sounds was quantified by fractal analysis. The fractal analysis data were then analysed by ANOVA using SAS (Version 6.4, SAS Institute, North Carolina) to determine differences between treatments. A Tukey's HSD test was used to indicate where differences existed.

The fractal dimensions of the acoustic signatures collected instrumentally were compared with the individual's sound wave data using a Pearson Product Moment Correlation analysis in SAS (Version 8.1, SAS Institute, North Carolina).

The means of the instrumental measures were correlated to mean sensory scores using Pearson Product Moment Correlation analysis in SAS (SAS V8.1, SAS Institute, North Carolina) to look at the relationships between the perceived textural properties of the extruded snacks and the instrumental and acoustic properties of the products.

3.4.2 Measurement of the volume of extrudates

One extrudate treatment from each of the clusters from the SSE experiment was selected based on the cluster analysis as discussed in section 3.2 and the volumes of the extrudates were measured using a gas pycnometer (Stec Inc VM-100, Kyoto, Japan). These volumes were used to calculate particle density, apparent density and substance density of the extrudate formulations selected from each cluster.

At the start of each testing day, the pycnometer was equilibrated using the empty sample cup. The cup (with known volume of 12.3cm^3) was placed into the instrument, the chamber was closed and the cup was thermally equilibrated to the temperature of the instrument (19.5°C). Equilibration was indicated by a beep on the machine (approximately 15 minutes after placing the cup in the chamber). After temperature equilibration helium gas was injected through an inlet on the rear of the pycnometer at a rate of 1$kg.cm^{-2}$.G. Upon completion of pressurization, the gas was automatically released into a second chamber. The volume of the empty cup was calculated by the machine and displayed as a volume measure. This volume was stored in the memory of

the pycnometer and was automatically subtracted from the volume of the sample prior to displaying the sample volume on the control panel.

To compensate for any day-to-day variability which may have occurred during testing, also at the beginning of each testing day, a correction factor was determined. The volume of a stainless steel ball (with an actual volume of 28.96g.cm^{-3}) was determined. The ball was placed into the sample cup and after thermal equilibration its volume was determined by the pycnometer. The correction factor was the measured volume of the ball divided by the actual volume of the ball. This correction factor was used in the calculation of density of all extrudates tested on that day.

As the extrudates being tested had volumes of below 20g.cm^{-3} (the sensitivity of the instrument), the stainless steel ball used to calculate the correction factor was added with the extrudates to the sample cup during every test. This raised the volume within the sample cup to above 20g.cm^{-3}.

Prior to starting the volume measurements, extrudates from each formulation were prepared. It was required that the extrudates be modified to obtain volume measurements which could be used to calculate particle density and substance density. For particle density (ρ_{part}), the extrudates were coated in paraffin wax. As particle density is a measure of the density of a product including all closed pores but excluding those pores open to the surface, dipping the extrudates in wax ensured that the open pores were not exposed. Prior to applying the wax coating, the weight of the extrudates was measured and recorded to four decimal places

To coat the samples required for the particle density calculation, flake paraffin wax (Scientific Supplies Ltd. Auckland) was melted in a glass beaker in a water bath at 80°C. After the wax was melted, extrudate samples were dipped into the melted wax in the beaker until an even coating covered the sample. For dipping, a thread was tied around the extrudate and a glass rod was used to submerge the extrudate into the wax. After each coating, the extrudate was visually inspected to ensure that wax covered the entire surface. If any part of the extrudate was exposed, the extrudate was re-dipped into the wax. The extrudates were left to dry between each coating. In total, six coats of

paraffin wax were applied to each extrudate. After dipping they were weighed to four decimal places again and the weight recorded.

Substance density (ρ_s) is the density of a product which has been thoroughly broken down to remove all pores. The extrudates were modified by grinding them to a fine powder using a mortar and pestle. The weight of the crushed sample was measured and recorded to four decimal places.

Apparent density (ρ_{app}) is a measure of the density of a product, including all open pores; therefore, all open pores within the extrudate must be accessible to helium gas during volume measurements. For this to occur, the extrudates were weighed and placed in the sample chamber in an unmodified state (i.e., not coated or crushed).

Volume readings were conducted on each of the prepared samples. For both particle and apparent density, one extrudate of known weight was placed in the sample cup in the pycnometer along with the stainless steel ball. After temperature equilibration, the volume of the extrudate was determined by the pycnometer. This volume was recorded for the density calculations. For each replicate of testing, the volume reading from the pycnometer was measured in quadruplicate. These data were then averaged to obtain one volume measure per replicate of testing. Three replicates of testing of each extrudate formulation were conducted.

For substance density, a weighed amount of crushed extrudates was placed into the sample cup of the pycnometer with the stainless steel ball. After temperature equilibration, the volume of the extrudate was determined by the pycnometer. This volume was recorded for the density calculations. For each replicate of testing, the volume reading from the pycnometer was measured in quadruplicate. These data were then averaged to obtain one volume measure per replicate of testing. A single replicate of testing of each extrudate formulation was conducted for substance density because it was assumed that crushing removed all of the pores from the extrudates therefore, the substance density would not differ significantly within each formulation tested.

3.4.3 Density calculations

For particle density calculation, the weight of the wax was determined through subtraction of the initial extrudate weight from the waxed extrudate weight. This weight was then used to calculate the volume of wax as shown in equation 3.2.

Equation 3.2:

$$\text{Volume of wax } (\text{cm}^3) = \frac{\text{mass of wax (g)}}{\text{density of wax } (\text{g.cm}^{-3})}$$

where the density of paraffin wax is 0.9107g.cm^{-3}

The volume measurements from the pycnometer and the calculated volume of the wax were then used in equation 3.3 to calculate the particle density (ρ_{part}) of the extrudates.

Equation 3.3:

$$\rho_{part} \ (\text{g.cm}^{-3}) = \frac{\text{mass of unwaxed sample (g)}}{\text{volume of sample } (\text{cm}^3) - \text{volume of wax } (\text{cm}^3)} \text{ x CF}$$

$$\text{Where CF} = \frac{\text{measured volume of stainless steel bal}}{\text{actual volume of stainless steel ball}}$$

Substance density (ρ_s) and apparent density (ρ_{app}) were calculated using equation 3.4.

Equation 3.4:

$$\rho_s \text{ and } \rho_{app} \ (\text{g.cm}^{-3}) = \frac{\text{mass of sample (g)}}{\text{volume of sample } (\text{cm}^3)} \text{ x CF}$$

$$\text{Where CF} = \frac{\text{measured volume of stainless steel bal}}{\text{actual volume of stainless steel ball}}$$

3.4.4 Determination of porosity

The apparent density, particle density and substance density were then used to calculate the porosity of the extrudates. Apparent porosity is a measure of the total porosity of the extrudate. It includes both the open and closed pores within the product. Using the apparent density and substance density, the apparent porosity (ε_{app}) was determined using equation 3.5.

Equation 3.5:

$$\varepsilon_{app} = 1 - \frac{\rho_{app}}{\rho_s}$$

Open-pore porosity (ε_{op}) is a measure of the volume of open pores within the product. It was calculated using equation 3.6.

Equation 3.6:

$$\varepsilon_{op} = 1 - \frac{\rho_{app}}{\rho_{part}}$$

Closed porosity (ε_{cp}) is a measure of the volume of closed pores within the extrudate and was calculated using equation 3.7.

Equation 3.7:

$$\varepsilon_{cp} = 1 - \frac{\rho_{part}}{\rho_s}$$

The apparent and particle density and apparent, open and closed porosity values were input into a spreadsheet and analysed by ANOVA (SAS Version 8.1, SAS Institute, North Carolina) to determine significant differences amongst extrudates for each of the porosity and density measures.

The mean scores for the significant measures were plotted against the sensory crispness scores to explore the relationships amongst crispness and the measures of porosity and density.

3.5 Results and discussion

3.5.1 Sensory, acoustic and instrumental analysis from the twin-screw extruder (TSE) experiment

During the TSE experiment, water was varied in two ways. First, during extrusion, different quantities of water were added into the extruder. In the presentation of results, this has been labelled m.c. during extrusion for moisture content during extrusion. Second, the water activity of the samples at the time of consumption was altered by equilibrating all moisture content samples in four constant water activity environments (a_w = 0.11 to 0.44). This has been given the label of a_w during consumption.

3.5.1.1 Effect of moisture content during extrusion on extrudate texture

A trained panel of 7 people developed a set of descriptive terms for the textural assessment of the TSE extrudates. These terms included crispness, pitch, loudness, crumbliness, toughness and density. Definitions for these attributes are found in Table 3.1. The panelists used these descriptors to evaluate the extruded snacks with widely varying water activities and processing moisture contents.

Panel results were analysed by ANOVA to evaluate the effect of moisture content and water activity on the perceived texture of extrudates. The perception of each of the sensory attributes was greatly affected by the moisture content during extrusion. Results are summarised in Table 3.2. These results are mean scores for each moisture content, averaged across the four water activities.

Table 3.1: Trained panel definitions for sensory characteristics of TSE extrudates

Crispness A combination of the noise produced and the breakdown of the product as it is bitten entirely through with the back molars
Pitch The intonation of the noise produced when biting the product with the back molars
Loudness The amount of noise produced when biting through the product with the back molars.
Crumbliness The type of breakdown of the product - does it fracture or does it crumble into bits like sawdust?
Toughness The amount of force required to compress the sample between the back molars
Density The airiness of the product - is there large air cells (less dense) or are the cells small and tightly packed (more dense)?

In general, as the moisture content during extrusion increased, the samples became significantly less crisp and crumbly and produced a lower pitched sound when bitten. The trends observed for these characteristics differed across the three moisture contents. For example, crumbliness significantly changed for all three moisture contents, but significant differences for crispness were seen only between 17.2% and 18.9% moisture content. Pitch differed between the 15.6% moisture content and the 18.9% moisture content only. Additionally, perceived density increased significantly as the moisture content increased from 15.6% to 17.2% moisture (Table 3.2).

Table 3.2: Sensory properties of TSE extrudates processed at different moisture contents

Sensory characteristics[2]		m.c. during extrusion[1] 15.6%	17.2%	18.9%
Crispness				
	Mean	6.9a[3,4]	7.1a	6.1b
	Std Error	0.18	0.17	0.24
Pitch				
	Mean	5.7a	5.5ab	5.1b
	Std Error	0.19	0.21	0.23
Loudness				
	Mean	5.0b	6.7a	4.9b
	Std Error	0.17	0.17	0.21
Crumbliness				
	Mean	6.4a	6.0b	5.5c
	Std Error	0.19	0.21	0.28
Toughness				
	Mean	2.8c	4.2a	3.7b
	Std Error	0.18	0.21	0.23
Density				
	Mean	2.8a	4.0b	3.7b
	Std Error	0.19	0.18	0.21

[1]Extrusion moisture contents of 15.6%, 17.2% and 18.9% correspond to extrudate moisture contents of 3%, 8% and 10%.
[2]Values range from 0 to 10, where a lower score indicates that less of the attribute was perceived by the panelists.
[3]Four extrudates at each moisture content were evaluated by 7 panelists in 4 replicates averaged across 4 water activities (n= 112).
[4] Means in the same row with the same letter are not significantly different (p>0.05).

The decrease in crispness as processing moisture content increased observed in Table 3.2 is similar to results observed by Chen *et al.,* (1991). Corn based extrudates produced at lower moisture contents (20% dry weight) were more viscous during the extrusion process, resulting in a greater pressure differential between the die and the atmosphere as the product exited the die. This produced a more puffed product which was crisp and airy (less dense), similar to the results observed in Table 3.2. Chen *et al.,* (1991) also observed that a high moisture product (30% dry weight) was less viscous and had a lower pressure differential when exiting the screws, producing a less puffed product. These results differ from those obtained by Faller and Heymann (1996), who found that high moisture content potato extrudates (25% dry weight) were harder, chewier and

crisper than those made with low feed moisture (19% dry weight). They stated that for a given extruder process, the higher the feed moisture, the lower the temperature and pressure within the extruder chamber. The difference in results between the two researchers could be due to the use of different starches (corn/potato) in the extrudates as well as the use of additional raw materials (oil and salt) by Faller and Heymann (1996) during the extrusion process. Feed material, feed rate, moisture content as well as processing conditions such as screw speed, temperature and screw configuration all have a significant effect on final product quality during the extrusion process (Hsieh *et al.,* 1990; Chen *et al.,* 1991; Faller *et al.,* 1995).

3.5.1.2 Effect of water activity on perceived product texture

Extrudates were equilibrated at various water activities (approximately fourteen days) and were then tested by the sensory panel. The data from the panel were analysed by ANOVA to evaluate the effect of water activity at consumption on the perceived texture of the extrudates. Sensory scores for each water activity were averaged across the three processing moisture contents. The results are presented in Table 3.3. An increase in water activity resulted in a decrease in crumbliness and an increase in toughness. For some measurements (crispness, pitch and density), the low water activity had no effect with differences observed at water activities of 0.33 or higher. At these higher water activities a decrease in crispness and pitch and an increase in density were observed.

Table 3.3: Sensory properties of TSE extrudates varying in water activities

Sensory characteristics[2]	a_w during consumption[1]			
	0.11	**0.22**	**0.33**	**0.44**
Crispness				
Mean	7.9a[3,4]	7.7a	7.0b	4.3c
Std Error	0.17	0.14	0.16	0.22
Pitch				
Mean	6.4a	6.1ab	5.5b	3.7c
Std Error	0.23	0.21	0.20	0.22
Loudness				
Mean	5.3b	6.0a	6.5a	4.4c
Std Error	0.20	0.19	0.20	0.27
Crumbliness				
Mean	8.1a	7.1b	5.9c	2.8d
Std Error	0.13	0.13	0.17	0.20
Toughness				
Mean	1.8d	2.7c	4.0b	5.8a
Std Error	0.16	0.21	0.19	0.20
Density				
Mean	2.4c	2.9c	3.6b	5.0a
Std Error	0.21	0.21	0.20	0.22

[1]The water activity was manipulated by storing the extrudates in desiccators over solutions of lithium chloride (a_w=0.11), potassium acetate (a_w=0.22), magnesium chloride (a_w=0.33) and potassium carbonate (a_w =0.44).

[2]Values range from 0 to 10, where a lower score indicates that less of the attribute was perceived by the panelists.

[3]For testing, three extrudates at each water activity were evaluated by 7 panelists in 4 replicates averaged across 3 moisture contents (n= 84).

[4] Means in the same row with the same letter are not significantly different (p>0.05).

The significant decrease in crispness at a water activity of 0.33 observed in Table 3.3 corresponds with that observed by others (Katz and Labuza, 1981; Van Hecke *et al.*, 1998; Waichungo *et al.*, 2000). Katz and Labuza, (1981) observed that snacks stored at a water activity range of 0.35 to 0.5 decreased in consumer acceptability of texture. Wiachungo *et al.*, (2000) reported that at water activities between 0.36 and 0.58, extruded snacks were low in fracturability and high in cohesiveness. Results from the current study indicate that above a water activity of 0.33, extrudates become less crisp and more tough.

The increase in perceived toughness of the extrudates as the water activity increased can be explained by the fact that water acts as a plasticizer. The partial plasticization of the

cell wall materials increased the cohesion of the structure, therefore increasing the toughness of the extrudate. This was due to the fact that the plasticized structure did not disintegrate easily, allowing the extrudate to remain intact and offering more resistance to deformation (Harris and Peleg, 1996). Toughness is not a textural attribute that is normally studied in crisp products. In the current study, the definition of toughness (Table 3.1) was similar to that of hardness defined by Seymour and Hamann (1988) which was; the force required to bite through the extrudate. Seymour and Hamann (1988) found that as the water activity increased, the force to bite through the extrudate increased. Therefore, the higher toughness values for higher water activity extrudates observed in Table 3.3 are not surprising.

3.5.1.3 Panelist variability in textural evaluations of crisp extrudates

A high degree of variability existed among the panelists, as evidenced by the significant panelist effect for all attributes tested (Table 3.4).

Although the panelists were trained to evaluate the sensory properties of the extruded snacks, significant panelist effects were observed for all sensory properties (Table 3.4). Training cannot eliminate all variation within a panel (Arnold and Williams, 1986). There will be variations between judges in the range of scoring used and variations in terms and scales between sessions of testing (Arnold and Williams, 1986). Although these differences were observed, differences amongst the samples based on water activity and moisture content were still obvious, indicating that these conditions had a profound effect on texture of the extrudates.

3.5.1.4 Moisture content by water activity interaction

This research explored the effect of processing conditions (the moisture content of the extruder) as well as water activity on the sensory properties of corn based extrudates. Data reported in Tables 3.2 and 3.3 are mean scores for the extrudates averaged across the water activity (for Table 3.2) and across the moisture content (for Table 3.3). However, how these two conditions interact must also be taken into consideration. This relationship was further explored by examining the ANOVA table to determine if

Table 3.4: ANOVA of sensory characteristics of TSE extrudates

Sensory parameter[1]	df	Sum of Squares	Mean Square	F-value	Probability
Crisp					
Moisture content[2]	2	67.78	33.89	19.37	0.0001
Water activity[3]	3	714.27	238.09	136.07	0.0001
Panelist	6	224.97	37.49	21.43	0.0001
Replication	3	2.48	0.82	0.47	0.70
Moisture content * water activity	6	59.01	9.83	5.62	0.0001
Error	315	551.16	1.74		
Pitch					
Moisture content	2	20.95	10.47	3.30	0.03
Water activity	3	361.54	120.51	38.01	0.0001
Panelist	6	302.49	50.41	15.90	0.0001
Replication	3	11.29	3.76	1.19	0.31
Moisture content * water activity	6	28.87	4.81	1.52	0.17
Error	315	998.8	3.17		
Loudness					
Moisture content	2	215.86	107.93	40.69	0.0001
Water activity	3	201.59	67.19	25.33	0.0001
Panelist	6	227.10	37.85	14.27	0.0001
Replication	3	20.07	6.69	2.52	0.05
Moisture content * water activity	6	94.81	15.80	5.96	0.0001
Error	315	835.61	2.65		
Crumbliness					
Moisture content	2	47.58	23.79	15.11	0.0001
Water activity	3	1366.52	455.51	289.21	0.0001
Panelist	6	120.42	20.07	12.74	0.0001
Replication	3	4.61	1.53	0.98	0.40
Moisture content * water activity	6	87.50	14.58	9.26	0.0001
Error	315	496.12	1.57		
Toughness					
Moisture content	2	120.35	60.17	35.48	0.0001
Water activity	3	753.37	251.12	148.08	0.0001
Panelist	6	346.15	57.69	34.02	0.0001
Replication	3	2.00	0.66	0.39	0.75
Moisture content * water activity	6	58.54	9.75	5.75	0.0001
Error	315	534.21	1.69		
Density					
Moisture content	2	93.94	46.97	17.78	0.0001
Water activity	3	322.19	107.39	40.66	0.0001
Panelist	6	372.88	62.14	23.53	0.0001
Replication	3	7.1	2.30	0.9	0.44
Moisture content * water activity		5.25	0.87	0.33	0.92
Error	273	829.345	2.64		

[1]Seven panelists evaluated 12 extrudates differing in moisture content and water activity in 4 replicates.
[2]Extrusion moisture contents of 15.6%, 17.2% and 18.9% correspond to extrudate moisture contents of 3%, 8% and 10%.
[3]The water activity was manipulated by storing the extrudates in desiccators over solutions of lithium chloride (a_w=0.11), potassium acetate (a_w=0.22), magnesium chloride (a_w=0.33) and potassium carbonate (a_w=0.44).

significant interactions were observed for any of the sensory properties tested. As shown in Table 3.4, significant moisture content by water activity interactions were observed for each of the sensory properties except for density. Plots of the mean moisture content by water activity scores for each characteristic are shown in Figure 3.9.

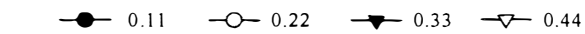
For crispness, pitch, loudness and crumbliness, a magnitude interaction was observed for the 0.44 water activity samples. This magnitude occurred across all moisture contents for crispness and pitch while for loudness it occurred with the 18.9% moisture content samples. The interaction for crumbliness can be attributed to, not only the magnitude interaction, but also to the cross-over effect of the 0.11 water activity sample between 15.6% and 17.2% moisture. There was an increase in toughness of the 18.9% samples stored at a water activity of 0.44, while for all other water activities and moisture contents, the toughness decreased.

Due to the presence of these interactions, the sensory data were re-analysed with the 0.44 water activity sample removed. This removed all significant interactions from the ANOVA table (shown in Appendix D). Mean sensory scores were recalculated and are shown in Appendix E. After removal of the 0.44 water activity data, mean sensory scores increased for all characteristics but toughness, which decreased. Separation of the samples based on Tukey's HSD analysis was slightly different than those observed in Table 3.3. However, the overall trends in the data did not change.

This relationship between the processing moisture content and the water activity of storage has not previously been reported in literature. Research evaluating the effect of either moisture content (Chen *et al.,* 1991; Barrett *et al.,* 1994) or water activity (Katz and Labuza, 1981; Hsieh *et al.,* 1990; Sauvageot and Blond, 1991; Van Hecke *et al.,* 1998) has been published. This current study, however, shows how these two interact. A change in the textural properties of corn based extrudates will occur, regardless of processing conditions, if the water activity of storage is too high.

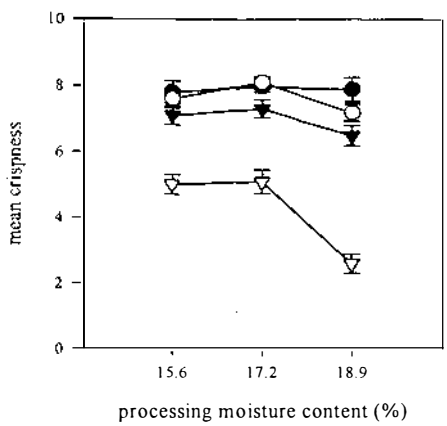
Figure 3.9: Interaction plots for sensory scores

- Sensory data collected from 7 panelists evaluating each sample in 4 replicates.
- Extrusion moisture contents of 15.6%, 17.2% and 18.9% correspond to extrudate moisture contents of 3%, 8% and 10%.
- The water activity was manipulated by storing the extrudates in desiccators over solutions of lithium chloride (a_w=0.11), potassium acetate (a_w=0.22), magnesium chloride (a_w=0.33) and potassium carbonate (a_w=0.44).
- For plots (a) through (f) the symbols correspond to the following water activities:

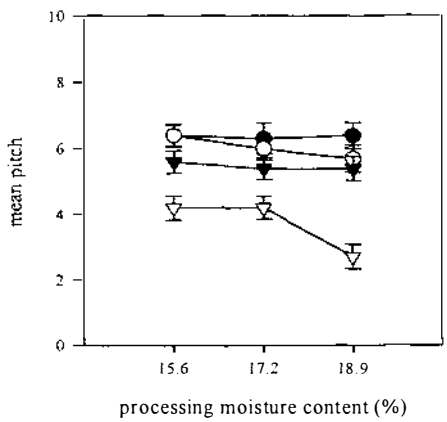


T = standard error of mean

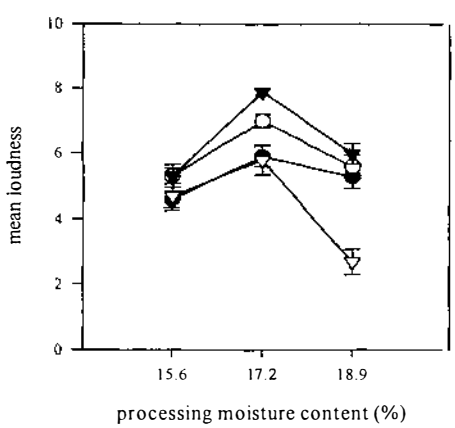
(a) Crispness



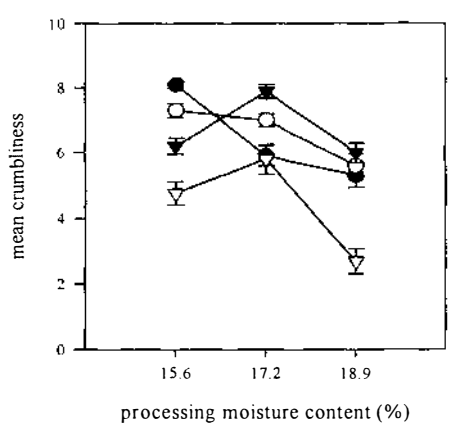
(b) Pitch



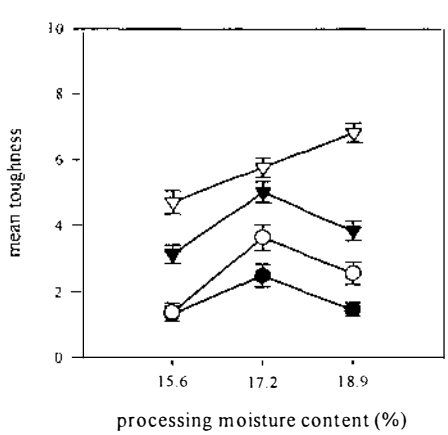
(c) Loudness



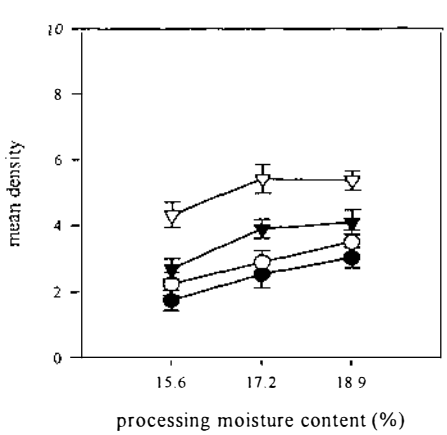
(d) Crumbliness



(e) Toughness



(f) Density



3.5.1.5 Inter-correlations of sensory characteristics

All responses from each panelist biting each extrudate (7 panelists, 4 water activities, 3 moisture contents and 4 replicates of testing) were correlated in the Pearson product moment correlation analysis. The correlation coefficients and the probabilities of significance are shown in Table 3.5.

As extrudates increased in crispness, they increased in crumbliness and decreased in toughness and perceived density. Also, as the crispness increased, the perceived sounds produced during biting became higher in pitch and increased in loudness (Table 3.5).

Vickers, (1984b) showed that when bitten into, crisp products produced a higher pitched sound than crunchy products. Certainly in the current study, the products which were considered to be the highest in pitch during biting were also considered to be the most crisp. Additionally, crisp products were perceived to be more dense. It has been suggested that differences in the structural and instrumental strength of products contribute to the different pitch levels (Vickers, 1984b). Increasing the stiffness and decreasing the density of products increases the frequency of the vibrations occurring during breakage, which then increases the pitch of the sound (Vickers, 1984b).

Crispness has been related to the loudness of sounds produced during biting and chewing (Christensen and Vickers, 1981). Crispness has also been significantly related to the firmness or hardness of crisp products (Vickers and Christensen, 1980; Vickers, 1981). The definition of toughness used in this current research is similar to other definitions of hardness and hardness has been correlated to crispness (Seymour and Hamann, 1988). Therefore, it is not surprising that a significant relationship existed between toughness and crispness.

Table 3.5: Interrelationships of sensory characteristics of extruded snacks

	Sensory characteristics				
Sensory characteristics	**Pitch**	**Loudness**	**Crumbliness**	**Toughness**	**Density**
Crispness					
r-value	0.55[1]	0.37	0.75	-0.49	-0.36
probability	0.0001[2]	0.0001	0.0001	0.0001	0.0001
Pitch					
r-value		0.36	0.56	-0.46	-0.41
Probability		0.0001	0.0001	0.0001	0.0001
Loudness					
r-value			0.31	-0.03	-0.04
Probability			0.0001	0.57	0.38
Crumbliness					
r-value				-0.69	-0.55
probability				0.0001	0.0001
Toughness					
r-value					0.65
Probability					0.0001

[1] Correlation coefficients (r-value)were calculated from sensory data collected from 7 panelists evaluating extrudates at 3 moisture contents and stored at 4 water activities in 4 replicates (n=336).
[2] Correlations are not significantly different at $p>0.05$.

3.5.1.6 Bone-conducted sound wave analysis

The bone-conducted bite sounds of each panelist biting into the TSE extrudates were collected and the amplitude-time data were plotted. These plots were analysed by Fast Fourier Transformation (FFT) to determine the predominant frequencies produced during the biting of the extrudate. For this analysis, the data from the amplitude-time plots were adjusted using the power transformation macro within SigmaPlot. The resulting FFT data from each extrudate were divided into 1kHz segments and the frequencies in each 1kHz range were averaged in order to provide a clearer picture of the main frequencies produced during biting of the snack products. The average frequency plots for each water activity, grouped by moisture content are shown in Figure 3.10. The zero frequency component is contributing to the large peak at 0kHz. It often has the highest amplitude of all components in a spectrum and is usually unimportant (Anonymous, 2001). For the majority of the curves, predominant frequencies occurred between 6 and 8kHz, as indicated by the increase in the amplitude of the mean scores at that frequency. There were few other differences in frequencies observed among the curves.

The frequencies observed for the recorded bite sounds (Figure 3.10) are in line with published data (Lee *et al.,* 1988; Dacremont, 1995). Acoustically, crisp foods generate high pitched sounds that show a level of frequencies higher than 5 kHz (Dacremont, 1995) and potato chips show frequency ranges of 3-4 kHz and 6 kHz (Lee *et al.,* 1988).

In addition to the frequency analysis, the amplitude-time plots were characterised by determining the duration of the sound, mean height of the peaks of the bone-conducted sound wave, the number of peaks and the fractal dimension of the sound wave. The various parameters were analysed by ANOVA to determine if there were significant differences amongst samples extruded with different moisture contents or consumed at different water activities. Mean scores are presented in Tables 3.6 and 3.7.

The fractal dimension, a measure of the jaggedness of the sound waves, did not differ significantly between the sound waves produced from extrudates with differing moisture contents (Table 3.6).

Figure 3.10: Mean sound frequencies for extruded snacks

- FFT scores for sounds recorded during biting of extrudates
- Data averaged across 7 panelists
- For graph (a) to (c) the symbols correspond to the following water activities:

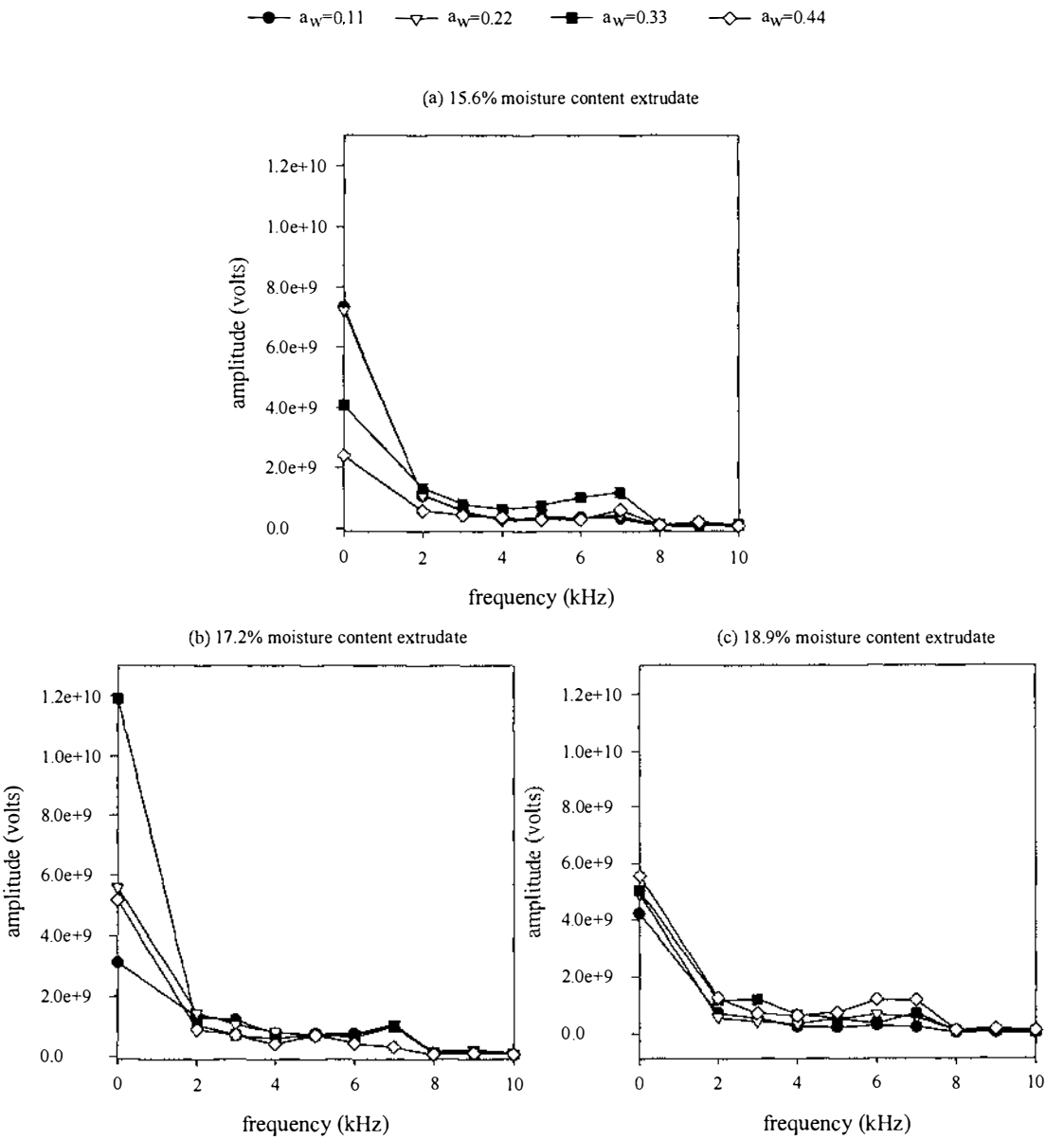


Table 3.6: Bone-conducted sound wave characteristics of TSE extrudates differing in moisture content

Bone-conducted sound wave characteristic	m.c. during extrusion[1] 15.6%	17.2%	18.9%
Fractal analysis[2]			
Mean	1.47a[6,7]	1.51a	1.48a
Std Error	0.01	0.01	0.01
Number of peaks[3]			
Mean	145a	180a	144.9a
Std Error	18.77	23.08	17.06
Mean height of peaks (volts)[4]			
Mean	599.1a	640.1a	614.2a
Std Error	44.97	48.52	41.22
Duration(s)[5]			
Mean	0.12a	0.13a	0.11a
Std Error	0.008	0.006	0.007

[1]Extrusion moisture contents of 15.6%, 17.2% and 18.9% correspond to extrudate moisture contents of 3%, 8% and 10%.
[2]The fractal dimension was calculated using the program by Russ, 1994.
[3]The number of peaks was determined by counting the number of peaks within the sound wave.
[4]Mean height of the peaks was determined by dividing the total height of each peak by the number of peaks.
[5]The duration of sound was the taken from the start of the bite to the point at which the extrudate broke while biting with the molars.
[6]The means for each sound wave characteristic were calculated from 7 panelists biting into the 4 extrudates differing in moisture content (n=28).
[7]Means in a row with the same letter are not significantly different ($p>0.05$).

In contrast, the fractal dimension was the only parameter which showed differences among the bite sound signatures of the extrudates stored at various water activities. Lower water activity extrudates had a more jagged amplitude-time curve, as shown by the higher fractal dimension, than the amplitude-time curve of extrudates stored at a water activity of 0.44 (Table 3.7).

Table 3.7: Bone-conducted sound wave characteristics of TSE extrudates differing in water activity

Bone-conducted sound wave characteristic	a_w during consumption[1] 0.11	0.22	0.33	0.44
Fractal dimension[2]				
Mean	1.53a[6,7]	1.52a	1.47ab	1.45b
Std Error	0.01	0.01	0.01	0.01
Number of peaks[3]				
Mean	186.9a	137.9a	148.8a	152.9a
Std Error	20.37	19.38	16.74	22.53
Mean height of peaks (volts)[4]				
Mean	564.7a	572.7a	658.7a	674.9a
Std Error	33.79	47.04	51.01	43.84
Duration (s)[5]				
Mean	0.13a	0.13a	0.11a	0.11a
Std Error	0.007	0.009	0.007	0.008

[1]The water activity was manipulated by storing the extrudates in desiccators over solutions of lithium chloride (a_w=0.11), potassium acetate (a_w=0.22), magnesium chloride (a_w=0.33) and potassium carbonate (a_w=0.44).
[2]The fractal dimension was calculated using the program by Russ, 1994.
[3]The number of peaks was determined by counting the number of peaks within the sound wave.
[4]Mean height of the peaks was determined by dividing the total height of each peak by the number of peaks.
[5]The duration of sound was the taken from the start of the bite to the point at which the extrudate broke while biting with the molars.
[6]The means for each sound wave characteristic were calculated from 7 panelists biting into the 4 extrudates differing in moisture content (n=28).
[7]Means in a row with the same letter are not significantly different ($p>0.05$).

No published literature exists discussing the use of fractal analysis for analysing acoustic signatures of individuals biting into crisp products. Fractal analysis has been used to study the jaggedness of stress-strain compression curves of crisp products (Barrett *et al.*,1994; Borges and Peleg, 1996; Norton *et al.*,1998), or as a measure of the acoustic signatures produced during instrumental compression of crisp food products (Tesch *et al.*,1995; Tesch *et al.*,1996). Acoustically, cheese balls and croutons exhibited apparent fractal dimensions 1.46 and 1.38 (for cheese balls and croutons, respectively) when compressed by instrumental means (Tesch *et al.*, 1995).

Peleg (1993) noted that although the jaggedness of a line can be determined using fractal analysis, it is not possible to know whether the jaggedness is due to the line's high amplitude or short wavelength. Combining the apparent fractal dimension with other methods may be required for properly characterizing a line. However, in the current study, none of the other measures adequately differentiated among the extrudates. One reason for this lack of significant difference could be due to physiological differences among the panelists. Hashimoto and Clark (2001) suggested that differences in sound transmissions may be due to skull densities and shapes causing different resonant frequencies within the skull, or variations in elastic tensions developed within the jaw altering the frequencies of the sound produced. Certainly the ANOVA results shown in Table 3.8 confirm that significant differences amongst the panelists were observed in terms of the jaggedness of their sound waves. This was exemplified by the significant differences amongst the panelists for mean height of the peaks, number of peaks and the fractal dimension of the curves.

Table 3.8: Characterisation of bone-conducted sound waves

Sound wave characteristic[1]	df	Sum of Squares	Mean Square	F-value	Probability
Fractal dimension[2]					
Moisture content	2	0.02	0.01	1.97	0.14
Water activity	3	0.08	0.02	4.96	0.00
Moisture content x water activity	6	0.07	0.01	2.24	0.04
Panelist	6	0.14	0.02	4.41	0.0008
Error	66	0.36	0.01		
Number of peaks[3]					
Moisture content	2	2.2×10^{-4}	1.1×10^{-4}	1.31	0.27
Water activity	3	2.8×10^{-4}	9.34×10^{-3}	1.07	0.36
Moisture content x water activity	6	9.8×10^{-4}	1.6×10^{-4}	1.87	0.09
Panelist	6	1.84×10^{-5}	3.0×10^{-4}	3.51	0.004
Error	66	5.74×10^{-5}	8.7×10^{-3}		
Mean height of peaks[4]					
Moisture content	2	2.4×10^{-4}	1.2×10^{-4}	0.32	0.72
Water activity	3	2.0×10^{-5}	6.8×10^{-4}	1.80	0.15
Moisture content x water activity	6	2.5×10^{-5}	4.14×10^{-4}	1.10	0.37
Panelist	6	1.6×10^{-6}	2.74×10^{-5}	7.14	0.0001
Error	66	2.5×10^{-6}	3.84×10^{-4}		
Duration of sound[5]					
Moisture content	2	5.34×10^{9}	2.67×10^{9}	1.80	0.17
Water activity	3	6.35×10^{9}	2.11×10^{9}	1.43	0.24
Moisture content x water activity	6	1.67×10^{10}	2.79×10^{9}	1.88	0.09
Panelist	6	1.47×10^{10}	2.45×10^{9}	1.65	0.14
Error	66	9.78×10^{10}	1.48×10^{10}		

[1]Sound waves were recorded from 7 panelists biting extrudates differing in processing moisture content and storage water activity using the molars.
[2]The fractal dimension was calculated using the program by Russ, 1994.
[3]Mean height of the peaks was determined by dividing the total height of each peak by the number of peaks.
[4]The number of peaks was determined by counting the number of peaks within the sound wave.
[5]The duration of sound was the taken from the start of the bite to the point at which the extrudate broke while biting with the molars.

3.5.1.7 Instrumental acoustic results

As well as recording bone-conducted sounds, sounds produced during instrumental compression of the TSE snacks were also recorded. The instrumental sound wave results were compared to the bone-conducted sound wave characteristics in order to compare instrumental sound results to physiological sound results. It was felt that an instrument would be less variable than a human for collection of acoustic recordings. To test this, a microphone was attached to the base of a TA-XTII texture analyser and the sounds produced during compression of extrudates by the compression probe were recorded. The fractal dimension of the sound waves, the number of peaks, the mean height of the peaks and the duration of the sounds produced during instrumental compression of the extrudates was calculated and the results were analysed by ANOVA.

Water activity significantly affected the jaggedness of the peaks, while moisture content did not. Results are detailed in Table 3.9 and 3.10. ANOVA results are found in Appendix F.

Table 3.9: Instrumental sound waves of TSE extrudates differing in moisture contents

Instrumental sound wave measure[2]		m. c. during extrusion[1]		
		15.6%	**17.2%**	**18.9%**
Fractal dimension[3]				
	Mean	1.33a[7,8]	1.32a	1.31a
	Std Error	0.01	0.009	0.01
Number of peaks[4]				
	Mean	164.5a	155.0a	168.1a
	Std Error	12.05	16.03	13.30
Mean height of peaks (volts)[5]				
	Mean	119.9a	152.1b	116.1a
	Std Error	18.18	16.12	6.82
Duration (s)[6]				
	Mean	0.12a	0.10a	0.11a
	Std Error	0.008	0.007	0.007

[1]Extrusion moisture contents of 15.6%, 17.2% and 18.9% correspond to extrudate moisture contents of 3%, 8% and 10%.
[2]Sound wave data was produced using a TA-XTII texture analyser.
[3]The fractal dimension was calculated using software by Russ, 1994.
[4]Mean height of the peaks was determined by dividing the total height of each peak by the number of peaks.
[5]The number of peaks was determined by counting the number of peaks within the sound wave.
[6]The duration of sound was the taken from the start of the bite to the point at which the extrudate broke while biting with the molars.
[7]Means were calculated from fractal data collected from four replicates of testing and four extrudates at each moisture content (n=16).
[8]Means in a row followed by the same letter are not significantly different ($p>0.05$).

Table 3.10: Instrumental sound waves of TSE extrudates stored at different water activities

Instrumental sound wave measure[2]	a_w during consumption[1] 0.11	0.22	0.33	0.44
Fractal dimension[3]				
Mean	1.37a[7,8]	1.35a	1.33ab	1.26b
Std Error	0.01	0.004	0.01	0.008
Number of peaks[4]				
Mean	190.6a	192.3a	167.0a	106.6b
Std Error	20.85	9.73	8.26	12.38
Mean Height of Peaks (volts)[5]				
Mean	137.1ab	154.1a	103.1c	127.4b
Std Error	24.84	22.51	3.74	7.75
Duration (s)[6]				
Mean	0.13a	0.11ab	0.12a	0.09b
Std Error	0.001	0.005	0.005	0.009

[1]The water activity was manipulated by storing the extrudates in desiccators over solutions of lithium chloride (a_w=0.11), potassium acetate (a_w=0.22), magnesium chloride (a_w=0.33) and potassium carbonate (a_w=0.44).
[2]Sound wave data was produced using a TA-XTII texture analyser.
[3]The fractal dimension was calculated using software by Russ, 1994.
The higher the fractal dimension, the more jagged the sound wave.
[4]Mean height of the peaks was determined by dividing the total height of each peak by the number of peaks.
[5]The number of peaks was determined by counting the number of peaks within the sound wave.
[6]The duration of sound was the taken from the start of the bite to the point at which the extrudate broke while biting with the molars.
[7]Means were calculated from fractal data collected from four replicates of testing and three extrudates at each water activity (n=12).
[8]Means in a row followed by the same letter are not significantly different (p>0.05).

The sound wave of the higher water activity extrudates was significantly less jagged than the sound wave of the extrudates stored at lower water (Table 3.10). This was also noted by a significantly lower number of peaks for the higher water activity sample than for all others. These instrumental acoustic results are consistent with results from the bone-conducted sounds collected from individuals (Table 3.7), where the lower water activity samples produced a more jagged sound wave.

3.5.1.8 Relationship between sensory and instrumental sound measures

A correlation analysis was carried out to explore the relationship between the bone-conducted sound waves and the instrumental sound waves. Results are shown in Table 3.11. Although both the instrumental and the sensory fractal dimensions showed similar trends in separating samples differing in water activity (based on Tukey's results in Tables 3.7 and 3.10), the correlation between the two measures was not significant. The only variables showing any relationship were the number of peaks from instrumental sound waves and the bone-conducted fractal dimension. No other significant relationships were observed.

Although sound wave data have been collected from individuals biting into crisp products (Vickers and Bourne, 1976; Christensen and Vickers, 1981; Vickers, 1981; Dacremont, 1995) as well as from instrumental compression of crisp products (Mohamed *et al.,* 1982; Seymour and Hamann 1988; Tesch *et al.,* 1995; Tesch *et al.,* 1996), there are no published reports comparing results from the two techniques. In this research, the lack of a significant relationship between sound wave variables from the two techniques was probably due to variability in bone-conducted sound waves amongst the samples tested.

Jowitt and Mohamed (1980) stated that recording bite sounds using instrumental methods can eliminate variability in recorded sounds observed when human bite sounds are recorded. These researchers assumed that similar acoustic results would be observed for instrumental as for bone-conducted sound recordings. This research, however, suggests that this may not be true. Although the Tukey's results for both bone-conducted (Table 3.7) and instrumental measures (Table 3.10) show similar separation

of the samples based on fractal dimensions, the correlation analysis does not show a relationship between the two measurement types.

Table 3.11: Relationship between sensory and instrumental sound wave characteristics

Instrumental sound wave characteristic	Bone-conducted sound wave characteristic			
	Fractal dimension[1]	Number of peaks[2]	Height of peaks[3]	Duration[4]
Fractal dimension[1]				
r-value	0.21[5,6]	-0.07	-0.55	0.24
Probability	0.50	0.81	0.06	0.45
Number of peaks[2]				
r-value	0.70	-0.42	0.37	-0.02
Probability	0.01	0.16	0.23	0.92
Height of peaks[3]				
r-value	0.008	-0.33	0.15	0.32
Probability	0.97	0.28	0.62	0.29
Duration[4]				
r-value	0.08	-0.25	0.10	0.01
Probability	0.80	0.42	0.73	0.90

[1]The fractal dimension was calculated using the program by Russ, 1994.
[2]The number of peaks was determined by counting the number of peaks within the sound wave.
[3]Mean height of the peaks was determined by dividing the total height of each peak by the number of peaks.
[4]The duration of sound was the taken from the start of the bite to the point at which the extrudate broke while biting with the molars.
[5]The means of acoustic measure for each sample (3 moisture contents x 4 water activities) were used to calculate the correlation coefficient (n=12).
[6] Correlations are not significant at probability of > 0.05.

3.5.1.9 Relationship between sound wave characteristics and perceived texture

A Pearson Product Moment correlation analysis was conducted to determine if a relationship existed between the perceived textural properties of the TSE extruded snacks and all sound measurements (from bone-conducted and instrumental sound waves).

Correlation coefficients and the probability of significance amongst the sensory characteristics and bone-conducted sound wave measures are shown in Table 3.12. As crispness and crumbliness increased, the jaggedness of the bone-conducted sound waves (as measured by the fractal dimension) increased. Similar trends were noted for pitch and crumbliness. Loudness, toughness and density were not significantly correlated to the fractal dimensions.

Although significant, the low correlation coefficient obtained between sensory crispness and the fractal dimensions can be attributed to the great deal of variability in individual acoustic curves. In published literature, other acoustic measures have been related to sensory crispness. Equivalent sound level, a measure of sound intensity recorded during instrumental compression, has been correlated to sensory crispness (r=0.70) (Mohamed *et al.,* 1982) as has sound pressure level at 1.2-1.9kHz, a measure of sound magnitude recorded during instrumental compression (r=0.89) (Seymour and Hamann, 1988). However, the apparent fractal dimension of individuals biting samples has never been measured.

Of the other sound wave parameters measured, correlations were observed between crispness and duration of the sound. A significant relationship between these two measures (r=0.87) was also observed by Vickers (1987) when studying crisp potato chips.

The lack of significant relationships observed between crispness and mean height of the peaks and number of the peaks (Table 3.12) is contradictory to published data. Crispness was found to be significantly correlated to the mean height of the peaks of sound produced during the biting of various crisp foods (Edmister and Vickers, 1985) and to the number of peaks of sound produced during the biting of potato chips

Table 3.12: Correlations between sensory characteristics and sound wave characteristics

Sensory characteristic[2]	Bone-conducted sound wave characteristic[1]			
	Duration of sound	Mean height of peaks	Number of peaks	Fractal dimension
Crispness				
r-value	0.67[3]	-0.45	0.33	0.68
Probability	0.01[4]	0.14	0.29	0.01
Pitch				
r-value	0.64	-0.51	0.29	0.62
Probability	0.02	0.09	0.36	0.03
Loudness				
r-value	0.54	0.17	0.40	0.49
Probability	0.07	0.59	0.19	0.10
Crumbliness				
r-value	0.64	-0.55	0.32	0.68
Probability	0.02	0.06	0.31	0.01
Toughness				
r-value	-0.52	0.61	-0.18	-0.52
Probability	0.08	0.03	0.56	0.07
Density				
r-value	-0.40	0.60	-0.02	-0.43
Probability	0.19	0.03	0.95	0.17

[1]Sound waves were recorded from 7 panelists biting extrudates differing in processing moisture content and storage water activity using the molars.
[2] Sensory properties collected from 7 panelists evaluating extrudates in 4 replicates.
[3]Calculated from the mean scores of extrudates at 3 moisture contents and stored at 4 water activities (n=12).
[4]Correlations are not significant at probability of >0.05.

(Vickers, 1987). One reason for this difference in results could be the methodologies used. Edmister and Vickers (1985) recorded bite sounds from one individual and correlated this to sensory measures from others. Vickers (1987) recorded bite sounds from four individuals and selected the best sounds for evaluation by others. In comparison, the current study involved recording bite sounds from eight individuals and correlating these sounds with their perception of crispness, meaning that all data used in the analysis originated from the same individuals. The large inter-panelist variability suggests it is important to test acoustics on the same panelists used to measure crispness.

The correlation coefficients and probability of significance amongst the sensory characteristics and the instrumental sound wave measures are shown in Table 3.13. Similar to the bone-conducted fractal dimension data, the apparent fractal dimension of the instrumental sound waves was significantly correlated to crispness, pitch and crumbliness. The most significant correlation occurred between the instrumental fractal dimension and the perceived density of the product.

Fractal dimensions have been shown to be significantly correlated with acoustic recordings of instrumental compression (Tesch *et al.*, 1995) and instrumental measures of texture (Barrett *et al.*, 1994; Wollny and Peleg, 1994). However, in this study, it has been shown that there is a stronger relationship between sensory crispness and the jaggedness of the peaks collected from individuals than the jaggedness of the peaks of sound produced instrumentally (as evidenced by the higher r-values shown in Table 3.12).

Table 3.13: Correlations between sensory characteristics and instrumental sound characteristics

Sensory characteristic[2]	Instrumental sound wave characteristic[1]			
	Duration of sound	Mean height of peaks	Number of peaks	Instrumental fractal dimension
Crispness				
r-value	0.53[3]	0.57	0.20	0.61
Probability	0.07[4]	0.05	0.51	0.03
Pitch				
r-value	0.59	0.53	0.20	0.61
Probability	0.03	0.07	0.53	0.03
Loudness				
r-value	0.006	0.36	-0.08	0.15
Probability	0.98	0.23	0.79	0.62
Crumbliness				
r-value	0.62	0.57	0.23	0.61
Probability	0.03	0.05	0.45	0.03
Toughness				
r-value	-0.68	-0.46	-0.22	-0.61
Probability	0.01	0.12	0.47	0.03
Density				
r-value	-0.76	-0.46	-0.27	-0.72
Probability	0.003	0.12	0.38	0.008

[1]Sound waves were recorded from 7 panelists biting extrudates differing in processing moisture content and storage water activity using the molars.
[2] Sensory properties collected from 7 panelists evaluating extrudates in 4 replicates.
[3]Calculated from the mean scores of extrudates at 3 moisture contents and stored at 4 water activities (n=12).
[4]Correlations are not significant at probability of >0.05.

3.5.2 Sensory, acoustic and instrumental analysis from the single-screw extruder (SSE) experiment

3.5.2.1 Perceived texture of extrudates produced using the single-screw extruder

Extrudates produced using the single-screw extruder were evaluated by a trained panel of ten experienced panelists. Definitions for the textural assessment of snacks extruded using the single-screw extruder are located in Table 3.14.

Table 3.14: Definitions for sensory characteristics of SSE extrudates

Crispness
A combination of the noise produced and the breakdown of the product as it is bitten entirely through with the back molars
Loudness
The amount of noise produced when biting through the product with the back molars.
Fracturability
The type of breakdown of the product - does it fracture or does it crumble into bits like sawdust?
Hardness
The amount of force required to compress the sample between the back molars
Density
The airiness of the product - are there large air cells (less dense) or are the cells small and tightly packed (more dense)?

The sensory data collected from the panel were analysed by cluster analysis using the average linkage algorithm to categorise data into smaller groupings for further analysis. Based on the clustering results, 7 clusters of extrudates were identified. The cluster tree for the groupings is located in Appendix G. Mean sensory scores for each cluster are shown in Table 3.15.

Table 3.15: Cluster groupings for extrudates based on sensory scores

Cluster number	n[2]	Mean sensory scores for each cluster[1]				
		Crispness	Loudness	Fracturability	Hardness	Density
1	10	4.1	1.2	1.5	1.1	7.6
2	2	7.7	6.0	5.8	3.4	7.2
3	5	6.3	2.6	3.2	1.8	8.4
4	3	5.2	8	8.1	8.8	0.6
5	7	7.3	4.7	4.9	2.7	7.7
6	5	6.6	7.5	7.7	7.0	1.8
7	4	7.3	7.1	7.1	5.2	3.7

[1]Sensory data collected from 10 panelists evaluating each sample 3 times.
[2]n = number of extrudates in each cluster

One extrudate treatment from each cluster was selected to conduct measurements of extrudate volume in order to calculate the density and porosity of the extrudates. The formulation selected and the moisture content, monoglyceride content and rice bran content for each selected formulation are shown in Table 3.16.

Table 3.16: Formulations selected from each cluster and their ingredient levels

Cluster number	Formulation number	Moisture content (%)	Monoglyceride content (%)	Rice bran content (%)
1	1	15	0	0.5
2	2	16	0.5	0
3	8	15	0.5	0
4	12	16	1	1
5	13	13	0.5	1
6	18	13	1	1
7	22	13	1	0

3.5.2.2 Physical measures of extrudate structure

The density and porosity measures for the extrudate treatments within each cluster were analysed by ANOVA. Extrudate treatments differed significantly in porosity and density. The mean scores for each of the measures for each cluster are shown in Table 3.17. The ANOVA table is located in Appendix H.

Differences were observed amongst five of the clusters for particle density. Particle density is used in the calculation of closed pores; therefore, it follows that if particle density differs, then closed porosity will also differ. Extrudates in cluster 1 exhibited a large volume of closed pores, indicating that these samples were most porous. These samples also exhibited the smallest particle density. Extrudates in cluster 4 had the smallest volume of closed pores within the extrudate, indicating that these samples were less porous. These samples had the highest particle density. Open porosity (the ratio of the pores open to the surface of the extrudates to the total volume of the extrudates) did not differ amongst the clusters (Table 3.17).

These results suggest an extrudate which is not very dense has a higher number of closed pores in comparison to an extrudate that is very dense. It would be of interest to analyse the samples using image analysis to evaluate the size of the closed pores and look at the thickness of the cell walls surrounding the pores to obtain a complete picture of the physical structure of the samples.

Table 3.17: Physical properties of extruded snacks

Physical measure[1]	Extrudate cluster						
	1	2	3	4	5	6	7
Apparent density ($g.cm^{-3}$)[2]							
Mean	0.10b[7,8]	0.14b	0.30ab	0.80a	0.14b	0.30ab	0.17ab
Std Error	0.005	0.002	0.21	0.0007	0.005	0.01	0.07
Particle density ($g.cm^{-3}$)[3]							
Mean	0.80e	1.21c	1.01d	1.52ab	1.10cd	1.62a	1.44b
Std Error	0.01	0.02	0.02	0.001	0.02	0.005	0.01
Apparent porosity[4]							
Mean	0.91a	0.91a	0.78ab	0.43b	0.90a	0.79ab	0.88ab
Std Error	0.004	0.001	0.15	0.0004	0.005	0.005	0.04
Open porosity[5]							
Mean	0.87a	0.89a	0.72a	0.44a	0.87a	0.80a	0.87a
Std Error	0.004	0.0004	0.19	0.0007	0.005	0.005	0.04
Closed porosity[6]							
Mean	0.33a	0.16c	0.24b	0.03e	0.25b	0.05e	0.08d
Std Error	0.01	0.01	0.01	0.007	0.01	0.004	0.007

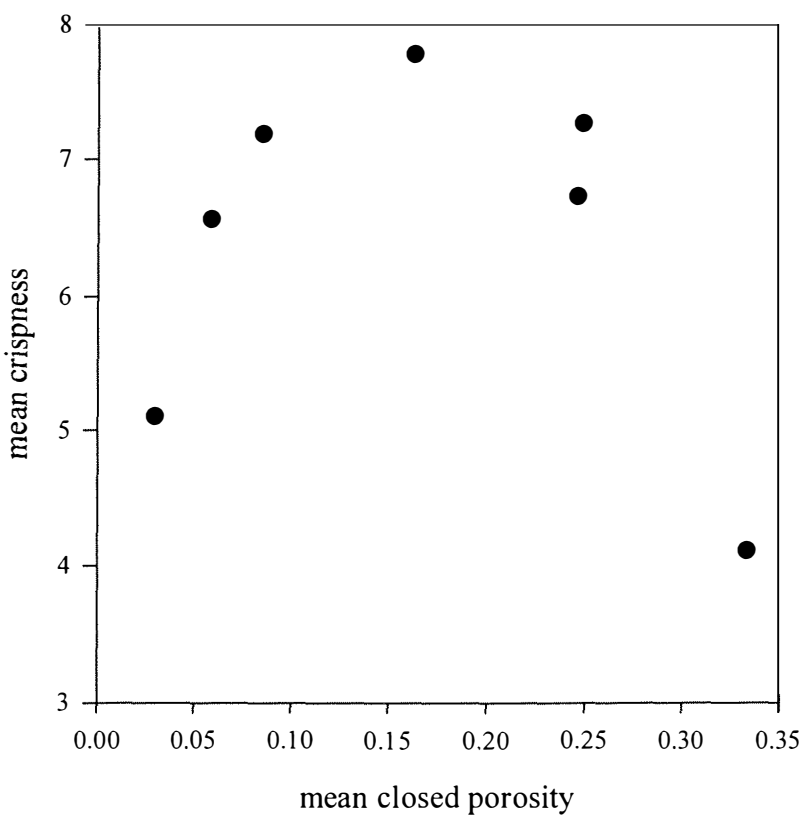
[1]Density and porosity measurements made using a helium pycnometer.
[2]Apparent density calculated using equation 3.4.
[3]Particle density calculated using equation 3.3.
[4]Apparent porosity calculated using equation 3.5.
[5]Open porosity calculated using equation 3.6.
[6]Closed porosity calculated using equation 3.7.
[7]Values are averaged over three replicates of testing.
[8]Means in a row followed by the same letter are not significantly different ($p>0.05$).

3.5.2.3 Relationship between sensory crispness and structural properties of extrudates

The relationship between the perceived crispness of the extrudates and the porosity of the extrudates is shown in Figure 3.11.

Figure 3.11: Textural and structural relationship for extruded snack samples

- Crispness was evaluated by a trained panel of 10 panelists evaluating each sample 3 times (n=30).
- Closed porosity was calculated using equation 3.7.
- Mean closed porosity determined by averaging across 3 replicates (n=3).
- The standard errors are too small to be visible under each symbol on the graph.



There was a general trend for crispness to increase to a maximum value, followed by a decrease, as the closed porosity of the extrudates increased (Figure 3.11). For the extrudates used in this study, the maximum closed porosity occurred at 0.15 and 0.20. Extrudates with a lower porosity may have more cellular material per cross-sectional

area, meaning that they are perceived to be hard. This is confirmed in Figure 3.12. The perceived hardness was highest for the products with the lowest volume of closed pores and hardness decreased as the volume of closed pores increased. As the products became more cellular, the increase in the porosity may have contributed to the perception of crispness during biting. After the optimum point (between 0.15 and 0.2 closed porosity) the product appears to have become too cellular to be considered crisp. The products may be too "airy" to produce the sounds as well as the resistance to bite required for the products to be considered crisp. Anecdotal comments from the panelists during biting of the "airy" samples indicated that they did not classify these products as crisp products as they were too light and airy to produce a sound.

Moore *et al.,* (1990) observed that as bran level increased in an extrudate formulation, the apparent density increased and the product became more resistant to breaking (using instrumental compression). Oil addition has also been shown to increase the expansion of extrudates and produce a more porous product (Faller and Heymann, 1996). This is particularly evident at low feed moisture contents (16%) and high oil contents (4%). It has been suggested that this is due to the development of a cross-linking matrix trapping water vapour when it is flashed off at the die. In the current study, formulation 4 which had the highest level of moisture, monoglyceride and bran exhibited the highest apparent density and the lowest closed porosity of all samples. From a sensory perspective, this product was perceived to be the loudest and hardest sample amongst the samples tested (Table 3.15).

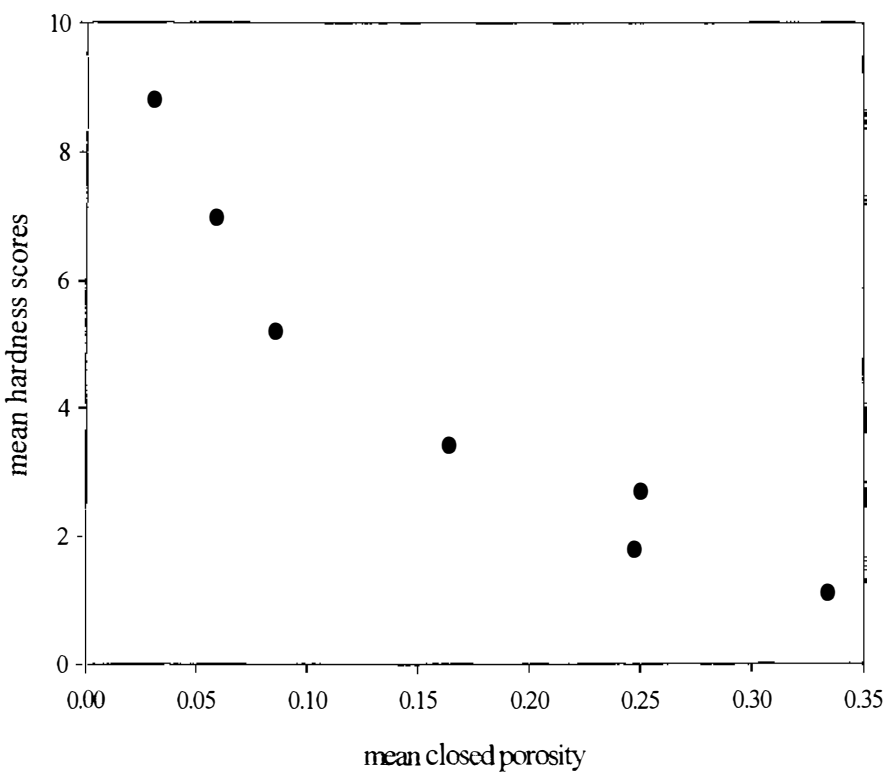
The relationship between crispness and closed porosity is not one that has been previously reported. Cellularity and bulk density have been shown to influence the instrumental and physical properties of strength and fracture of extrudates. This, in turn, affects the crispness of the extrudates (Barrett *et al.,* 1994). However, these researchers studied cell size and not volume of pores. Future research should focus on combining cell size, porosity and even cell wall thickness to determine which factors have the greatest effect on the perceived crispness of the product.

These structural measures should then be related to measures of the sound waves produced during biting into the snacks. It is hypothesized that the extrudates with little

porosity would produce low frequency bone-conducted sounds. Others have shown that products such as carrots and almonds which are dense products with little porosity produce an intermediate level of bone-conducted sounds and generate low pitched sounds, while products such as flaky pastries generate higher pitched air-conducted sounds (Dacremont, 1995). Future research to test this hypothesis needs to be conducted.

Figure 3.12: Impact of closed porosity on sensory hardness

- Hardness was evaluated by a trained panel of 10 panelists.
- Closed porosity was calculated using Equation 3.7.
- Mean closed porosity determined by averaging across 3 replicates (n=3).
- Standard error bars are too small to be visible under the symbols on the graph.



3.6 Conclusions

The main objective of this research was to assess the use of fractal analysis as a means for characterising bite sounds. Corn-based extrudates were produced using a twin-screw extruder. Processing moisture content and water activity at consumption were modified. From this research, the following conclusions can be made.

- The moisture content during extrusion affected the perceived textural properties of the extrudates. As the moisture content increased, crispness, pitch and crumbliness decreased and perceived density increased.

- The water activity of the extrudates when consumed was very important. A high water activity resulted in a decrease in crispness and an increase in toughness.

- A significant interaction was observed between the water activity and the processing moisture content. At all processing moisture contents, extrudates at the highest water activity were much less crisp than at all other water activities.

- Although significant panelist effects were observed, this did not obscure the effect of moisture content during extrusion and water activity when consumed. These two variables have a profound influence on crispness of corn-based puffed snacks.

- Bite sounds recorded from individuals biting into the extrudates could be mathematically characterised by their apparent fractal dimension. This fractal dimension showed a higher correlation with crispness. Physiological bite sounds showed a better correlation to crispness than sounds recorded during instrumental compression.

- Bone-conducted sound waves were not related to those from instrumental acoustic recordings.

A second objective of this research was to conduct a preliminary investigation on the relationship between structure and perceived texture. The structure of corn-based extrudates, produced using a single-screw extruder, was altered through different formulations. Trained sensory panel results were compared with structural measures of the extrudates. It was concluded that:

- An expanded corn snack is characterised by an open porous structure. These pores comprise, in part, a network of inter-connected bubbles of varying dimensions and, in part, a series of isolated bubbles that are completely enclosed within a protein-starch cell wall. These latter pores are termed "closed pores", a reference to their lack of a direct pathway to the external environment.

- Structurally, the volume of closed pores present in an extrudate has an effect on the perception of crispness. Crispness reaches a maximum at a closed pore volume between 0.15 and 0.2. With further increases in closed pores, crispness decreases.

CHAPTER 4 : PHYSIOLOGICAL MEASURES AND THEIR RELATIONSHIP TO CRISPNESS

Research into crispness perception often includes a measure of the breaking strength of the product, recorded via instrumental means combined with sound wave measures (Mohamed *et al.,* 1982; Vickers, 1987; Seymour and Hamann, 1988). Although the breaking strength provides a consistent objective measure of the amount of force or work required to break the sample using instrumental means, what it does not provide is an indication of the amount of physiological force required by an individual to bite through the sample. In this study, bite forces produced during first bite were measured using a bite force apparatus. These forces were then combined with the fractal dimension of air-conducted and bone-conducted sound waves to develop predictive equations of crispness. This will be useful for gaining an understanding of the effect of physiological factors (sounds and bite forces) on the perception of crispness of dry crisp snacks.

4.1 Experimental methods

4.1.1 Preparation of samples

Samples were produced using the Clextral twin-screw extruder (model BC21) explained in sections 3.1.1-3.1.3. The material used for extruding was standard corn grits (Speci 220 from Corson Grain, Gisborne, New Zealand). The grits had a moisture content of 14 ± 1% and a sauter mean diameter of 455.36 ± 1.2 μm. The corn grits were fed into the extruder at a feed rate of $3.03 \times 10^{-3} kg.s^{-1}$. The water flow rate was 1.05×10^{-4} $kg.s^{-1}$. A screw speed of 546 RPM was used and the barrel temperatures of zones 1 to 4 (from feed to die) were, respectively, 80°C, 120°C, 150°C and 180° C . The samples were cut using the cutter on the extruder which was set at a speed of 49 RPM.

Following extrusion, the samples were placed on racks and dried for 25 minutes in a forced-air oven at 100 ± 1°C. Following drying the samples were cooled and sealed in high-density polyethylene bags (thickness 195μm) for transportation to the Albany Campus of Massey University.

4.1.2 Sensory methods for assessing texture of extrudates

To fully understand the texture of the extrudates, three sensory techniques were used in this study. First, a consumer survey was conducted to ascertain what textural property New Zealand consumers would use to describe an extruded snack food product. In the survey, consumers were presented with four products, all which produced a snapping noise upon breaking, one of the characteristics of a crisp product (Vickers and Bourne, 1976). The products used were: the extruded snack product described in section 4.1.1, Cruskits™, a toasted extruded crisp bread containing wheat flour, rye meal and rice flour (Arnott's Biscuits, Australia); Twisties™, an extruded corn based product flavoured with cheese produced by Bluebird Foods (New Zealand) and Pringles™ potato chips (Proctor and Gamble Manufacturing, Belgium). The extruded snack product was stored in a desiccator at 20°C over a saturated salt solution of lithium chloride (a_w =0.11). The extrudates were weighed in trays in which they were stored and when weight change was constant (±0.001g) over 24 hours, they were removed from the desiccator and stored in foil laminate packaging until used. All of the commercial samples were purchased from a local supermarket one day prior to beginning the test. For testing, all products were removed from their packaging and placed in low-density polyethylene (40μm thick) zip lock bags. These bags were labelled with three-digit codes corresponding to the sample treatment.

Although the Pringles™ sample is not cellular, this product was known to be crisp based on evidence in the literature (Vickers and Bourne, 1976). These chips produce noise upon breaking due to the curvature of the potato chip. Because of their known crispness, the Pringles™ were therefore selected as a method for validating the results collected using New Zealand consumers.

For the survey, one hundred and six (106) consumers of snack foods attending the Albany wine and jazz festival were asked to eat each sample and complete a survey asking what textural property they felt each sample exhibited. Testing was conducted at various locations around the Massey University Campus during the course of the festival. Individuals were approached and asked if they ate snack foods and would like to participate in a survey about snack foods. If they agreed, the task was explained and the survey was completed. Testing was conducted at the table where the individual was

seated. For the survey, the four test products were presented to each individual along with a survey form. The individuals were instructed to try each product and to indicate which characteristic (from a list of crisp, crunchy or crackly) best described their perception of its texture. Only one characteristic could be chosen for each sample. Responses were made by ticking the box labelled with the appropriate characteristic beside each product listed. An example of the survey is shown in Appendix I. Sample presentation to the consumers was randomised across all samples.

Survey data were analysed using a factorial correspondence analysis program written in SAS (Version 8.1, SAS Institute, North Carolina). For this analysis the frequency with which each textural characteristic (crisp, crunchy or crackly) was chosen to represent the texture of each snack product was determined. The frequencies were then placed in a contingency or cross-tabulation table, with the textural properties located in columns and the samples located in rows. Following this, the data were normalised by dividing the contents of each cell in the contingency table by the square root of the row and sum totals. This is termed a profile distance and it is calculated to obtain symmetrical object/variable scaling of the data (Piggott and Sharman, 1986).

The normalised data were then analysed using principal components analysis (PCA) and principal coordinates analysis (PCO). These two analyses provided a description of the data in terms of a set of factors for both the samples (using PCO) and the descriptors (using PCA). The relative loading of both the samples and the descriptors on each factor was obtained and plotted, allowing for the determination of association amongst the elements in the contingency table (Piggott and Sharman, 1987). The maximum number of factors which are plotted is the minimum of the number of rows and columns minus one. In this study, the minimum number of columns was three, leading to two factors.

A trained panel was then used to evaluate the crispness, hardness, sound duration and brittleness of the extruded snacks described in section 4.1.1. The crispness of the snacks was modified by altering the water activity of the samples. For testing, the samples were removed from the storage bags and stored at 20°C over saturated salt solutions. The salt solutions used were: lithium chloride (a_w = 0.11), potassium acetate (a_w = 0.22), magnesium chloride (a_w = 0.33) and potassium carbonate (a_w = 0.44) (Greenspan,

1977). Samples were weighed in the trays in which they were stored and when weight change was constant (±0.001g) over 24 hours they were removed from the desiccators and stored in foil laminate packaging for two weeks, until testing. The water activity of the samples was verified using a water activity meter (Decagon CX2).

The panelists for the trained panel were recruited from the local community. Twelve individuals responded to a newspaper advertisement in the community paper. These individuals were invited to attend an information evening about the project where the objectives of the research were discussed and the time commitment required of the panelists was outlined. From the twelve panelists who were originally recruited, eight were selected, based on interest in the research and their availability to complete the project.

Terminology development and training of the panel occurred over ten 1-1½ hour sessions. During training, panelists were presented with samples of extrudates which were representative of those to be tested. The panelists were instructed to bite the extruded products and individually record the characteristics that described the texture of the product and to record how they would define each characteristic. These terms and definitions were then discussed as a group. Redundant characteristics and those which the panelists did not agree on were discarded. These characteristics were then combined with those that the panel leader had compiled. Under the guidance of the panel leader, the definitions were discussed and formalized for each characteristic so that all panelists were evaluating the products in a similar manner. Subsequent training sessions were used to train the panelists in the evaluation of each characteristic. The training sessions were used to train panelists to consistently evaluate each characteristic using a 10cm line scale as well as to introduce the panelists to the range of samples they would be ultimately testing. Each training session followed a similar format. At each session, panelists were trained to evaluate two or three characteristics only. Characteristics were chosen by the panel leader prior to the start of training. The panel would be instructed as to which characteristics would be trained for in a given session and the definitions of the characteristics were written on a whiteboard. Panelists were presented with examples which displayed extremes of each characteristic to be used as references for anchoring

their evaluations on the line. Where possible, these samples were typically extrudates that had been modified to exhibit extremes of the characteristic.

To ensure that panelists understood each characteristic and could discriminate amongst samples displaying a range of each characteristic, panelists were provided with four samples with a wide spread of the intensity of that characteristic. All samples were presented to the panelists labelled with three digit codes and sample presentation was randomized so that all panelists received the samples in a different order. The panelists were then asked to rank, from one to four (where 1 was most intense and 4 was least intense) the four samples exhibiting the characteristic. Following the ranking test, results of the test were discussed with the panelists. If problems were encountered with understanding the characteristic or ranking of the samples, then further samples were presented to the panelists and the definition was discussed until everyone was able to agree on the characteristic and could adequately evaluate samples for the characteristic.

Following the ranking test, panelists were then asked to evaluate the same samples (labelled with different three digit codes) using a 10cm unstructured line scale anchored and labelled with appropriate end points. Each panelist measured their responses and results were discussed. This discussion highlighted panelists who were having difficulties evaluating samples for the characteristic and also showed panelists how their results compared to the others. If there were large discrepancies in placement of responses on the line scale, panelists were encouraged to move their responses to better align with the others.

This format was then repeated for each characteristic. During the last part of each training session, the panelists evaluated four samples for all of the characteristics that they had been trained for in the current training session, as well as any characteristics that they had been trained for in previous training sessions. Results from these evaluations were shown to the panelists at the beginning of the next training session. At that time, discussions were held regarding the results, problem areas were highlighted and if the panel leader felt that further training was required for a particular characteristic then it was held at that point.

Once all the characteristics had been introduced and the panelists were able to adequately evaluate samples for all of the characteristics, the last two training sessions were used as practice for the panelists. During these practice sessions, two sets of six samples (labelled with a three digit code) were presented to the panelists in a randomised order and the samples were evaluated for all characteristics using a 10cm unstructured line scale labelled with appropriate anchors. Results were discussed and panelists were given an opportunity to have further training on any characteristic. Within the six samples presented during the practice sessions, at least two samples were duplicated in order to determine the discriminative ability of the panelists. Results were analysed by ANOVA to ensure that the panel could discriminate amongst samples and that all panelists were reproducible in their responses.

Following training, testing was conducted. Four sessions of testing were required in order to complete four replicates of testing. In each session, samples from each of the four treatments were evaluated. Sample presentation across the four treatments within each session was randomized so that each panelist received the samples in a different order. All testing was conducted in individual sensory booths in the sensory evaluation laboratory, Albany Campus, Massey University. All tests were conducted under white lighting within the booths. During testing, panelists were given filtered water as a palate cleanser. One half hour prior to testing, samples were removed from their storage bags and placed in low-density polyethylene zip lock bags (40μm thick). All bags were labelled with a three-digit blinding code corresponding to each sample treatment. Each bag held five pieces of the extrudate treatment. The panelists were instructed to eat as many samples as were required to complete the testing. All samples were approximately 22mm long and 10mm in diameter.

The samples were evaluated for characteristics of crispness, hardness, sound duration, brittleness. All responses were scored on 10cm unstructured line scales labelled with appropriate anchors for each characteristic. A copy of the questionnaire used by the panelists is shown in Appendix J.

Upon completion of testing, all line scales were measured from 0 using a ruler and responses were recorded in centimeters to one decimal place. Data were then saved as a text file for analysis in SAS.

The sensory data were analysed to determine if significant differences existed among samples, panelists and replicates using a program written in SAS (Version 8.1, SAS Institute, North Carolina). Significant differences were determined by ANOVA using SAS. A Tukey's Honestly Significant Difference (HSD) test was used to establish differences. All results were significant at 95% confidence.

Finally, a laboratory panel was conducted using 39 consumers of snack foods. These panelists were recruited from the local community. The panelists ranged in age from 18 to 55. All indicated that they were in good dental health and contained their own teeth. They were required to attend one testing session where they completed an evaluation of the crispness of the snack foods. Extrudates were prepared as described in section 4.1.1 and then stored at 20°C over saturated salt solutions. These salt solutions used were: lithium chloride (a_w = 0.11) and potassium carbonate (a_w = 0.44) (Greenspan, 1977). Samples were weighed in the trays in which they were stored and when weight change was constant (±0.001g) over 24 hours they were removed from the desiccators and stored in foil laminate packaging for two weeks, until testing. The water activity of the samples was verified using a water activity meter (Decagon CX2).

Panelists were provided with a questionnaire with a 10cm line for crispness. The anchors on the line were "not crisp" on the left hand side and "very crisp" on the right hand side. Three replicates of testing were completed in one session. Within each replicate, sample presentation across panelists was randomized so that half the panelists evaluated the 0.11 water activity sample first and half evaluated the 0.44 water activity sample first.

All testing was conducted in a central location. Panelists were seated at tables, with their backs to the other panelists to minimise distractions. During testing, panelists were given filtered water as a palate cleanser. One half hour prior to testing, samples were removed from their storage bags and placed in low-density polyethylene zip lock bags

(40μm thick). All bags were labelled with a three-digit blinding code corresponding to each sample treatment. Each bag held 3 pieces of the extrudate treatment. The panelists were instructed to eat as many samples as were required to complete the testing. All samples were approximately 22mm long and 10mm in diameter.

Upon completion of testing, all line scales were measured from 0 using a ruler and responses were recorded in centimeters to one decimal place. Data were then saved as a text file for analysis in SAS.

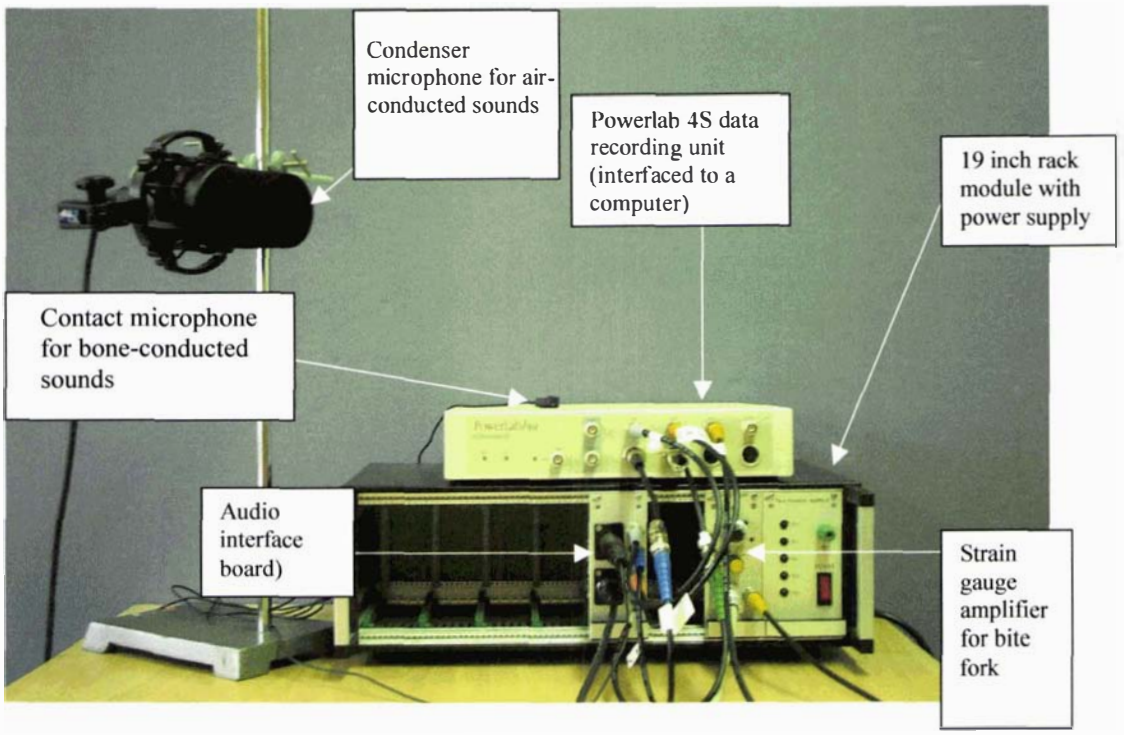
4.1.3 Collection of bone- and air-conducted sounds

A Powerlab/4S data recording unit (ADInstruments, Australia) was used to collect air-conducted and bone-conducted sounds (Figure 4.1). This multi-channel system was capable of simultaneously recording data from four inputs. The software (Chart4) associated with the Powerlab/4S data recording unit was used to analyse the collected data. Bone-conducted sounds were recorded using a contact microphone with a frequency range of 10Hz to 18 kHz (C411PP micro mic III; AKG Acoustics, Vienna, Austria). Air-conducted sounds were collected using a diaphragm condenser microphone (C414B-ULS; AKG Acoustics, Vienna, Austria) with a frequency range of 20Hz to 20 kHz.

The signals generated by both microphones were transmitted via an audio interface board to the Powerlab data acquisition unit (Figure 4.1). The data acquisition unit was interfaced to a computer loaded with Chart4 software (ADInstruments, Australia).

The Powerlab converted the sounds picked up by the microphones into digital signals for further processing, similar to the MacQuisition unit described in section 3.3. For all recordings, the sampling rate for the experiment was set at 40,000 points per second using the Chart4 software. All sound wave data were recorded in volts and plotted as voltage versus time. All voltage-time data were exported from the Chart4 software as data files and stored for further analysis.

Figure 4.1 : Equipment setup for recording air-conducted and bone-conducted sounds



Prior to collecting the sound recordings, both the bone-conducted and air-conducted microphones were tested to ensure the microphones were detecting sounds at appropriate frequencies. The bone-conducted microphone was attached to the skin above the mastoid bone of the panelist. A mechanical vibrator (Pasco Scientific, Model SF-9324) attached to a Goldstar voltage signal generator was touched to the incisors of the panelist. Various frequencies of vibration were played onto the front teeth one frequency at a time. These frequencies were 10Hz, 50Hz, 75Hz, 100Hz, 1kHz and 10kHz. The frequency spectrum of the voltage-time curve was produced using the spectrum option in the Chart4 software package. The spectrum option conducted a FFT of the data. The spectrum was then visually inspected to ensure that each frequency of vibration that was played onto the front teeth was correctly recorded by the system.

To test the air-conducted microphone, a mechanical vibrator (Pasco Scientific, Model SF-9324) attached to a Goldstar voltage signal generator was placed 3cm in front of the

condenser microphone. Frequencies of 10Hz, 50Hz, 75Hz, 100Hz, 1kHz and 10kHz were sequentially played into the microphone and the sound waves recorded from the microphone. The recorded voltage-time data were analysed using the spectrum analysis in Chart4. The spectrum was then visually inspected to ensure that each frequency of vibration that was played into the microphone was correctly recorded by the system.

Once the system had been checked to ensure that it was properly recording all frequencies, the recording of sounds produced during biting was undertaken. For recording the bone-conducted sound, the contact microphone was taped to the skin on the mastoid bone behind the ear of each panelist. In this study, the placement of the contact microphone was moved from the mandibular bone on the cheek (as discussed in section 3.3) to the mastoid bone behind the ear so that it did not interfere with the air-conducted sound microphone. The air-conducted sounds were detected using the condenser microphone placed 3cm from the ear canal of each panelist

Once the microphones had been properly placed for testing, pre-testing was undertaken with each panelist to ensure that the voltage range for recording was correct for each panelist. It was crucial to ensure voltage recordings were not "clipped" because they fell outside the settings of the recording software. The range for a given panelist was set using samples of crisp products being tested. The equipment was initially set on low sensitivity and the panelist bit a test sample. Then, the sensitivity was increased to better encompass the actual range and another sample was tested. Once verified, the testing of the samples began.

During testing, samples (approximately 22mm long and 10mm in diameter) were given to the panelists for biting. All samples were sealed in low-density polyethylene zip lock bags (40μm thick) and were labelled with a three-digit code corresponding to a sample treatment. Panelists were instructed to remove the sample from the bag, place the sample between their front teeth and bite the sample in two with their front teeth. For all testing, four replicates of each sample were recorded. For each panelist, all testing was conducted in one session.

All recordings were conducted in a quiet room which contained the researcher, the panelist and the microphones. All other equipment was placed in a separate room to ensure that no equipment noise affected the sound recordings. A check of the background noise in the room showed that no extraneous noises were recorded by the air-conducted microphone during testing.

4.1.4 Characterisation and analysis of sound waves

The acoustic signatures collected during simultaneous recording of the bone-conducted and air-conducted sound waves were analysed by fractal analysis as outlined in section 3.3.1. The fractal dimensions for each sample, panelist and replicates were analysed using a 3-way ANOVA in SAS (Version 8.1, SAS Institute, North Carolina) to determine if differences existed among samples, panelists and replicates. A Tukey's Honestly Significant Difference test was used to indicate where differences existed. All results were significant at 95% confidence.

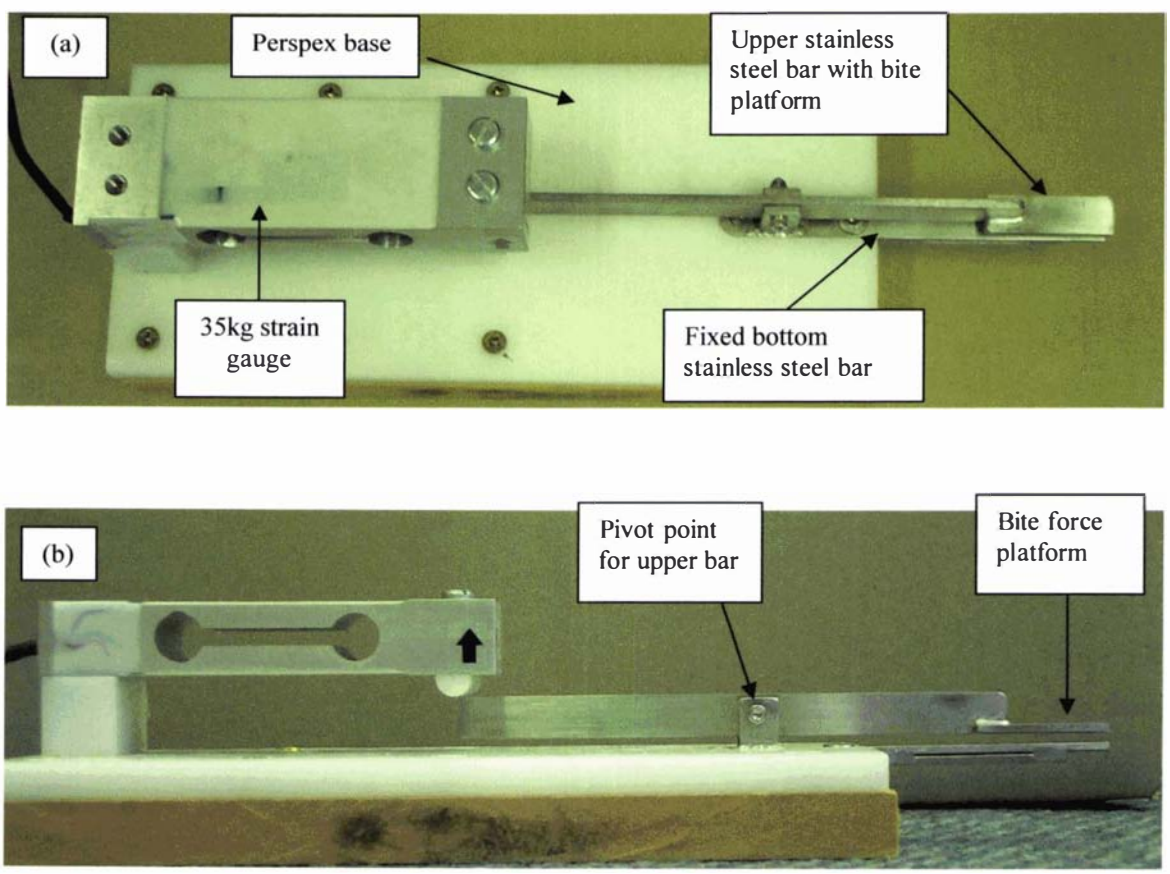
4.1.5 Bite force apparatus set up

The bite force apparatus used for collecting bite force data is shown in Figure 4.2. The apparatus was constructed using a 35kg strain gauge and two stainless steel bars mounted onto a perspex base (245 x 105mm). The bottom stainless steel bar was 120mm in length, 12mm wide and 2.5mm thick. Fifty mm of length of the bar was embedded into the plastic and held in place with two bolts. To prevent flex within the apparatus during biting, the bottom bar was reinforced with a second stainless steel plate which increased the thickness of the bar from 2.5mm to 6mm. The thickness of the last 12mm of the bottom bar was decreased to 2.5mm. This provided a bite guide for panelists to place their bottom teeth against during biting.

The top stainless steel bar of the apparatus was 190mm in length, 12mm wide and 2.5mm thick. The top bar was attached with a 5mm screw to a vertical support 91mm from the strain gauge. The screw acted as a pivot point for the top bar, allowing it to move into the strain gauge during biting. The end of the top bar was formed into a small platform (30mm long x 13mm wide x 2.5mm thick) for placing the sample during biting.

The strain gauge of the bite force apparatus was attached to a strain gauge amplifier within the rack module with power supply shown in Figure 4.1. The power supply was interfaced to a computer loaded with Chart4 software (ADInstruments, Australia).

Figure 4.2: Bite force apparatus as shown from a) top view and b) side view



The bite force apparatus was tested for linearity using an EZ-Test texture analysis unit (Shimadzu Corporation, New Zealand). The EZ-Test was designed to measure the strength of various materials. It consisted of a 500N load cell attached to a cross head. The cross head moved vertically at a constant speed, controlled by a DC servo motor. The EZ-Test was interfaced to a PC computer loaded with WinAGS Lite software (Shimadzu Corporation, New Zealand). The software was used both to set the cross head speed and to record the force on the load cell as the cross head moved onto the bite force platform.

For testing, an 80mm stainless steel probe was attached to the cross head. The speed of the cross head was set to 0.83mm.s^{-1}. The bite platform was placed under the edge of the probe and the amount of force in newtons (N) required to compress the bite force platform was recorded. The force values were exported from the WinAGS software.

During compression with the EZ-Test, the movement of the top bar of the bite force apparatus was registered by the strain gauge and recorded in Chart4 as a voltage-time curve. The voltage reading was exported from the Chart4 software. It was plotted against the amount of force exerted (N) on the bite apparatus recorded by the EZ-Test. This plot is shown in Figure 4.3. The relationship between applied force and measured force was not linear. The best fit was a cubic polynomial (r^2=0.99) as shown by Equation 4.1.

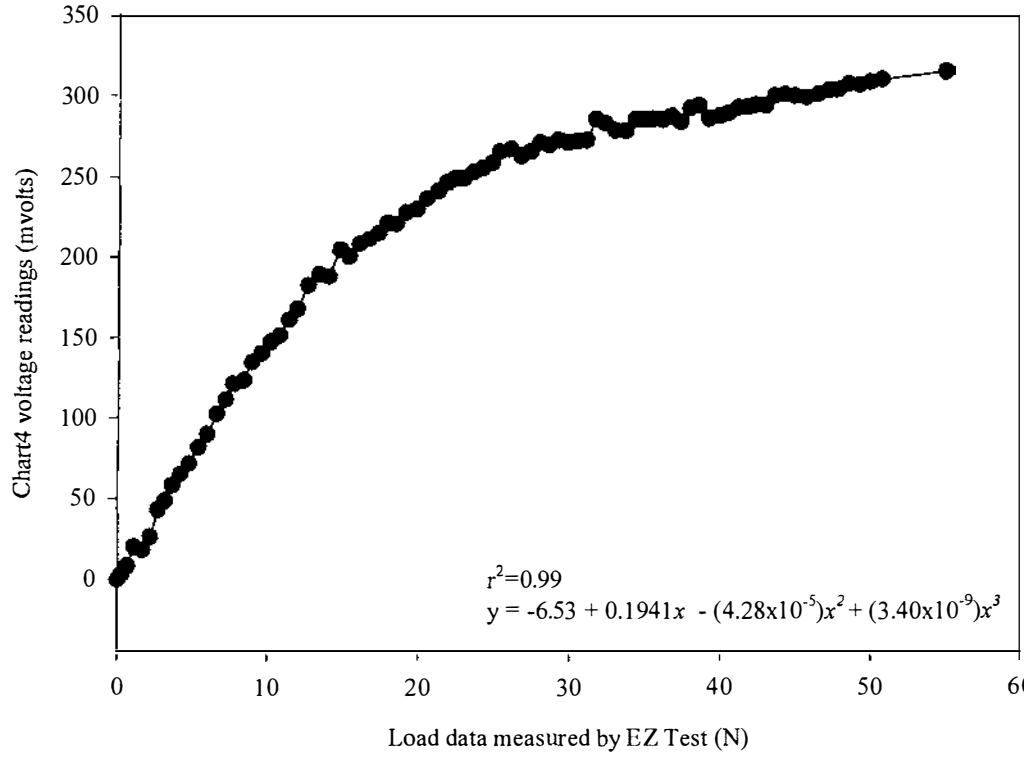
Equation 4.1:

$$y = -6.53 + 0.1914x - (4.28 \times 10^{-5})x^2 + (3.40 \times 10^{-9})x^3$$

Where y=measured force
x= applied force

For all measurements, recorded data were adjusted via the equation by using the arithmetic function in Chart4. This allowed readings in one channel to be arithmetically converted while the data were being collected in another channel.

Figure 4.3: Calibration curve for bite force testing apparatus



At the beginning of each data collection session, the voltage input was converted to a force input (N) on the Chart4 software. For conversion, a 0.09N mass and a 0.9N mass were placed on the platform of the bite force apparatus. The voltages displayed when each of these weights were placed on the platform were noted and then typed into the units conversion function of the Chart4 software.

The bite force apparatus was cleaned thoroughly with 95% ethanol prior to each person completing the bite test. As protection for the panelists' teeth, a disposable latex covering was placed over the bite platform at the start of each testing session. Each panelist was allowed to have as many practice bites as were required to feel comfortable biting down on the bite apparatus. Testing began once the panelists indicated that they felt comfortable making the bite.

Samples of each product treatment were placed into low-density polyethylene zip lock bags (40μm thick). Each bag had a 3-digit code which was used for identification of the

treatment. During testing, a sample was removed from the bag and placed on the upper platform of the bite force apparatus and bitten into with the front teeth until it was sheared in half. For all testing, four replicate bites of each sample were made. All samples were approximately 22mm in length and 10mm in diameter. All treatments were assessed in each session. All four replicates of one sample were tested before starting the next treatment.

All bite data were recorded using the Chart4 software. The force-time data from the arithmetically converted software were saved as text files for analysis.

4.1.6 Characterisation and analysis of the bite force data

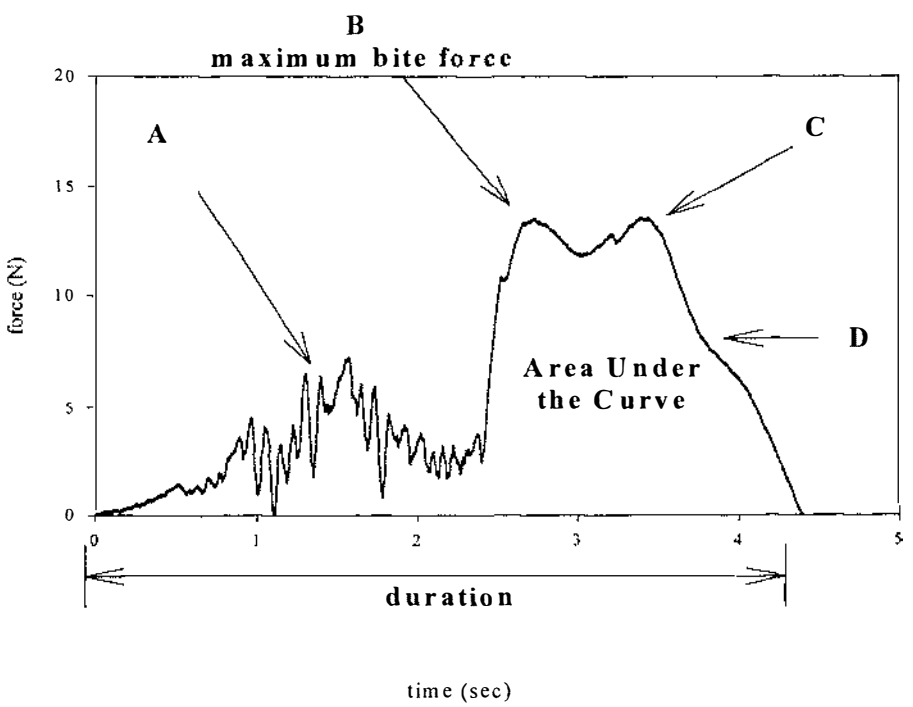
The parameters of duration, maximum bite force and area under the bite force curve were calculated for each of the arithmetically converted force-time curves. A typical force-time curve is shown in Figure 4.4. Duration was determined from the start of A through to the end of D (Figure 4.4). The maximum bite force was the force which occurred at the instance of fracture and this was assessed by selecting the first peak on the curve (B in Figure 4.4). In some instances a double peak was recorded (C in Figure 4.4). The second peak is the end of the fracture and in some instances may be overestimated if the teeth come together after breaking through the sample. For this reason, the first peak was selected as the maximum force reading. Area under the bite force curve was calculated by integrating the force-time data from the start of the bite (Figure 4.4) to the point where zero force was achieved upon removal of the teeth from the bite force apparatus (Figure 4.4). The area under the curve value was computed using the integration function within the Chart4 software. Using the maximum force value, the fracture stress of the sample was determined by dividing the maximum force value by the area of the bite force platform.

These parameters (maximum force, duration, area under the curve and the calculated stress) were exported from Chart4 and saved as a text file. The data were analysed by ANOVA in SAS (Version 8.1, SAS Institute, North Carolina) to determine if differences existed amongst the samples, the panelists and the replicates of biting as well as to look at any sample by panelist interactions. A Tukey's HSD test was used to

indicate where significant differences existed. All results were significant at 95% confidence.

Figure 4.4: Typical bite force curve

- A bite force curve from one panelist biting into an extruded sample with a water activity of 0.11.
  - A - the initial point of contact with the sample
  - B – instance of fracture - maximum bite force
  - C – teeth coming together at end of fracture
  - D – opening of mouth and removal of teeth from bite force apparatus
- Duration is the time from the start of the test (A) to the end of D.
- Area under the curve is calculated using the integration function in Chart4.



4.1.7 Instrumental testing of samples

Instrumental testing was conducted using an EZ-Test table top tester (Shimadzu Corporation) to confirm the bite force measurement results. The EZ-Test has a similar setup to the TA-XTII textural analyser described in section 3.4. The EZ-Test consisted of a moving crosshead with a 500N load cell attached to it. A probe was attached to the load cell and the cross head was programmed to move at a set speed into the sample. Compression testing and puncture testing were conducted using the EZ-Test. For

compression, a perspex probe (60mm in diameter) was used. For the puncture test, a 2mm diameter stainless steel puncture probe was used.

For both the puncture and the compression test, samples of the extruded snacks (22mm long and 10mm in diameter) were placed on a 118mm diameter stainless steel base and the cross head was programmed to move 8.3mm.s^{-1} into the sample on the base. A force-time curve was recorded using WinAGS Lite software (Shimadzu Corporation, Japan) loaded onto a personal computer interfaced to the EZ-Test instrument. Five replicates of each treatment were tested.

The force-time readings recorded using the WinAGS Lite software were analysed to obtain maximum force to compress and maximum force to puncture. These data were analysed by using SAS (Version 8.1, SAS Institute, North Carolina) to determine if significant differences existed amongst samples for each force reading. A Tukey's HSD test was conducted in SAS to indicate where significant differences existed. All results were significant at 95% confidence.

The relationship between the bite force parameters of maximum force, duration and area under the curve and the instrumental compression and puncture test results of maximum force was examined using a Pearson Product Moment Correlation analysis in SAS (Version 8.1, SAS Institute, North Carolina).

4.1.8 Relationship between sensory and objective measures

To look at the relationships between the perceived textural properties of the extruded snacks and the bone-conducted and air-conducted acoustic properties of the products, the sensory data collected from the trained panel and the acoustic measures were correlated using Pearson Product Moment Correlation analysis in SAS (SAS Version 8.1, SAS Institute, North Carolina).

The trained panel sensory data were also correlated to the bite force parameters of maximum force, duration and area under the curve as well as to the instrumental compression and puncture test results of maximum force by Pearson Product Moment Correlation analysis in SAS (Version 8.1, SAS Institute, North Carolina).

4.1.9 Development of regression equations from sensory data

Air-conducted sounds from the trained panel and instrumental force measures were used to develop regression equations to predict crispness as perceived by the trained panelists. All regression analysis was conducted using SAS (Version 8.1, SAS Institute, North Carolina).

Crispness results and physiological measures collected from the 39 individuals evaluating two water activity samples were analysed by ANOVA to look at differences between samples and panelists. The sensory data for each panelist were then analysed by a one-way ANOVA to develop groupings based on crispness perception. The data in each group were re-analysed by one-way ANOVA for each panelist to look at sample separation by panelist based on the physiological measures. Regression equations were developed by analysing the data from all 39 individuals. All analyses were conducted using SAS (Version 8.1, SAS Institute, North Carolina).

4.2 Results and discussion

4.2.1 Consumer survey of extruded snacks.

Consumers have defined a crisp product as one that breaks/snaps/cracks easily and has an element of firmness (Szczesniak, 1988). A crisp product is also cellular, with the cells being responsible for the sounds emitted during breaking (Vickers and Bourne, 1976). Although extruded snacks fit the description of a crisp product, in addition to being labelled crisp, extrudates have also been called crunchy (Barrett *et al.,* 1994; Guraya and Toledo, 1996; Norton *et al.,* 1998) and crackly (Norton *et al.,* 1998). To determine what descriptors New Zealand consumers use to describe the texture of extrudates, a consumer survey was conducted.

Data collected from the survey presented to 106 consumers were analysed using factorial correspondence analysis. The cross-tabulation (or contingency) table showing the number of times each sensory descriptor (in columns) was applied to each sample (in rows) is shown in Table 4.1.The factor plot showing the loading of each sample and textural property on each factor, obtained by PCO and PCA (respectively) is shown in Figure 4.5.

Table 4.1: Frequency that consumers described the texture of various dry foods

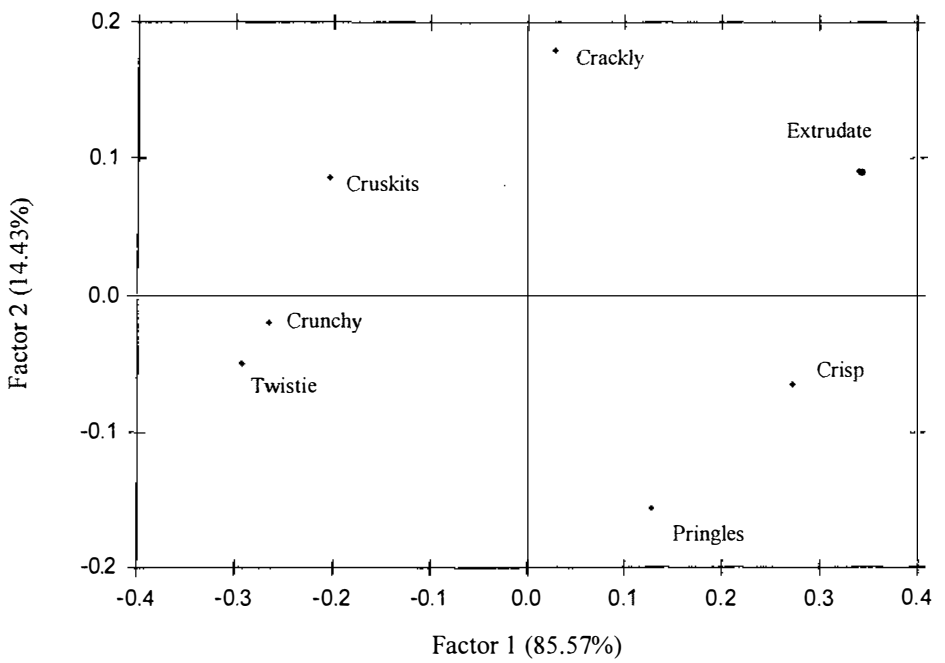
	Descriptor selected by consumer		
Product	**Crisp[1]**	**Crunchy**	**Crackly**
Pringles™[2]	50	37	19
Twisties™[2]	29	53	24
Cruskits™[2]	29	48	29
Extruded test product[3]	53	22	31

[1]Responses collected from 106 consumers.
[2]Commercial products sourced from a local supermarket.
[3]Produced using a twin-screw extruder and stored in a desiccator over a lithium chloride (a_w=0.11) saturated salt solution until equilibrium was reached.

New Zealand consumers considered Pringles™ potato chips crisp (Table 4.1). This is in agreement with Dacremont *et al.,* (1991) and Vickers and Bourne (1976). Additionally, the extruded test product was considered crisp (by comparison to Pringles™ potato chips). However, Twisties™ and Cruskits™ were considered to be crunchy.

Figure 4.5: Factorial correspondence analysis plot for consumer evaluation of texture

- Factor 1 can be described as a crunchy-crisp dimension
- Factor 2 can be described as a crackly dimension



Eigenvalues and proportions of variance (or inertia) from the PCO and PCA analysis show that Factor 1 explained about 86% of the inertia of the data and factor 2 explained about 14% (Figure 4.5). Based on the loadings on factor 1, this dimension can be described as a crisp – crunchy axis, with samples loading high on the positive end of the axis best described as crisp and those loading high on the negative end of the axis described as crunchy. The extruded test product, loads high on the positive end of the axis and can therefore be associated with crisp textures while Twisties™ (located in the lower left quadrant) and Cruskits™ are associated with a crunchy texture. Pringles™

potato chips are also associated with a crisp texture. The crisp-crunchy axis shown in Figure 4.5 is also similar to that observed by Dacremont *et al.,* (1991).

Factor 2 can be described as a crackly dimension, with samples with high positive scores also being described as crackly. Cruskits and extrudates have an element of crackliness to them, loading high on factor 2.

A trained panel was then used to evaluate the snacks stored at a range of water activities for crispness as well as hardness, sound duration and brittleness. The definitions of these characteristics are shown in Table 4.2. Mean scores for each sample for each characteristic evaluated by the trained panel are shown in Table 4.3. Crispness results were consistent to those of the earlier study (Table 3.3) where the lower water activity samples were more crisp than samples stored at higher water activity. There was a trend to longer sound duration as water activity increased. Hardness increased with increasing water activity. Conversely, brittleness decreased with increasing water activity. Thus, hardness and brittleness were inversely related.

Table 4.2: Trained panel definitions for sensory characteristics of extrudates

Crispness A combination of the sound and the force to bite and chew as perceived on first bite
Hardness Place the food between your incisors and bite down. Evaluate the force required to bite through the food with your incisors.
Sound Duration The number of pops heard when biting with the incisors with the lips closed. Evaluate on first bite only.
Brittleness The type of breakdown of the product. Does it shatter when bitten into or does it squish on first bite?

The sensory evaluation results obtained confirm the results of others (Valles Pamies *et al.,* 2000) who showed that extruded puffed products with no sugar had a loss of crispness at a water activity of 0.31. Waichungo *et al.,* (2000) showed a critical water

activity (the water activity at which textural characteristics changed) of between 0.36 and 0.58 for extruded puffed corn starch. Above a water activity of 0.36, the extruded samples were low in fracturability and high in cohesiveness. Hardness increased to a maximum at a water activity of 0.9. Sauvageot and Blond (1991) studied the change in texture of both commercial cereals and extruded experimental products and stated that crispness only decreased slightly when water activities increased from 0 to 0.5 but that the rapid changes in crispness occurred from water activities of 0.5 to 0.84.

Table 4.3: Descriptive analysis of sensory characteristics of extrudates

	Extrudate a_w[1]			
Sensory Characteristic	**0.11**	**0.22**	**0.33**	**0.44**
Crispness[2]				
Mean	6.4a[3,4]	6.0a	4.5b	3.9b
Std Error	0.33	0.29	0.36	0.41
Hardness				
Mean	2.4c	3.0c	4.4b	5.6a
Std Error	0.33	0.37	0.37	0.36
Sound Duration				
Mean	2.9b	3.0ab	3.5ab	3.9a
Std Error	0.27	0.37	0.28	0.27
Brittleness				
Mean	5.3a	5.1a	4.6b	3.8c
Std Error	0.36	0.38	0.28	0.26

[1]The water activity was manipulated by storing extrudates in desiccators over solutions of lithium chloride (a_w =0.11), potassium acetate (a_w = 0.22), magnesium chloride (a_w= 0.33) and potassium carbonate (a_w= 0.44).
[2]All data input onto 10cm line scales where 0=low or not and 10= high or very of the characteristic.
[3]8 panelists evaluated four replicates of each sample (n=32)
[4]Means in a row followed by the same letter are not significantly different (p>0.05).

4.2.2 Panelist variability

The ANOVA results for the trained panel (Table 4.4) show significant panelist variability, no significant replicate variability but significant panelist*sample variability for crispness and brittleness. The interaction plot for crispness is shown in Figure 4.6.

The interaction plot for crispness shown in Figure 4.6 indicates that there was a general downward trend for crispness as the water activity increased. The significant interactions observed for crispness may be partially attributed to a magnitude effect where the panelists use different parts of the scale to score their perceptions. For example, the crispness of the 0.11 water activity sample ranged from 4.5 up to 7.9 amongst panelists. Additionally, panelists 1 and 3 showed some confusion in the crispness of the 0.11 and 0.22 water activity samples, allocating a higher crispness score to the 0.22 water activity samples than the 0.11 water activity samples. Although this interaction was significant, differences in sensory properties were still observed amongst the water activity samples indicating that water activity had a profound effect on perceived texture.

Figure 4.6: Interaction plot for crispness

- Data presented are mean crispness scores for each panelist evaluating each water activity sample for crispness. Four replicates of evaluations were conducted by each panelist.

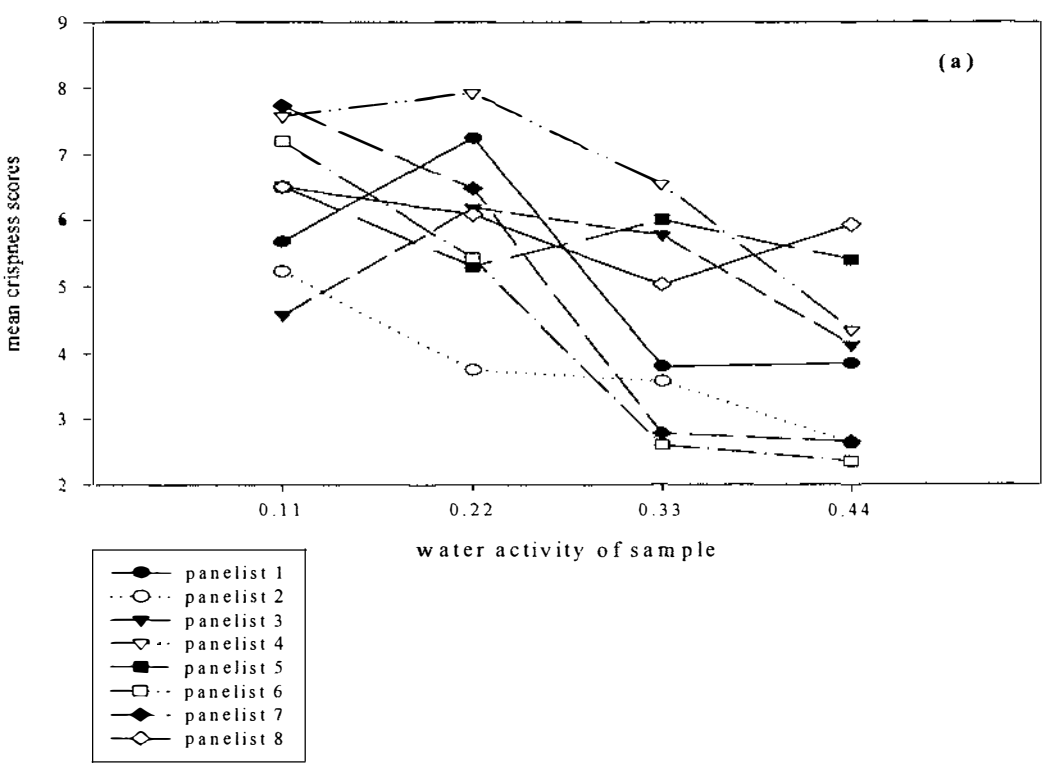


Table 4.4: ANOVA of sensory characteristics of extrudates

Sensory characteristic[1]	df	Sum of squares	Mean Square	F-value	Probability
Hardness					
Sample[2]	3	197.39	65.79	29.24	<0.0001
Panelist	7	255.66	36.52	16.23	<0.0001
Replication	3	3.03	1.01	0.45	0.78
Panelist*Sample	21	61.40	2.92	1.30	0.21
Panelist*Replication	21	42.23	2.01	0.89	0.59
Sample*Replication	9	11.73	1.30	0.58	0.80
Error	63	141.78	2.25		
Crispness					
Sample	3	135.31	15.57	4.96	<0.0001
Panelist	7	88.02	45.10	17.81	0.002
Replication	3	3.90	1.30	0.51	0.67
Panelist*Sample	21	107.58	5.12	2.02	0.02
Panelist*Replication	21	72.17	3.43	1.36	0.17
Sample*Replication	9	44.36	4.92	1.95	0.06
Error	63	159.57	2.53		
Sound duration					
Sample	3	21.47	7.15	4.32	0.007
Panelist	7	176.78	25.25	15.23	<0.0001
Replication	3	5.08	1.69	1.02	0.38
Panelist*Sample	21	47.06	2.24	1.35	0.17
Panelist*Replication	21	46.16	2.19	1.33	0.19
Sample*Replication	9	17.76	1.97	1.19	0.31
Error	63	104.46	1.65		
Brittle					
Sample	3	41.18	13.72	10.39	<0.0001
Panelist	7	91.25	13.03	9.87	<0.0001
Replication	3	1.97	0.65	0.50	0.68
Panelist*Sample	21	151.63	7.22	5.47	<0.0001
Panelist*Replication	21	48.56	2.31	1.75	0.05
Sample*Replication	9	24.20	2.68	2.04	0.05
Error	63	83.22	1.32		

[1]8 panelists evaluated 4 replicates of samples with water activities of 0.11, 0.22, 00.33 and 0.44.
[2]The water activity was manipulated by storing the extrudates in desiccators over solutions of lithium chloride (a_w =0.11), potassium acetate (a_w =0.22), magnesium chloride (a_w= 0.33) and potassium carbonate (a_w= 0.44).

4.2.3 Fractal analysis of bone- and air-conducted sound waves

The fractal dimensions of air-conducted and bone-conducted sound waves were calculated and analysed by ANOVA. These results are shown in Table 4.5. Air-conducted sound waves differed significantly in jaggedness; however, bone-conducted sound waves did not. Significant panelist effects were observed for both the air-conducted sound waves and the bone-conducted sound waves.

Table 4.5: ANOVA for fractal dimensions of sound waves

Sound wave measures[1]	df	Sum of Squares	Mean Square	F-value	Probability
Air-conducted fractal dimension[2]					
Panelist[3]	7	0.10	0.01	3.61	0.0015
Sample[4]	3	0.15	0.05	12.47	<0.0001
Replicate	3	0.003	0.001	0.28	0.83
Error	110	0.46	0.004		
Bone-conducted fractal dimension[5]					
Panelist	7	0.25	0.03	20.89	<0.0001
Sample	3	0.005	0.001	1.09	0.35
Replicate	3	0.0005	0.0001	0.10	0.95
Error	110	0.19	0.0017		

[1]Air-conducted sound was recorded using a condenser microphone.
[2]The fractal dimension of the sound waves was calculated using software by Russ, 1994.
[3] 8 panelists evaluated 4 samples with water activities of 0.11, 0.22, 0.33 and 0.44 over 4 replicates.
[4]The water activity was manipulated by storing the extrudates in desiccators over solutions of lithium chloride (a_w= 0.11), potassium acetate (a_w=0.22), magnesium chloride (a_w= 0.33) and potassium carbonate (a_w=0.44).
[5]Bone-conducted sound was recorded using a contact microphone attached to the skin on the mastoid bone. The fractal dimension of the sound wave was calculated using software by Russ, 1994.

The mean fractal dimensions for both air-conducted and bone-conducted sound waves are shown in Table 4.6. The air-conducted sound wave produced during the biting of samples with low water activity (0.11 and 0.22) were similar, with no significant difference in jaggedness. Additionally, the jaggedness of the 0.33 and the 0.44 water activity samples were similar with no significant differences. However, the jaggedness between the two low water activity samples (0.11 and 0.22) was significantly greater than for the two higher water activity samples (0.33 and 0.44).

The fractal dimensions of the acoustic signatures from the bone-conducted sounds were not significantly different (Table 4.6). One reason for this may be the large degree of panelist variability observed for the bone-conducted sound waves which obscured any differences amongst the samples. Additionally, mean scores among the samples range from 1.33 to 1.35, indicating that there was not a great deal of difference in the jaggedness of the bone-conducted sounds. Perhaps the vibrations produced during biting of the extrudates were not strong enough to produce different responses amongst the samples tested. Or, perhaps the sound was well filtered by bone, flesh and skin by the time it reached the contact microphone.

Table 4.6: Fractal dimensions of sound waves

	Extrudate a_w[1]			
Sound wave measure[2]	**0.11**	**0.22**	**0.33**	**0.44**
Air-conducted fractal dimension[3]				
Mean	1.61a[5,6]	1.60a	1.53b	1.53b
St Error	0.007	0.007	0.01	0.01
Bone-conducted fractal dimension[4]				
Mean	1.34a	1.34a	1.33a	1.35a
St Error	0.008	0.008	0.01	0.01

[1]The water activity was modified by storing the extrudates in desiccators over solutions of lithium chloride (a_w= 0.11), potassium acetate (a_w= 0.22), magnesium chloride (a_w= 0.33) and potassium carbonate (a_w= 0.44).
[2]The fractal dimension of the sound wave was calculated using software by Russ, 1994.
[3]Air-conducted sound was recorded using a condenser microphone.
[4]Bone-conducted sound was recorded using a contact microphone attached to the skin on the mastoid bone.
[5]8 panelists evaluated each sample over 4 replicates (n=32).
[6]Means in a row followed by the same letter are not significantly different (p>0.05).

4.2.4 Sensory and sound wave relationships

Sensory panel scores and the fractal analysis of the air- and bone-conducted sounds were analysed using Pearson Product moment correlation analysis. All data used in the analysis were means. Results are expressed in terms of correlation coefficients and their probabilities and are summarised in Table 4.7.

Table 4.7: Relationships between sensory scores and sound wave fractal dimensions of extrudates

	Sensory characteristic[1]			
Sound wave measure[2]	**Crispness**	**Hardness**	**Sound duration**	**Brittleness**
Air-conducted fractal dimension[3]				
r-value	0.98[5]	-0.97	-0.92	0.97
Probability	0.01[6]	0.02	0.08	0.02
Bone-conducted fractal dimension[4]				
r-value	0.17	0.20	-0.10	-0.23
Probability	0.82	0.79	0.89	0.76

[1]Sensory characteristics were evaluated by a trained panel of 8 trained panelists.
[2]The fractal dimension of the sound wave was calculated using software by Russ, 1994.
[3]Air-conducted sound was recorded using a condenser microphone.
[4]Bone-conducted sound was recorded using a contact microphone attached to the skin on the mastoid bone.
[5]Correlation coefficients (r-values) were calculated from the mean scores of the 4 water activity samples (n=4).
[6]Correlations are not significant at probabilities of >0.05.

The bone-conducted fractal dimension was not correlated to any sensory characteristic. The air-conducted fractal dimension showed significant correlations to crispness, hardness and brittleness, but no significant correlation (95% confidence) to sound duration. These results show that when the crispness and the brittleness increased, the air-conducted sound waves became more jagged. Sound is generated by the rapid destruction of the food structure as the teeth bite into the sample (Jowitt and Mohamed, 1980). The excess energy produced by the destruction of multiple cell walls within the product is released as sound (Ablett *et al.*, 1986). The significant negative correlation

between hardness and the air-conducted acoustic sound waves indicates that as hardness increased, the jaggedness decreased. The acoustic signature of a hard sample typically exhibited one large peak representing the "snap" which occurred when the teeth broke through the hard sample.

4.2.5 Effect of samples on the bite force curves

For the collection of bite force measurements, each panelist was required to bite through a sample placed on the bite platform of the bite force apparatus. The amount of force required to break the sample was recorded directly into a computer as a force-time curve. A visual inspection of the bite force curves showed two distinct types of curves (shown in Figures 4.7a-d and 4.8).

The force-time curves in Figure 4.7(a-d) are typical of those recorded from seven of the eight panelists. The curves have some obvious characteristics. The preliminary jagged increase in force (A in Figure 4.7a) was due to hesitancy by the panelists to initiate biting into the sample until it was securely fastened between the teeth and the bite platform. Once the sample was secure, the panelists proceeded to carry out the bite. This led to a sharp increase in bite force, leading to the maximum force applied to the sample during shearing of the sample with the teeth. In some instances, a double peak was recorded. This first peak (B in Figure 4.7a) was the point of fracture and was selected as maximum force. The second peak (C in Figure 4.7a) was the final point of fracture and in this case was overestimated due to the teeth coming directly into contact with the bite force apparatus, following the fracture of the sample. The force was reduced (D in Figure 4.7a) as the panelists released their teeth from the bite force apparatus.

One panelist's force-time curve did not follow this pattern. The curve is shown in Figure 4.8. This panelist applied a constant amount of force over a relatively long period of time in order to break the samples. The bite force curve from this panelist did not show one peak force that decreased after breakage of the sample. For this panelist, as the samples became harder, a longer bite, rather than a stronger force was important for breaking the sample.

The double sharp rise and fall of the bite force curves (shown in Figure 4.7) observed in this study for the majority of the panelists has also been observed by others (Bearn, 1973). Heath and Lucas, (1988) suggest that the double hump is due to the initial fracture of food such as biscuits during the early stages of chewing. The same double peak curve does not occur when biting foods that do not fracture, such as chewing gum (Bearn, 1973).

Figure 4.7: Bite force curves for each sample

- Plots contained bite force curves collected from one panelist.
  - (a) Extruded sample with a water activity of 0.11
  - (b) Extruded sample with a water activity of 0.22
  - (c) Extruded sample with a water activity of 0.33
  - (d) Extruded sample with a water activity of 0.44
- Points in Figure 4.6(a) refer to
  - A - start of bite
  - B - initial point of fracture
  - C - point of final fracture – the large peak is due to the teeth coming together after fracture
  - D - reduction of force due to removal of teeth

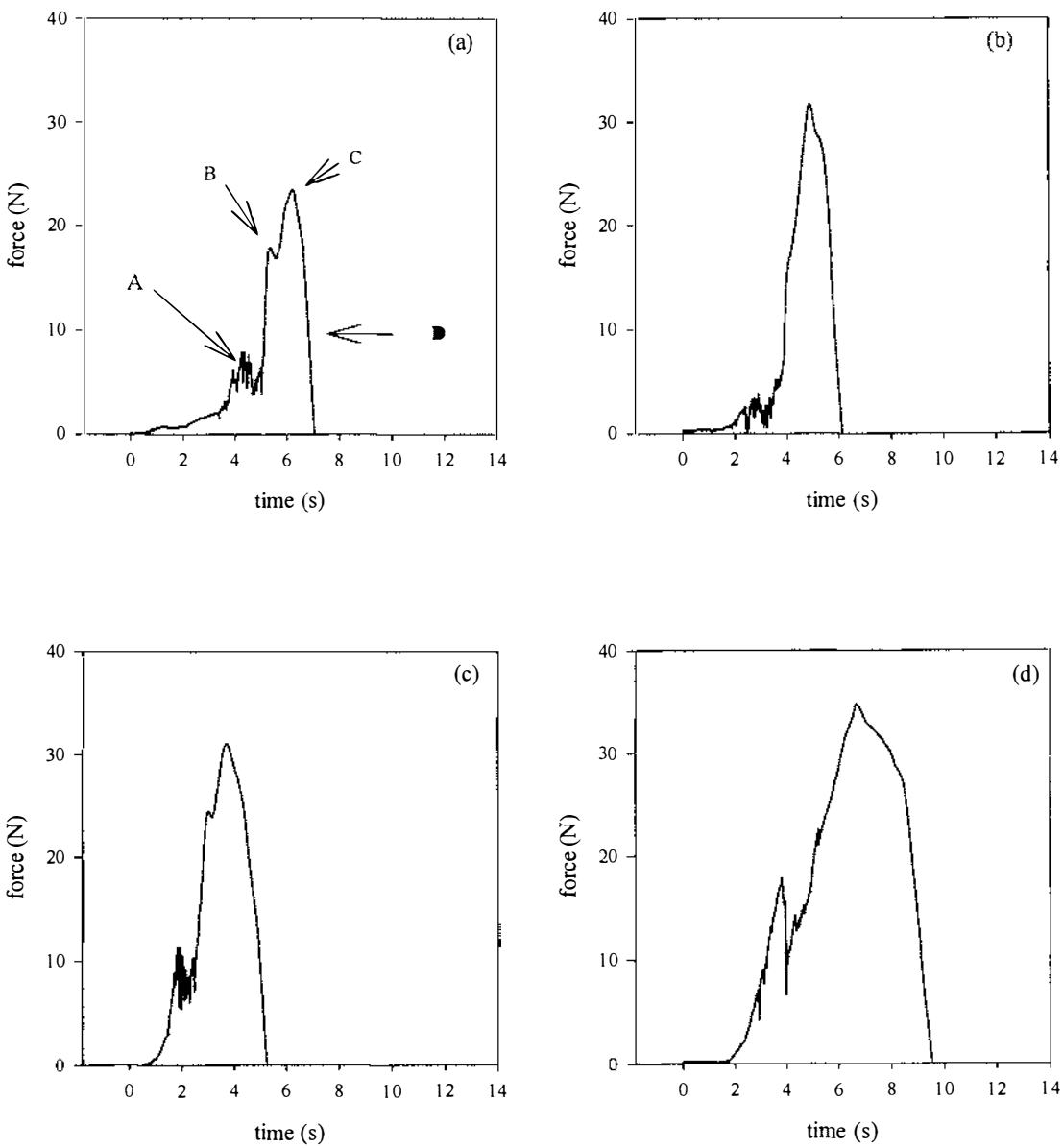
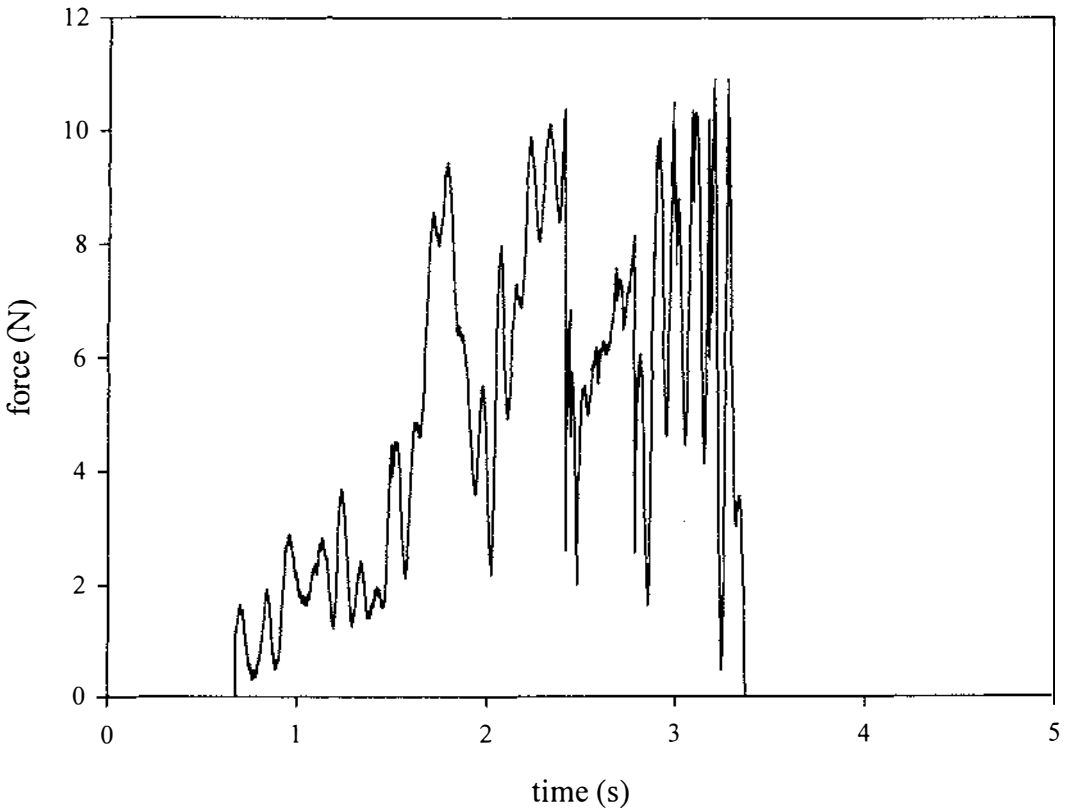


Figure 4.8: Bite force curve of panelist differing from others

- Bite force curve recorded from one panelist who displayed no maximum force and a long time to bite.
- Data in this curve is bite force data collected during biting of an extruded sample with a water activity of 0.44



4.2.6 Analysis of bite force curve parameters

Analysis of variance was conducted on the bite force parameters of maximum bite force, stress, duration of the bite and the area under the curve from all panelists. The detailed analysis is provided in Table 4.8. A summary of the mean bite force results is presented in Table 4.9.

There were significant effects of sample on the maximum bite force, area under the curve and duration of the bite (Table 4.8). The samples fall into two groupings for bite force. The two higher water activity samples (0.33 and 0.44) required a significantly stronger bite force to break the sample than the lower water activity samples. Also samples with a higher water activity required a significantly longer time to bite through than samples with lower water activity (0.11, 0.22 and 0.33). Because of the longer duration and larger bite force, the 0.44 water activity sample had a significantly larger area under the curve than the lower water activity samples (Table 4.9).

Table 4.8: ANOVA results of bite force measures

Bite force measure	df	Sum of Squares	Mean Square	F-value	Probability
Maximum bite force (N)[1]					
Sample[2]	3	89.03	29.67	20.32	<0.0001
Panelist	7	5198.25	742.60	508.63	<0.0001
Replication	3	2.84	0.94	0.65	0.57
Panelist*Sample	21	119.24	5.68	3.89	0.0001
Error	85	124.34	1.46		
Stress ($N.mm^{-2}$)[3]					
Sample	3	57.46	19.15	20.28	<0.0001
Panelist	7	3354.02	479.16	507.35	<0.0001
Replication	3	1.87	0.62	0.66	0.57
Panelist*Sample	21	76.98	3.66	3.88	<0.0001
Error	85	80.27	0.99		
Duration (s)[4]					
Sample	3	4.0	1.3	23.16	<0.0001
Panelist	7	27.3	3.9	66.43	<0.0001
Replication	3	0.4	0.1	2.57	0.0594
Panelist*Sample	21	6.6	0.3	5.43	<0.0001
Error	86	5.0	0.05		
Area under curve (N.s)[5]					
Sample	3	70.50	23.50	25	<0.0001
Panelist	7	1004.13	143.44	152.59	<0.0001
Replication	3	10.68	3.56	3.78	0.01
Panelist*Sample	21	75.70	3.46	3.82	<0.0001
Error	85	80.21	0.94		

[1] Maximum bite force was the highest peak on the bite force curve collected using the bite force apparatus.
[2]The water activity was manipulated by storing the extrudates in desiccators over solutions of lithium chloride (a_w=0.11), potassium acetate (a_w=0.22), magnesium chloride (a_w=0.33) and potassium carbonate (a_w=0.44).
[3] Stress was calculated by dividing maximum force by the area of the bite force platform.
[4] Duration was calculated as the time from the start of the bite until the force was removed.
[5] The area under the curve was calculated using the integration function in the Chart4 software.

Table 4.9: Bite force parameters of extrudates

Bite force measure	Extrudate a_w[1]			
	0.11	**0.22**	**0.33**	**0.44**
Maximum force (N)[2]				
Mean	22.5a[6,7]	22.5a	27.4b	30.4b
Std error	2.35	2.54	2.74	2.64
Stress ($N.mm^{-2}$)[3]				
Mean	7.4a	7.5a	8.5b	9.1b
Std error	1.01	1.08	0.99	0.94
Duration (s)[4]				
Mean	0.9a	1.1a	1.0a	1.5b
Std error	0.07	0.09	0.08	0.17
Area under curve (N.s)[5]				
Mean	5.8a	6.8a	7.8a	12.7b
Std error	1.07	1.66	1.17	1.96

[1]The water activity was manipulated by storing the extrudates in desiccators over solutions of lithium chloride (a_w=0.11), potassium acetate (a_w=0.22), magnesium chloride (a_w=0.33) and potassium carbonate (a_w =0.44).
[2]Maximum bite force was the highest peak on the bite force curve collected using the bite force apparatus.
[3]Stress was calculated by dividing maximum force by the area of the bite force platform.
[4]Duration was calculated as the time from the start of the bite until the force was removed.
[5] The area under the curve was calculated using the integration function in the Chart4 software.
[6]Means derived from data from 8 panelists biting 4 replicates of each sample (n=32).
[7]Means in a row followed by the same letter are not significantly different (p>0.05).

The bite force apparatus used in this study is similar to that used by others (Trulsson and Johansson, 1996b; Paphangkorakit and Osborn, 1998). This apparatus involved the use of a bite force platform to accommodate the placement of a sample. Such a system allowed for the collection of information from normally dentate individuals. However, it suffered from the disadvantage that such a setup is not typical of normal chewing

behaviour. The panelists must bite down on the sample placed on a platform until the sample breaks. This may be difficult for some individuals, as the platform acts as a barrier between the bottom teeth and the top teeth, making it difficult to ensure that the teeth have broken through the sample. However, all panelists used in the study indicated that with practice, it was not difficult to adapt to biting in such a manner.

Although direct comparisons to published bite force values are not possible due to different experimental setups and different foods tested, the bite force measurements obtained in the current study (Table 4.9) were within the range of forces noted by others. Brittle pharmaceutical tablets required 60N to 70N of force to break, measured using intra-oral miniature force transducers (Mioche and Peyron, 1995). Carrots required between 6.4N and 17.2N to break (Anderson, 1956), Swiss Rye Bread required bite forces of approximately 39N (Graf *et al.,* 1974). The mean bite force of apples was shown to be between 5.8N and 13.2N and biscuits registered a force of between 5.8N and 23.2N using strain gauges implanted within artificial dentition (Bearn, 1973).

4.2.7 Individual variability in bite force measurements

There were significant panelist effects for each of the four bite force parameters. Mean scores for each panelist for the four parameters are shown in Table 4.10. There were large differences in the bite forces amongst the panelists, ranging from 8.8N (panelist 6) up to 82.3N (panelist 7). Panelists were more consistent with the duration of the bite, with all bites taking between 0.6 seconds (panelist 8) and 2.2 seconds (panelist 6) from the start of the bite through to the removal of the teeth after breakage of the sample. However, the variation was significant.

A more thorough mathematical examination of the panelists' performance was prescribed to ascertain which bite force parameter(s) the panelists were using to differentiate amongst the samples. This was done by calculating a one-way ANOVA for each panelist, using sample as the independent variable. A summary of these ANOVA results is located in Table 4.11 and mean scores and Tukey's HSD responses of the panelists evaluating each sample are shown in Table 4.12.

Table 4.10: Mean panelist scores for bite force parameters

	Panelist							
Bite force measure	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**
Maximum force (N)[1]								
Mean	29.4c[5,6]	23.5d	50.0b	16.6e	32.3c	8.8f	82.3a	15.6e
Std Error	2.64	3.43	3.33	4.11	1.56	0.88	2.15	2.05
Stress ($N.mm^{-2}$)[2]								
Mean	7.7c	6.4d	12.9b	4.5e	8.4c	2.4f	21.3a	4.3c
Std Error	0.08	0.10	0.10	0.13	0.05	0.02	0.07	0.06
Duration (s)[3]								
Mean	0.6d	1.0cd	1.4b	0.9d	1.0cd	2.2a	1.3bc	0.6d
Std Error	0.08	0.09	0.19	0.12	0.09	0.42	0.14	0.07
Area under the curve (N.s)[4]								
Mean	6.3bc	5.4c	25.7a	3.3c	10.3b	5.4c	8.9a	3.4c
Std Error	1.47	1.17	4.60	0.98	1.37	1.76	3.13	0.58

[1]Maximum bite force was the highest peak on the bite force curve collected using the bite force apparatus.
[2]Means in a row with the same letter are not significantly different ($p>0.05$).
[3]Duration was calculated as the time from the start of the bite until the force was removed.
[4]The area under the curve was calculated using the integration function in the Chart4 software.
[5]Averaged across 4 replicates of testing (n=4).
[6]Stress was calculated by dividing maximum force by the area of the bite force platform.

Table 4.11: Panelist probability values for bite force measures

	Maximum force (N)[1,2]		Duration (s)[3]		Area under the curve (N.s)[4]	
Panelist	**F-value**	**Probability**	**F-value**	**Probability**	**F-value**	**Probability**
1	48.77	<0.0001	15.89	0.0002	47.77	<0.0001
2	3.66	0.06	12.64	0.0005	9.33	0.0018
3	3.28	0.06	6.51	0.0073	8.85	0.0023
4	11.12	0.0009	1.54	0.2560	13.22	0.0004
5	4.54	0.02	6.24	0.0085	4.92	0.0187
6	8.33	0.0036	5.74	0.0113	10.00	0.0187
7	2.16	0.17	1.15	0.38	1.06	0.42
8	0.92	0.46	1.21	0.35	1.62	0.25

[1]Each panelist bit 4 replicates of samples differing in water activities of 0.11, 0.22, 0.33 and 0.44.
[2]Maximum bite force was the highest peak on the bite force curve collected using the bite force apparatus.
[3]Duration was calculated as the time from the start of the bite until the force was removed.
[4]The area under the curve was calculated using the integration function in the Chart4 software.

Panelists could be placed into one of three groupings based on this analysis (Table 4.11). Four panelists differentiated between samples by maximum bite force and duration of the bite (panelists 1, 4, 5 and 6). Two panelists (panelists 7 and 8) failed to differentiate between any samples tested. For these two, there were no significant differences amongst the samples for any of the bite force parameters. Two panelists (panelist 2 and 3) differentiated amongst the samples based on duration of the bite. The differences amongst the samples based on area under the curve for these panelists were due solely to the differences in the length of the bite for the four samples.

The variability among individuals during mastication, as shown in Table 4.12, has been documented by others (De Boever *et al.,* 1978; Paphangkorakit and Osborn, 1998; Bourdiol and Mioche, 2000) and has been attributed to physiological and anatomical characteristics of individuals. Various factors can influence the recording of maximum bite force including gender differences, age, and dentition (Hagberg, 1987). Women exhibit a lower biting force than men when biting with molars, however when biting with incisors, identical bite forces are observed between the two sexes (Jenkins, 1978). Denture wearers exert approximately one-third of the bite forces of individuals with

Table 4.12: Inter-panelist variability in bite force measurements

Bite force parameter	Sample	Panelist 1	2	3	4	5	6	7	8
Maximum bite force (N)[1]	0.11	28.4d[5,6]	22.5a	43.1a	7.8c	30.3b	7.8bc	78.4a	10.1a
	0.22	22.5c	19.6a	51.9a	13.7bc	30.3ab	8.8c	87.2a	14.7a
	0.33	32.3b	23.5a	53.9a	19.6ab	35.3a	9.8ab	80.4a	14.7a
	0.44	36.2a	29.4a	53.9a	26.4a	34.3ab	10.7a	80.4a	19.6a
Stress ($N.mm^{-2}$)[2]	0.11	7.3c	5.9a	11.0a	2.2c	7.8b	2.2bc	21.1a	4.7a
	0.22	5.9d	5.1a	13.2a	3.7bc	7.9ab	1.9c	22.4a	3.8a
	0.33	8.3b	6.2a	13.8a	5.1ab	9.2ab	2.6ab	20.7a	3.8a
	0.44	9.3a	7.6a	13.8a	6.9a	8.8a	2.8a	20.7a	5.0a
Duration (s)[3]	0.11	0.5c	0.9b	1.23b	0.7ab	1.1ab	1.5b	1.3a	0.5a
	0.22	0.7ab	0.8b	1.46ab	1.0ab	0.9ab	2.1b	1.1a	0.6a
	0.33	0.5bc	1.0ab	1.15b	0.9b	0.8b	1.7b	1.5a	0.7a
	0.44	0.9a	1.2a	1.92a	1.0a	1.2a	3.3a	1.4a	0.7a
Area under the curve (N.s)[4]	0.11	3.9b	4.9a	15.6c	0.9ab	10.7ab	1.9b	22.5a	2.9a
	0.22	3.9b	2.9a	28.4ab	1.9b	6.8b	3.9b	29.4a	1.9a
	0.33	4.9b	4.9a	21.5bc	3.9ab	8.8ab	5.8ab	39.3a	2.9a
	0.44	10.7a	7.8a	36.2a	4.9a	12.7a	9.8a	29.4a	3.9a

[1]Maximum bite force was the highest peak on the bite force curve collected using the bite force apparatus.
[2]Stress was calculated by dividing maximum force by the area of the bite force platform.
[3]Duration was calculated as the time from the start of the bite until the force was removed.
[4]The area under the curve was calculated using the integration function in the Chart4 software.
[5]Means averaged across 4 replicates of testing (n=4).
[6]Panelist means in each column for each bite force parameter followed by the same letter are not significantly different ($p>0.05$).

normal dentition (Jenkins, 1978). With regard to age, biting forces increase with age up to adolescence and then they do not increase after this stage (Bates *et al.,* 1975). For this current study, all eight subjects were female. Thus, gender differences cannot be examined. The ages of the subjects varied between 40 and 60, indicating that age should not have been a factor in the bite force variability. The dentition of each subject was noted prior to the beginning of the study and all subjects bit into the samples using natural teeth.

Differences in bite forces could be attributable to inflammation of the tissues surrounding the teeth causing pain, a clinical dysfunction such as bruxism (teeth clenching) or perhaps due to a sensitivity of the oral tissues to pressure causing a sensation of pain during biting (Carlsson, 1974). Although none of the panelists commented on pain during biting, perhaps the fear of pain during biting (due to biting on the platform) altered their normal bite pattern. The use of intra-oral bite force transducers could alleviate this problem.

The bite force responses for panelist 7 were interesting in that they were consistently between 78N and 87N and were significantly higher than all other panelists' bite forces. ANOVA results for this panelist showed that both the bite force and the duration of bite did not differ among the four samples. Some individuals bite with forces approaching their maximum bite force and this may be the situation for panelist 7. Maximum bite forces were not recorded in this study therefore, it is not possible to confirm this belief. A review of maximum bite forces published in the literature indicates that maximum bite forces range from 88N through to 725N (Hagberg, 1987), depending on the bite force apparatus used and the dental state of the individual tested. Individuals who bite into food products with their maximum bite force undergo fatigue very rapidly during chewing of food (Möller, 1966).

4.2.8 Relationship between sensory scores and bite force measures

Mean scores from the sensory descriptive analysis and the bite force measurements were analysed by Pearson product moment correlation. The results are shown in Table 4.13.

As the samples increased in perceived sensory hardness, the amount of force and the stress required to bite through the samples also increased. Conversely, as the sensory crispness and brittleness of the samples increased, less force and stress were required to bite through the samples (Table 4.13).

No significant relationships were observed between the bite force measures of duration and area under the curve and any sensory properties.

The rheological properties of food products have an effect on the sensory cues used for the perception of hardness (Peyron and Mioche, 1994). It has been concluded that the forces developed during biting tests provide the main sensory input for hardness perception of these products. With products which are brittle in nature, hardness perception occurs when the breakage point of the sample is reached (Mioche and Peyron, 1995). The change in texture as water activity increases has been attributed to the breakage of inter-molecular bonds in the crystalline matrix of the product, where the incorporated water causes plasticization (Slade and Levine, 1991; Roos *et al.*, 1996). This plasticization causes the product to sustain a higher deformation or strain prior to breaking (Attenburrow *et al.*, 1992) causing an increase in perceived hardness and a decrease in crispness.

Although it has been stated that the forces developed during biting provide the main sensory input for hardness perception, few published papers have explored the relationship between sensory perception of hardness and physiological bite force measurements. Peyron and Mioche (1994) and Mioche and Peyron (1995) have used a form of paired comparison testing for hardness to select samples which were the most hard within a pair of samples. These were then subjected to instrumental testing in order to obtain a measure of the instrumental stress of the product to compare to physiological bite force measures. This, however, has not provided information regarding the

quantitative measure of hardness which can be obtained using a trained panel. One of the only studies that have attempted to obtain quantitative information for relating to bite measurements involved obtaining information from one individual regarding his perception of the elasticity, chewiness, resistance to initial chewing, ease of disintegration, amount of residue and juiciness of meat samples using a 3-point scale. This partially dentate individual then bit through samples of meat using dentures containing strain gauges implanted within them (Tornberg *et al.*, 1985).

The results from the current study illustrate that quantitative sensory measurements of both hardness and brittleness are strongly correlated to physiological bite force measurements.

Table 4.13: Relationship between sensory scores and bite force measures

	Sensory characteristic[1]			
Bite force measure	**Hardness**	**Crispness**	**Sound duration**	**Brittleness**
Maximum Force (N) [2]				
r-value	0.99[6]	-0.98	0.87	-0.99
Probability	0.007[7]	0.01	0.12	0.007
Stress ($N.mm^{-2}$)[3]				
r-value	0.98	-0.97	0.83	-0.98
Probability	0.01	0.02	0.16	0.01
Duration (s)[4]				
r-value	0.75	-0.73	0.68	-0.78
Probability	0.24	0.26	0.31	0.21
Area under the curve (N.s)[5]				
r-value	0.88	-0.87	0.82	-0.90
Probability	0.11	0.12	0.17	0.09

[1]Sensory characteristics were evaluated by a trained panel of 8 trained panelists biting 4 replicates of each sample.
[2]Maximum bite force was the highest peak on the bite force curve collected using the bite force apparatus.
[3]Stress was calculated by dividing maximum force by the area of the bite force platform.
[4]Duration was calculated as the time from the start of the bite until the force was removed.
[5]The area under the curve was calculated using the integration function in the Chart4 software.
[6]Correlation coefficients (r-values) were calculated from the mean scores of the 4 water activity samples (n=4).
[7]Correlations are not significant at probabilities of >0.05.

4.2.9 Instrumental assessment of force

The extruded snack samples were subjected to both compression and puncture testing using an EZ-Test texture analysis instrument. The data for the force to compress and puncture each sample were analysed by ANOVA (Table 4.14)

Table 4.14: ANOVA results for instrumental testing of extrudates

Instrumental measure	df	Sum of Squares	Mean Square	F-value	Probability
Compression force (N)[1]					
Sample[2]	3	175.52	58.50	27.74	<0.0001
Error	16	33.73	2.10		
Puncture force (N)[3]					
Sample	3	1.66	0.55	9.10	0.0009
Error	16	0.98	0.061		

[1] Compression testing was conducted using an EZ-Test machine and a 60mm diameter compression probe travelling at a speed of 8.3mm.s^{-1}.
[2]The water activity was manipulated by storing the extrudates in desiccators over solutions of lithium chloride (a_w=0.11), potassium acetate (a_w=0.22), magnesium chloride (a_w=0.33) and potassium carbonate (a_w=0.44).
[3]Puncture testing was conducted using an EZ-Test machine and a 10mm diameter puncture probe travelling at a speed of 8.3mm.s^{-1}.

The mean forces required to puncture and compress the extrudates are located in Table 4.15. Both puncture forces and compression forces were significantly higher for the samples with a higher water activity. Mean puncture forces were lower than mean compression forces for all samples evaluated.

The lower forces for breakage during puncture than for compression testing of the samples is not surprising. Puncture forces are always lower than compression forces of the sample due to the differences in the size of the probes used to break the sample (Olthoff *et al.,* 1986). In this study, the puncture probe was 2mm in diameter, which punctured a small hole into the middle of the sample during testing, producing

compression of the sample only under the probe. With puncture testing, shearing also occurs along the part of the sample touching the probe as it moves into the sample. Puncture testing does not totally destroy the sample as the probe is punching a hole into a small portion of the sample. With compression, however, irreversible damage to the sample occurs due to the size of the compression probe being used. In this study, the compression probe was 60mm in diameter, crushing a sample with a length of 22mm. Because of this larger surface area, a larger compression force was produced during testing than for the puncture test as evidenced in Table 4.15.

Table 4.15: Instrumental force measures of extruded snacks

	Extrudate a_w[1]			
Instrumental measures	**0.11**	**0.22**	**0.33**	**0.44**
Compression force (N)[2]				
Mean	14.7b[4,5]	16.6b	21.5b	38.2a
Std Error	0.58	3.33	0.98	1.86
Puncture force (N)[3]				
Mean	1.9b	1.9b	1.9b	3.9a
Std Error	0.19	0.39	0.19	0.49

[1]The water activity was manipulated by storing the extrudates in desiccators over solutions of lithium chloride (a_w=0.11), potassium acetate (a_w=0.22), magnesium chloride (a_w=0.33) and potassium carbonate (a_w=0.44).
[2]Compression testing was conducted using an EZ-Test machine and a 60mm diameter compression probe travelling at a speed of 8.3mm.s^{-1}.
[3]Puncture testing was conducted using an EZ-Test machine and a 10mm diameter puncture probe travelling at a speed of 8.3mm.s^{-1}.
[4]Averaged across 5 replicates of testing (n=5).
[5]Means in a row followed by the same letter are not significantly different (p>0.05).

4.2.10 Relationship between instrumental and bite force measures

Pearson Product Moment Correlation analysis was used to determine relationships between instrumental measurements of firmness and bite force measurements. Results are shown in Table 4.16.

As the forces to compress the sample and puncture the sample increased, the area under the bite force curve also increased. Also, the duration of the bite force increased as the compression force and puncture force increased. There were no significant relationships between either instrumental force measure and the maximum bite force and stress applied to the sample during biting.

It was assumed that a significant relationship between the instrumental forces and the bite force would be observed. Although significant at 90% probability, at 95% probability, a strong relationship does not exist amongst compression and puncture forces and maximum bite force. This study evaluated samples ranging from 0.11 to 0.44, perhaps a larger range of samples differing in hardness need to be measured. Also, perhaps a better test to have been conducted was a shear test. With shear testing, the sample is cut through with a blade, which is a movement closer to that occurring during biting with the incisors.

There was, however, a strong significant relationship between area under the bite force curve and the compression and puncture forces produced by instrumental testing. This significant relationship may be partly due to the duration of the bite, which was also significantly related to instrumental force measures. Area under the curve is an integral of the duration of the bite and the maximum force and it would follow that if either duration or maximum force were significantly related to instrumental measures then area under the curve would be as well.

Table 4.16: Correlation of instrumental and physiological force measures

Instrumental measures	Bite force curve parameters			
	Maximum Force (N)[1]	Stress(N.mm^{-2})[2]	Duration (s)[3]	Area under the curve
Compression force (N)[5]				
r-value	0.93[7]	0.92	0.96	0.98
Probability	0.06[8]	0.07	0.03	0.01
Puncture force (N)[6]				
r-value	0.91	0.91	0.97	0.98
Probability	0.08	0.08	0.02	0.01

[1]Maximum bite force was the highest peak on the bite force curve collected using the bite force apparatus.
[2]Stress was calculated by dividing maximum force by the area of the bite force platform.
[3]Duration was calculated as the time from the start of the bite until the force was removed.
[4]The area under the curve was calculated using the integration function in the Chart4 software.
[5]Compression testing was conducted using an EZ-Test machine and a 60mm diameter compression probe travelling at a speed of 8.3mm.s^{-1}.
[6]Puncture testing was conducted using an EZ-Test machine and a 10mm diameter puncture probe travelling at a speed of 8.3mm.s^{-1}.
[7]Correlation coefficients were calculated from the mean scores of four samples differing in water activities (0.11, 0.22, 0.33 and 0.44).
[8]Correlations are not significant at a probability >0.05.

4.2.11 Development of models to predict crispness based on instrumental measures

The instrumental force data were combined with the acoustic data from the panelists to develop predictive equations for crispness. Regression equations are shown in Table 4.17.

Table 4.17: Regression equations based on instrumental force

Instrumental test	Regression equation	r^2	MSE[1]
Puncture	Crispness=-17.12 + 15.28air^{**2,3} - 0.005force^{**4}	0.70	0.80
Compression	Crispness=-17.05 + 14.99air** - 5.2x10^{-4}force	0.63	0.88

[1]MSE=mean square error
[2]** p=0.01
[3] air is air-conducted sound collected from 8 panelists biting samples differing in water activity
[4] force is instrumental force collected using an EZ-Test texture testing instrument.

Similar to other equations developed (Vickers, 1987) the equations show a positive air-conducted sound and a negative force contribution to crispness. These regression equations, however, must be interpreted with care as it is based on data from four samples and four replicates of testing. This is the limit of observations which should be used in regression equations. This equation does confirm, however, that objective measures can be used to predict crispness using the methodologies developed in this research.

4.2.12 Development of models to predict crispness

There were too few data using trained panelists to mathematically calculate a meaningful regression analysis. A final trial, using 39 consumers, was designed to gather crispness data and physiological measures in order to develop regression equations to predict crispness. Two samples were chosen from the trained panel trials; extrudates with water activities of 011 and 0.44, as these were the only significantly different levels of crispness. Panelists were asked to assess crispness of these samples. They were each measured for physiological bite force and sounds, in the identical manner to the trained panelists. The resulting data were analysed in exactly the same manner as that from the trained panel.

There was a significant difference in crispness between the two samples, as see in Table 4.18. However, there were no significant differences in either air-conducted or bone-conducted sound. Maximum bite force was also the same. Only duration and area under the bite force curve showed any significant difference linked to crispness. These results were unexpected.

Table 4.18: Consumer panel measures of extruded snacks

	Extrudate a_w[1]	
Measures	**0.11**	**0.44**
Sensory crispness[2]		
Mean	6.7a[7,8]	4.5b
Std Error	0.21	0.23
Air-conducted fractal dimension[3]		
Mean	1.60a	1.59a
Std Error	0.007	0.006
Bone-conducted fractal dimension		
Mean	1.48a	1.47a
Std Error	0.006	0.005
Maximum bite force[4]		
Mean	35.3a	35.3a
Std Error	2.90	1.54
Duration (s)[5]		
Mean	0.8a	0.9b
Std Error	0.01	0.03
Area under curve ($N.s^{-1}$)[6]		
Mean	8a	10b
Std Error	0.005	0.007

[1]The water activity was manipulated by storing the extrudates in desiccators over solutions of lithium chloride (a_w=0.11) and potassium carbonate (a_w=0.44).
[2]Sensory data collected using a 10cm line scale where 0=not crisp and 10=very crisp.
[3]Fractal dimensions were determined using the software by Russ, 1994.
[4]Maximum bite force was the highest peak on the bite force curve collected using the bite force apparatus.
[5]Duration was calculated as the time from the start of the bite until the force was removed.
[6]The area under the curve was calculated using the integration function in the Chart4 software.
[7]Mean based on 39 individuals biting each sample in triplicate (n=80).
[8]Means in a row followed by the same letter are not significantly different (p>0.05)

The ANOVA table (Table 4.19) shows significant panelist effects for all measures. Because of the large degree of variability amongst panelists and the lack of significant differences between samples based on the sound and maximum bite force measurements, the data were reviewed in greater detail. First, the sensory data were examined by a one-way ANOVA to determine which panelists consistently perceived differences in crispness between the two samples evaluated. A summary of the F-values and probabilities calculated for each panelist are shown in Table 4.20.

Table 4.19: ANOVA results for consumer panel measurements

Measure	df	Sum of Squares	Mean Square	F-value	Probability
Crispness					
Sample[1]	1	257.49	257.49	66.96	<0.0001
Panelist	37	623.03	16.83	4.38	<0.0001
Error	189	726.77	3.84		
Fractal dimension of air-conducted sound[2]					
Sample	1	0.005	0.005	1.06	0.30
Panelist	34	0.42	0.01	2.50	<0.0001
Error	173	0.86	0.005		
Fractal dimension of bone-conducted sound					
Sample	1	0.002	0.002	1.50	0.22
Panelist	34	0.68	0.02	12.34	<0.0001
Error	173	0.28	0.001		
Maximum bite force (N)[3]					
Sample	1	$2.4x10^{-6}$	$2.4x10^{-6}$	1.61	0.20
Panelist	34	$4.2x10^{-8}$	$1.1x10^{-7}$	7.74	<0.0001
Error	188	$2.2x10^{-8}$	$1.5x10^{-6}$		
Duration (s)[4]					
Sample	1	0.66	0.66	12.01	0.0007
Panelist	34	13.81	0.37	6.80	<0.0001
Error	188	10.33	0.05		
Area under curve ($N.s^{-1}$)[5]					
Sample	1	$1.6x10^{-4}$	1666.5	8.67	0.0036
Panelist	34	$9.0x10^{-5}$	2447.3	12.66	<0.0001
Error	188	$3.6x10^{-4}$	193.77		

[1]The water activity was manipulated by storing the extrudates in desiccators over solutions of lithium chloride (a_w=0.11), and potassium carbonate (a_w=0.44).
[2]Fractal dimensions were determined using the software by Russ, 1994.
[3]Maximum bite force was the highest peak on the bite force curve collected using the bite force apparatus.
[4]Duration was calculated as the time from the start of the bite until the force was removed.
[5]The area under the curve was calculated using the integration function in the Chart4 software.

Table 4.20: Probabilities for each panelist evaluating crisp extrudates

Panelist	F-value	Probability	Panelist	F-value	Probability
1[1]	17.08	0.01	**21**	20.20	0.006
2	16.80	0.01	**22**	10.75	0.03
3	21.23	0.01	**23**	17.68	0.01
4	17.46	0.01	**24**	38.22	0.003
5	0.11	0.75	**25**	70.14	0.001
6	3.75	0.12	**26**	2.05	0.2251
7	0.19	0.68	**27**	0.85	0.40
8	2.98	0.15	**28**	1.66	0.26
9	0.23	0.65	**29**	3.57	0.13
10	1.22	0.33	**30**	0.19	0.68
11	0.01	0.99	**31**	0.71	0.44
12	2.67	0.17	**32**	270.75	<0.0001
13	4.40	0.10	**33**	168.92	0.002
14	12.29	0.02	**34**	7.02	0.05
15	1.43	0.29	**35**	108.99	0.0005
16	2.63	0.18	**36**	0.01	0.9148
17	0.02	0.9	**37**	0.95	0.38
18	39.96	0.003	**38**	4.19	0.11
19	0.02	0.89	**39**	0.63	0.47
20	0.10	0.76			

[1]each panelist evaluated 3 replicates of 2 samples differing in water activities of 0.11 and 0.44

Based on this analysis, two groupings of panelists were identified; those who could perceive differences in crispness and those who could not. Of the 39 panelists, 15 were able to consistently differentiate between the 0.11 and 0.44 water activity samples for crispness, while 24 could not. ANOVA was conducted on the physiological data from both groupings to look for trends in the data.

As seen in Table 4.21, the group consistently differentiating the crispness of the two samples (group 1) scored the mean crispness of the two samples over 4cm apart. This was significantly different. The other group showed no significant crispness difference between the two samples. This is an expected outcome, given the selection of the data. The physiological measures for group 1, however, were statistically the same as for group 2 as well as for all panelists combined. There was no statistical improvement, therefore, by differentiating panelists based on their ability to consistently identify crisp products.

The physiological data within group 1 (those panelists consistently discriminating between samples) were re-analysed using a one-way ANOVA by panelist. Results for each individual by crispness grouping are shown in Table 4.22.

For two panelists (panelists 14 and 24), the differences in crispness may have been influenced mainly be the sounds produced during biting. For two others (panelists 2 and 25) it may have been influenced by bite force (as shown by the significant area under the curve). The remaining panelists do not show differences between the samples based on any of the physiological measures. Interestingly, when the same analysis was completed on group 2 panelists (those that could not consistently discern crispness between the two samples), there were similar links to physiological measures. Four panelists had significant relationships with air-conducted sound to crispness (13, 15, 20 and 29). Two panelists had differences based on maximum bite force (9 and 10) and eight had differences based on area under the bite force curve (6, 9, 10, 12, 15, 26, 27 and 36) (Appendix K). Clearly, therefore, there appears to be no consistent or meaningful relationship of physiological measurements to crispness.

Table 4.21: Sensory and physiological measures for two groups of consumers

	Group 1[1]		Group 2[2]	
Measure	**0.11**	**0.44**	**0.11**	**0.44**
Crispness[3]				
Mean	7.5a	3.4b	6.1a	5.1a
Std Error	0.26	0.30	0.29	0.30
Fractal dimension of air-conducted sound[4]				
Mean	1.60a	1.59a	1.60a	1.59a
Std Error	0.01	0.01	0.01	0.01
Fractal dimension of bone-conducted sound				
Mean	1.47a	1.46a	1.48a	1.48a
Std Error	0.01	0.25	0.01	0.01
Maximum force[5]				
Mean	43.1a	37.2a	37.2a	29.4a
Std Error	6.50	2.42	2.14	2.11
Duration[6]				
Mean	0.86a	0.99b	0.77a	0.87b
Std Error	0.04	0.06	0.03	0.03
Area under the curve[7]				
Mean	9.1a	11.3b	9.4a	7.8b
Std Error	0.05	1.16	0.11	0.99

[1]n=15
[2]n=24
[3]Crispness was evaluated using a 10cm line scale where 0=not crisp and 10=very crisp.
[4]Fractal dimensions were determined using the software by Russ, 1994.
[5]Maximum bite force was the highest peak on the bite force curve collected using the bite force apparatus.
[6]Duration was calculated as the time from the start of the bite until the force was removed.
[7]The area under the curve was calculated using the integration function in the Chart4 software.

Table 4.22: The significance of physiological measures on panelists who consistently differentiate crispness (group 1)

Panelist	Air-conducted fractal dimension[1]		Bone-conducted fractal dimension[2]		Maximum bite force[3]		Area under the bite force curve[4]	
	F-value	Probability	F-value	Probability	F-value	Probability	F-value	Probability
1[5]	0.09	0.77	0.25	0.64	0.52	0.51	1.75	0.25
2	4.61	0.09	0.29	0.62	0.74	0.43	26.25	0.006
3	0.63	0.47	0.20	0.69	0.00	0.98	3.61	0.13
4	0.01	0.94	1.19	0.33	0.000	0.97	0.79	0.42
14	11.7	0.02	5.28	0.08	11.87	0.02	17.59	0.01
19	0.01	0.93	1.09	0.35	0.36	0.56	0.06	0.81
22	1.72	0.24	0.25	0.64	0.22	0.65	0.12	0.74
23	1.90	0.23	0.23	0.65	0.93	0.38	0.19	0.68
24	14.49	0.01	10.08	0.03	0.17	0.70	0.01	0.93
25	4.61	0.09	8.27	0.04	2.98	0.15	314.34	<0.0001
26	0.09	0.77	6.76	0.06	0.37	0.57	0.09	0.78
33	0.03	0.87	0.27	0.63	0.09	0.78	0.03	0.87
34	2.21	0.21	1.56	0.28	0.27	0.63	0.55	0.5
35	1.21	0.33	1.40	0.30	0.87	0.40	0.34	0.58
36	0.63	0.47	0.00	0.98	0.07	0.64	0.01	0.93

[1]Air-conducted sound was recorded using a condenser microphone. The fractal dimension of the sound waves was calculated using software by Russ, 1994.
[2]Bone-conducted sound was recorded using a contact microphone attached to the skin on the mastoid bone. The fractal dimension of the sound wave was calculated using software by Russ, 1994.
[3]Maximum bite force was the highest peak on the bite force curve collected using the bite force apparatus.
[4]The area under the curve was calculated using the integration function in the Chart4 software.
[5]Measures were made for each panelist evaluating 3 replicates of 2 samples differing in water activity.

The bite force curves for each panelist were also visually examined for obvious differences in bite force patterns. Mean bite forces for each panelist are shown in Appendix L. Although there were significant differences amongst panelists based on maximum force, duration and area under the curve, panelists were similar in their bite force patterns. The individual panelist differences as seen during the trained panel experiments were not apparent with the 39 consumers.

Clearly there were no advantages in separating panelists based on their crispness discrimination or any of the physiological measures. Despite a lack of statistical significance in some of the physiological measures, an attempt was made to produce regression models to predict crispness. As expected, the resulting regression equations (Appendix M) were meaningless and lacked any predictive ability. The squares of the regression coefficients for these equations ranged from 0 to 0.1. When regression equations were developed from the group 1 data (those who could consistently discriminate based on crispness), equally poor predictive models were obtained.

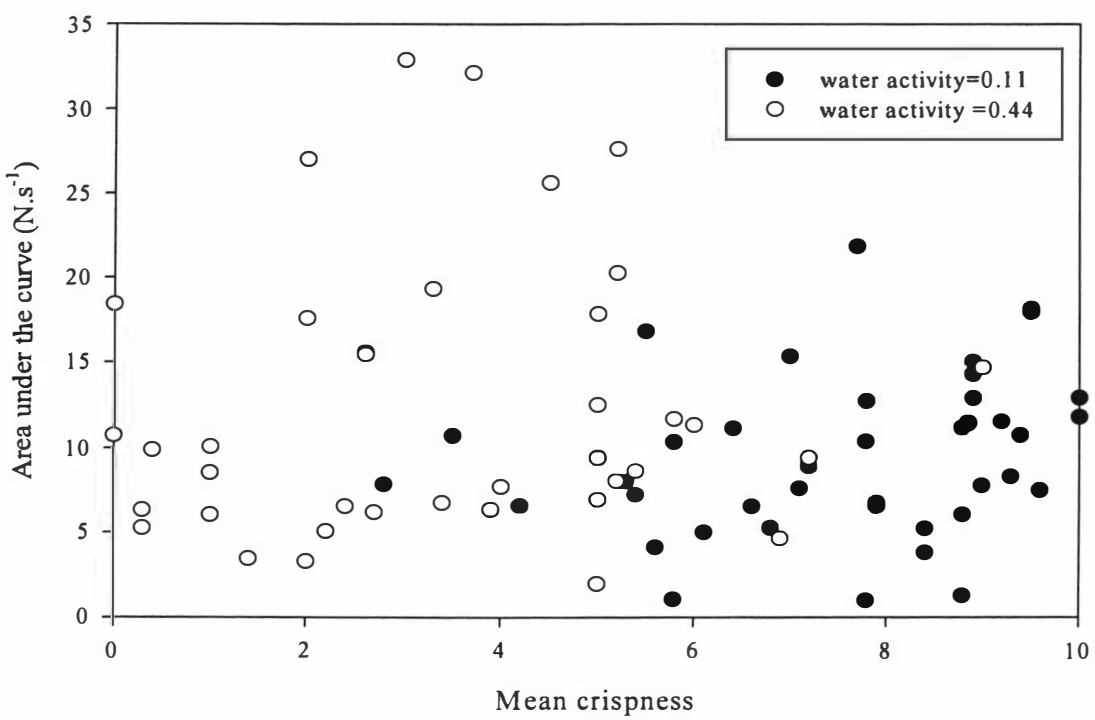
These results are different from published literature, as well as the previous experiments with trained panelists. Published literature has reported sound data collected from only up to 4 individuals (Vickers, 1987). The trained panel used in this study contained sounds from 8 individuals. In reality, such low numbers of panelists technically pose an invalid constraint on the development of regression analyses. This was the reason for doing a study with large numbers of consumers. However, when physiological measures were evaluated for a large number of individuals, there was no relationship between maximum bite force and/or sounds and crispness.

There are various reasons for a failure to achieve equations for predicting crispness including:

- Measurement techniques which are not accurate or precise
- Uncontrolled variability within the sample
- Large inter-panelist variability
- No relationship between variables tested

The measuring techniques used to collect both bite force and sound data were identical to those used for the trained panel. Similar to the methodology used for the trained panelists, the consumers were allowed as many practice bites as required when using the bite force apparatus so that they felt comfortable biting into the sample. Because of the identical apparatus and setup, it was anticipated that the results obtained from the consumers would be similar to those obtained from the trained panelists. The area under the bite force curve showed significant differences between the two samples (Table 4.18), and it was expected that this would be useful for predicting crispness. However, a plot of the area under the bite force curve and crispness (Figure 4.9) shows a great deal of variability within the data set. As expected, there was a trend for a higher crispness score at lower water activities. The spread of data across the area under the curve for the 0.11 water activity samples ranged from between $1N.s^{-1}$ and about $20N.s^{-1}$. However the range of data for the 0.44 water activity sample extended to as high as $35N.s^{-1}$, with a larger proportion of the results above $15N.s^{-1}$ (Figure 4.9). Wang and Stohler (1990) observed that as hardness increased, reproducibility of instrumental measures decreased. Perhaps a similar phenomenon is happening with the higher water activity samples in this study.

Figure 4.9: Relationship between crispness and area under the curve



This variability may have been prevented through the use of more sophisticated, intra-oral bite force transducers. These force transducers are placed in the mouth and the samples are bitten into as would occur with a normal bite (Mioche and Peyron, 1995), eliminating the invasive nature of the equipment used in the current study. This equipment, however, was not available to the researchers in New Zealand.

The inability to model crispness may also be due to uncontrolled variability within the sample. Clearly with high water activity samples, greater variability in the data was observed. Water acts as a plasticiser, causing a toughening of the cell walls of the extrudates (Harris and Peleg, 1996). It is possible that an interaction existed between the water activity of the samples and the physical structure of the sample.

Large inter-panelist variability may be obscuring these results. Variability can be expected, as individuals differ in their physiological makeup (Lawless and Heymann, 1998). It has been documented that differences in the size and shape of the oral cavity will affect bite sounds (Lee *et al.*, 1988; Lee *et al.*, 1990). Bite forces have been shown to differ between individuals as well as within individuals tested on different days (De Boever *et al.*, 1978). In this study, all testing was conducted on one day, eliminating any day to day variability which may have been present. However, bite forces may differ between individuals for psychological reasons. Mood and motivation can have an effect on recorded bite force measures (Marklund and Wennström, 1972; Paphankorakit and Osborn, 1998). It is not known if these factors had an effect on the bite force data collected in this study. The factors would need to be measured or controlled to ensure that they were not affecting recorded bite forces.

A final explanation for the lack of predictive ability may be because there is no relationship between the variables tested. The hypothesis that crispness perception is comprised of sounds and forces has only been tested using small numbers of individuals and mechanical measures of force. Only three papers have been published where regression equations have been produced for predicting crispness (Mohamed *et al.*, 1982; Vickers, 1987; Seymour and Hamann, 1988). Of these, only one has used physiological sound data (Vickers, 1987). The sounds were recorded from four individuals biting into crisp samples and the best sounds were selected for analysis. The

other papers recorded sounds produced during instrumental fracture (Mohamed *et al.*, 1982; Seymour and Hamann, 1988). In each of the three papers, no physiological bite forces were recorded. All forces were measured instrumentally. Although instrumental force and sound results have been used to develop regression equations, the cause and effect relationship between crispness and physiological bites and sounds cannot be observed. This is the first time that physiological data from a large number of panelists were collected and attempts made to relate them to crispness. Results from this study of physiological measures of crisp extrudates do not support the hypothesis that crispness is a combination of force and sounds. It is possible that there is a key variable or variables which have not yet been identified which relate to crispness. The poor predictive ability of the regression equations based on physiological data suggest that consumer perception of crispness is more complex than just combining bite forces and sound, as previous researchers have done.

More work needs to be conducted to investigate physiological measures and how they relate to crispness data collected from a large pool of individuals. It should be possible to separate individuals into groupings based on similarities in physiological responses. Individuals showing similar trends in physiological measures could then be combined to determine how each variable affects crispness perception within the group. For this, a greater number of crisp samples (more than two) would need to be tested. One method which has been used for obtaining different crispness levels has been to use a variety of crisp commercial products (Vickers, 1981; Edmister and Vickers, 1985). However, it is not possible to control the structure of the products using such a technique. In the current research, differences in crispness were achieved with products with a similar structure by modifying the water activity of the extrudates. This, however, is limited by the range of crispness that can be achieved. Within a water activity range of 0.35 to 0.5, the critical water activity of extrudates has been reached and crispness decreases to below optimum level (Katz and Labuza, 1981). In order to have a large range of samples, it becomes necessary to produce samples markedly differing in crispness using the extruder. However, to produce extrudates differing in crispness yet having a similar structure has yet to be achieved using the twin-screw extruder located in the pilot plant at Massey University. Once these different ranges of crispness can be achieved, sufficient data can be collected to be able to develop regression equations for

individuals. It will then be possible to further explore physiological measures and how they relate to crispness.

4.3 Conclusions

There were two main objectives to this research. The first was to explore the relationship between physiological measures of bite force, air-conducted and bone-conducted sounds and sensory perception of crispness using a trained panel. The following conclusions were drawn from this research:

- Crispness, brittleness and hardness were related to the physiological bite force.
- Air-conducted sound was related to crispness; however, bone-conducted sound was not.
- Physiological force was related to both instrumental compression and puncture forces.
- Regression equations predicting crispness using instrumental force measures and bite sounds were consistent with published literature. Air-conducted sounds were positively related to crispness. Instrumental force was a negative contributor to crispness.

There were too few data using trained panelists to mathematically calculate a meaningful regression analysis. Therefore a second objective was to develop regression equations to predict crispness using data collected from a larger pool of individuals. The following conclusions were drawn:

- The outcomes of the regression analysis were different than those published in literature. The predictive ability of the developed regression equations was low.
- The hypothesis that sound and force are required for crispness perception was not supported by this research. There are a number of possible reasons for this

including, variability in physiological measures, a lack of accuracy in measuring techniques, uncontrolled variability in the samples, key variables are missing or perhaps no relationship exists between crispness and the physiological measures.

CHAPTER 5 : SUMMARY OF CONCLUSIONS AND RECOMMENDATIONS

5.1 Conclusions

The overall aim of this research was to establish a relationship between sensory crispness and direct physiological measures of bite force and air-conducted and bone-conducted sounds. Although it has been proposed that force and sound are related to crispness, a direct cause and effect relationship has not been published.

The following conclusions can be made from this research:

- Fractal analysis was a useful method for characterising the jaggedness of sound waves from bite sounds of crisp extruded snacks.

- Sound wave measures collected from individuals biting samples were not related to sound wave measures from instrumental compression.

- Structure had an effect on sensory measures of crispness and hardness. Closed porosity showed a curvilinear relationship with crispness and an inverse relationship with hardness.

- Regression equations developed using instrumental force measures and air-conducted sounds were consistent with published results. Air-conducted sounds were positive contributors to crispness and force measures were negative contributors.

A bite force apparatus was designed to be able to collect bite force data. This apparatus was an intra-oral device which required individuals to bite down on samples on a metal plate. The pressure to bite through a sample was detected using a strain gauge. The strain gauge was interfaced to a computer loaded with a program which converted the data from the strain gauge into force. From the bite force data collected, the following conclusions can be drawn:

- The force data collected using the bite force apparatus was highly correlated to instrumental measures of force.

- Crisp corn based snacks differed in the amount of force and stress applied in order to bite through the crisp extruded snacks.

In order to develop regression equations with statistical validity, bite force and sound data were collected from a larger pool of individuals. These individuals also evaluated samples for crispness.

From the analysis of the data the following conclusions can be drawn:

- Regression equations developed using the data from the larger group of individuals did not show any cause and effect relationships between bite force and sounds and crispness.

- Large inter-panelist variability may be contributing to the inability to predict crispness.

- Sample variability at high water activities may also affect bite force measures.

- Consumer perception of crispness may be more complex than just bite force and sound and other variables need to be examined.

5.2 Recommendations for future work

There are various recommendations for future research which can be made. To date, all of the published literature contains crispness data collected from a small number of panelists (fewer than 10 people) leading to the hypothesis that crispness is a combination of sounds produced and the forces required during biting of crisp products. In the current research, the lack of fit of the large consumer panel results to the crispness model defined from the small sensory panel indicates that the proposed hypothesis was invalid. Crispness is a complex sensory attribute which is comprised of many individual terms. How these terms are combined by consumers when evaluating crisp products must be determined. Free Choice Profiling can be used for this. Having panelists use their own definitions during their evaluations of crisp products will show what characteristics are important for each individual when evaluating the products. After Free Choice Profiling, one-on-one interviews should be carried out to gain a better understanding of why each individual selected the terms that they used during the evaluation of the products. The terms and definitions used by consumers can then be used to obtain a better understanding of the concept of crispness.

The discrepancy in results from the two panels may be due to the suitability of the instrumentation used. The bite force apparatus designed for this study was an invasive bite fork which required panelists to bite down onto a bar in their mouths. Although results from this equipment correlated well with instrumental force measures the invasive nature of the equipment may have affected results obtained. More sophisticated tools should be used for measuring bite forces. Intra-oral force transducers placed in the mouth would remove the invasive nature of the bite fork and would allow for a more natural bite than that used in the current research.

One approach that would remove problems due to the direct instrumentation would be to "remove" each of the variables (sound and force) from the perception of crispness. Air-conducted sound could be "removed" (masked) by playing white noise through earphones placed over the panelist's ears. Bite forces could be "removed" by manually crushing the samples in the mouths of panelists. Crispness evaluated with and without

these variables would provide an indication of the relative importance of sound and force to crispness perception.

From an applied point of view, this research showed a significant interaction between water activity of extruded corn snack products and the moisture content during processing. Also storage at high water activities resulted in samples that were much lower in crispness across the three processing moisture contents. This indicates that no matter what processing conditions were used, if the shelf life conditions were not optimal then texture would be poor. This would have great implications for the snack food industry. Optimal shelf life conditions must be examined to determine the best combination of processing moisture content and storage conditions.

Fundamentally, a greater understanding of the effects of sample structure on crispness perception is yet to be achieved. This research showed that closed porosity had an effect on crispness and hardness. However, this is only one aspect of structure. It is important to understand the effects of cell wall thickness and the size of the cells on perceived texture. Microscopic analysis of cellularity should be conducted to evaluate cell wall thickness and size of the cells. This data could then be related to sensory properties to evaluate the effect of structure on the perceived textural properties of the products.

APPENDICES

Appendix A: Experimental design for extrusion project

Trial number	Moisture content	Monoglyceride	Rice Bran
1	15	0	0.5
2	16	0.5	0
3	15	0.5	0.5
4	14	0.5	1
5	15	1	0
6	13	0.5	0
7	14	0	0.5
8	15	0.5	0
9	13	0	0
10	15	0.5	1
11	16	0	0
12	16	1	1
13	13	0.5	1
14	16	0	0.5
15	14	1	1
16	13	0.5	0.5
17	15	1	0.5
18	13	1	1
19	16	1	0.5
20	14	1	0.5
21	14	0	0.5
22	13	1	0
23	14	0.5	0
24	16	0.5	0.5
25	16	0.5	1
26	14	0	1
27	13	1	0.5
28	15	1	1
29	15	0	1
30	14	0	0
31	13	0	0.5
32	15	0	0
33	13	0	1
34	16	1	0
35	14	1	0
36	16	0	1

Appendix B: Questionnaire completed by the first trained panel

Panelist_____

Date_____

SAMPLE #_____

CRISPNESS

PITCH

LOUDNESS

CRUMBLINESS

TOUGHNESS

DENSITY

Appendix C: Questionnaire completed by the second trained panel

Panelist _____

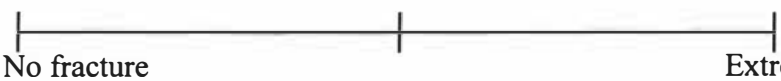
Date _____

SAMPLE:_____

CRISPNESS

LOUDNESS

FRACTURABILITY



HARDNESS

DENSITY

Appendix D: ANOVA results for TSE experiment with 0.44 water activity removed

Sensory parameter[1]	df	Sum of Squares	Mean Square	F-value	Probability
Crisp					
Moisture content[2]	2	14.16	7.08	4.44	0.01
Water activity[3]	2	40.03	20.01	12.56	0.0001
Panelist	6	166.53	27.75	17.42	0.0001
Replication	3	3.68	1.22	0.77	0.51
Moisture content * water activity	4	6.66	1.66	1.050	0.38
Error	234	372.84	1.59		
Pitch					
Moisture content[2]	2	4.02	2.01	0.7	00.49
Water activity[3]	2	31.94	15.97	5.56	0.004
Panelist	6	320.03	53.33	18.56	0.0001
Replication	3	8.42	2.80	0.98	0.40
Moisture content * water activity	4	2.59	0.64	0.23	0.92
Error	234	672.36	2.87		
Loudness					
Moisture content[2]	2	152.56	76.28	36.17	0.0001
Water activity[3]	2	57.43	28.71	13.61	0.0001
Panelist	6	192.48	32.08	15.21	0.0001
Replication	3	15.11	5.03	2.39	0.05
Moisture content * water activity	4	19.46	4.86	2.31	0.05
Error	234	493.55	2.10		
Crumbliness					
Moisture content[2]	2	4.99	2.49	1.66	0.19
Water activity[3]	2	208.73	104.36	69.47	0.0001
Panelist	6	84.78	14.13	9.41	0.0001
Replication	3	8.02	2.67	1.78	0.15
Moisture content * water activity	4	12.31	3.07	2.05	0.08
Error	234	351.55	1.50		
Toughness					
Moisture content[2]	2	109.16	54.58	36.14	0.0001
Water activity[3]	2	209.53	104.76	69.37	0.0001
Panelist	6	308.39	51.39	34.03	0.0001
Replication	3	1.35	0.45	0.30	0.82
Moisture content * water activity	4	4.37	1.09	0.72	0.57
Error	234	353.40	1.51		
Density					
Moisture content[2]	2	75.48	37.74	15.53	0.0001
Water activity[3]	2	55.55	27.77	11.43	0.0001
Panelist	6	295.80	49.30	20.29	0.0001
Replication	3	7.81	2.60	1.07	0.36
Moisture content * water activity	4	2.89	0.72	0.30	0.87
Error	234	568.49	2.42		

[1]Seven panelists evaluated 12 extrudates differing in moisture content and water activity in 4 replicates.
[2]Extrusion moisture contents of 15.6%, 17.2% and 18.9% correspond to extrudate moisture contents of 3%, 8% and 10%.
[3]The water activity was manipulated by storing the extrudates in desiccators over solutions of lithium chloride (a_w=0.11), potassium acetate (a_w=0.22), magnesium chloride (a_w=0.33) and potassium carbonate (a_w=0.44).

Appendix E: Mean sensory scores from the TSE experiment with 0.44 water activity removed

Sensory characteristics[2]		Moisture content during extrusion[1] 15.6%	17.2%	18.9%
Crispness				
	Mean	7.5ab[3,4]	7.7a	7.2b
	Std Error	0.17	0.18	0.13
Pitch				
	Mean	6.1a	5.9a	5.9a
	Std Error	0.19	0.21	0.21
Loudness				
	Mean	5.1c	6.9a	5.6b
	Std Error	0.19	0.19	0.16
Crumbliness				
	Mean	7.2a	6.9a	6.9b
	Std Error	0.16	0.19	0.17
Toughness				
	Mean	2.1c	3.7a	2.6b
	Std Error	0.17	0.19	0.21
Density				
	Mean	2.2a	3.5a	3.1a
	Std Error	0.19	0.12	0.12

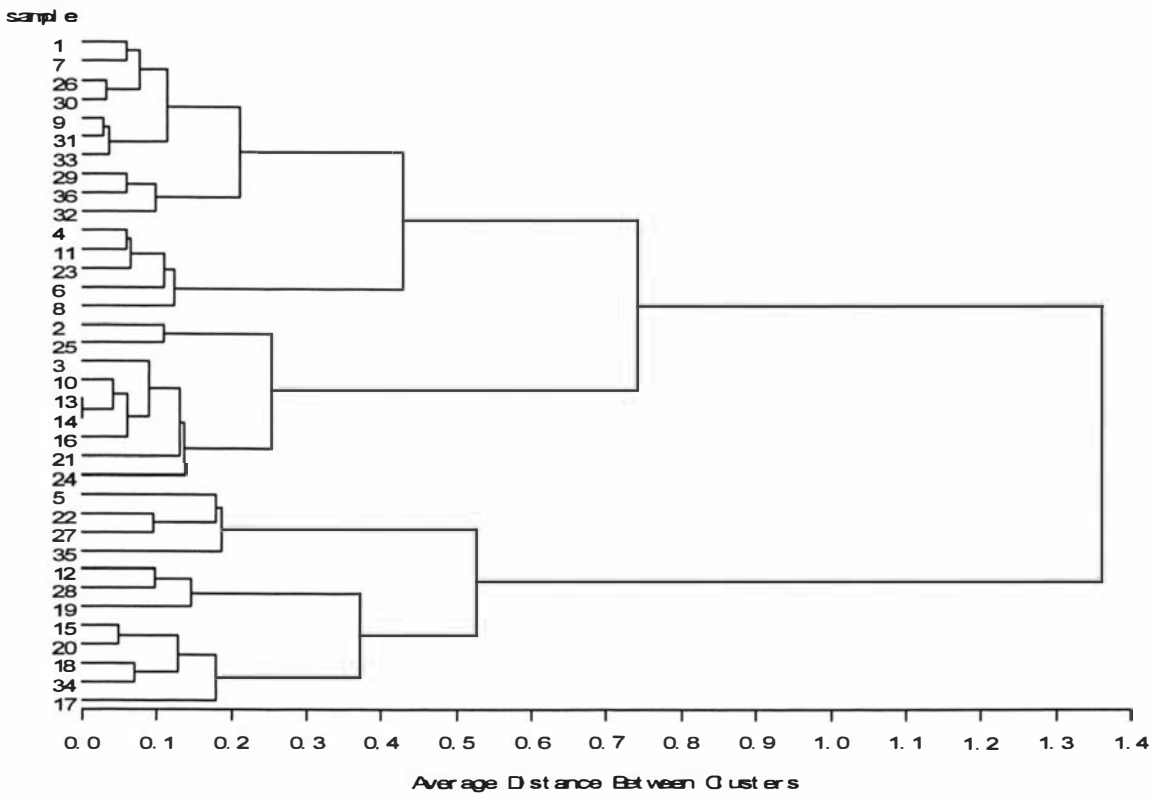
[1]Extrusion moisture contents of 15.6%, 17.2% and 18.9% correspond to extrudate moisture contents of 3%, 8% and 10%.
[2]Values range from 0 to 10, where a lower score indicates that less of the attribute was perceived by the panelists.
[3]Four extrudates at each moisture content were evaluated by 7 panelists in 4 replicates and 3 water activities (n= 84).
[4] Means in the same row with the same letter are not significantly different (p>0.05).

Appendix F: Instrumental sound wave analysis

Fractal dimension[1]	df	Sum of Squares	Mean Square	F-value	Probability
Moisture content[2]	2	0.01	0.005	1.3	0.27
Water activity[3]	3	0.06	0.02	6.01	0.002
Moisture content x Water activity	6	0.008	0.001	0.37	0.89
Error	36	0.13	0.003		
Number of peaks					
Moisture content	2	2328.81	1161.40	1.05	0.36
Water activity	3	46959.40	15653.13	14.17	<0.0001
Moisture content x Water activity	6	34506.78	5751.13	5.2	0.0007
Error	33	36463.50	1104.95		
Height of Peaks					
Moisture content	2	14927.90	7463.95	21.69	<0.0001
Water activity	3	32388.78	10796.26	31.38	<0.0001
Moisture content x Water activity	6	97946.93	16324.48	47.45	<0.0001
Error	33	11353	344		
Duration					
Moisture content	2	6.2×10^{-9}	3.1×10^{-9}	5.21	0.01
Water activity	3	1.3×10^{-10}	4.6×10^{-9}	7.73	0.0005
Moisture content x Water activity	6	8.0×10^{-9}	1.3×10^{-9}	2.24	0.06
Error	33	1.9×10^{-10}	6.0×10^{-8}		

[1]Fractal dimension calculated using software by Russ, 1994.
[2]Extrusion moisture contents of 15.6%, 17.2% and 18.9% correspond to extrudate moisture contents of 3%, 8% and 10%.
[3]The water activity was manipulated by storing the extrudates in desiccators over solutions of lithium chloride (a_w=0.11), potassium acetate (a_w=0.22), magnesium chloride (a_w=0.33) and potassium carbonate (a_w=0.44).

Appendix G: Cluster analysis tree for clustering 36 samples based on sensory properties



Appendix H: Structural measures of extruded snacks

Physical measure[1]	df	Sum of Squares	Mean Square	F-value	Probability
Apparent density ($g.cm^{-3}$)[2]					
Extrudate treatments in each cluster	6	0.78	0.13	4.15	0.03
Rep	2	0.06	0.03	0.98	0.4148
Error	8	0.25	0.03		
Particle density ($g.cm^{-3}$)[2]					
Extrudate treatments in each cluster	6	1.03	0.17	182.11	<0.0001
Rep	2	0.0001	0.00005	0.53	0.60
Error	8	0.007	0.0009		
Apparent porosity[2]					
Extrudate treatments in each cluster	6	0.36	0.06	4.05	0.03
Rep	2	0.03	0.01	1.030	0.39
Error	8	0.12	0.015		
Open porosity[2]					
Extrudate treatments in each cluster	6	0.31	0.05	2.03	0.17
Rep	2	0.04	0.02	0.8	0.48
Error	8	0.20	0.02		
Closed porosity[2]					
Extrudate treatments in each cluster	6	0.32	0.05	178.17	<0.0001
Rep	2	0.001	0.0008	2.88	0.11
Error	8	0.002	0.0003		

[1] 7 extrudates were analysed (one from each cluster outlined in Table 3.15 and 3.16)
[2]The physical measures were determined using a helium pycnometer.

Appendix I: Survey form for consumer survey of snack foods

SNACK FOOD TEXTURE

Tick the box with the word that best describes the texture of each food sample.

You can only tick one box for each sample

	Crackly	Crisp	Crunchy
Sample 604	☐	☐	☐
Sample 243	☐	☐	☐
Sample 195	☐	☐	☐
Sample 571	☐	☐	☐

Appendix J: Questionnaire completed by the third trained panel

Panelist _____

Date_____

SAMPLE:_____

CRISPNESS

Not crisp Very crisp

HARDNESS

Soft

Hard

SOUND DURATION

Short

Long

BRITTLENESS

Not brittle Very brittle

Appendix K: ANOVA results for panelists not able to discriminate based on crispness

Panelist	Air-conducted fractal dimension[1]		Bone-conducted fractal dimension[2]		Maximum bite force[3]		Area under the bite force curve[4]	
	F-value	Probability	F-value	Probability	F-value	Probability	F-value	Probability
5[5]	0.76	0.43	0.00	0.77	2.08	0.22	0.12	0.75
6	0.80	0.42	0.03	0.86	1.65	0.26	18.95	0.01
7	1.96	0.23	0.74	0.43	0.03	0.87	0.01	0.92
8	0.92	0.39	2.30	0.20	0.12	0.75	2.09	0.22
9	0.69	0.45	2.98	0.15	7.43	0.06	26.50	0.006
10	0.34	0.59	1.19	0.35	7.54	0.06	20.76	0.01
11	1.45	0.29	5.76	0.07	0.15	0.72	0.10	0.76
12	2.63	0.18	0.94	0.38	0.06	0.82	7.48	0.05
13	20.5	0.01	2.75	0.17	0.16	0.70	1.31	0.31
15	55.21	0.001	1.32	0.31	5.23	0.08	173.41	0.0002
16	0.69	0.45	2.06	0.22	0.49	0.52	0.59	0.48
17	0.00	0.99	1.51	0.30	2.56	0.20	1.47	0.31
19	0.12	0.74	0.95	0.38	0.64	0.46	0.93	0.38
20	10.49	0.03	0.00	0.95	0.00	0.99	0.17	0.7
26	5.87	0.07	9.26	0.03	0.73	0.44	7.28	0.05
27	0.55	0.49	8.54	0.04	2.47	0.19	22.79	0.008
28	5.79	0.07	0.30	0.6	1.86	0.24	2.80	0.16
29	8.81	0.04	0.49	0.52	0.08	0.79	2.84	0.16
30	0.83	0.41	1.12	0.34	0.04	0.84	0.02	0.88
31	0.05	0.83	0.19	0.68	4.13	0.11	0.76	0.43
36	0.05	0.83	0.00	0.99	2.58	0.18	8.75	0.04
37	4.32	0.10	0.44	0.54	0.00	0.99	0.02	0.90
38	0.64	0.46	0.00	0.94	1.70	0.26	0.14	0.72
39	1.33	0.31	1.43	0.29	0.41	0.55	0.12	0.74

[1]Air-conducted sound was recorded using a condenser microphone. The fractal dimension of the sound waves was calculated using software by Russ, 1994.
[2]Bone-conducted sound was recorded using a contact microphone attached to the skin on the mastoid bone. The fractal dimension of the sound wave was calculated using software by Russ, 1994.
[3]Maximum bite force was the highest peak on the bite force curve collected using the bite force apparatus.
[4]The area under the curve was calculated using the integration function in the Chart4 software.
[5]Measures were made for each panelist evaluating 3 replicates of 2 samples differing in water activity.

Appendix L: Mean bite forces for each panelist

Panelist	Maximum bite force (N)[1]		Duration (s)[2]		Area under the curve ($N.s^{-1}$)[3]	
	Mean	Std Error	Mean	Std Error	Mean	Std Error
1	42.1	3.21	1.5	0.12	20.5	2.41
2	40.2	4.01	1.2	0.22	17.6	4.42
3	48.0	5.22	0.8	0.08	10.7	1.60
4	41.1	5.60	0.8	0.04	12.7	1.65
5	8.2	0.38	0.6	0.12	4.9	0.41
6	9.8	0.68	1.1	0.0	3.9	0.45
7	36.2	6.80	0.7	0.12	6.8	1.66
8	15.6	1.60	0.7	0.04	1.0	0.28
9	32.3	3.60	0.8	0.04	7.8	1.20
10	26.4	4.01	0.9	0.2	9.8	1.65
11	11.7	1.60	0.9	0.04	2.9	0.80
12	16.6	0.41	0.5	0.16	1.9	0.32
13	57.8	0.88	1.4	0.04	33.3	3.66
14	28.4	5.22	0.5	0.2	3.9	0.84
15	13.7	1.60	0.7	0.04	2.9	0.85
16	33.3	6.82	0.7	0.04	6.8	0.11
17	16.6	3.50	0.6	0.04	3.9	1.22
18	49.0	8.02	0.7	0.02	12.7	2.45
19	53.9	8.41	0.5	0.05	10.7	1.23
20	65.7	4.01	0.7	0.06	22.5	1.67
21	53.9	8.80	0.6	0.05	9.8	2.47
22	74.5	48.20	0.6	0.12	3.9	0.88
23	22.5	2.00	0.9	0.06	5.8	1.60
24	13.5	3.21	0.8	0.02	7.8	0.86

Appendix L cont'd...

Panelist	Maximum bite force (N)[1]		Duration (s)[2]		Area under the curve ($N.s^{-1}$)[3]	
	Mean	Std Error	Mean	Std Error	Mean	Std Error
25	34.3	4.85	1.0	0.04	8.8	1.65
26	51.9	4.41	0.7	0.01	10.7	0.82
27	12.5	5.63	0.6	0.04	4.9	1.61
28	38.2	5.22	1.1	0.02	9.8	0.44
29	32.3	4.40	0.8	0.01	5.8	1.63
30	45.1	3.52	1.0	0.02	12.7	2.00
31	40.2	7.41	0.8	0.01	8.8	0.87
32	35.3	3.96	0.8	0.02	6.8	2.45
33	33.3	3.30	0.8	0.03	6.8	1.68
34	32.3	4.32	1.4	0.01	9.8	2.67
35	36.2	6.51	0.7	0.2	7.8	0.87
36	34.3	6.55	0.7	0.16	5.8	0.86
37	33.3	3.21	0.6	0.18	3.9	1.22
38	27.4	1.75	0.6	0.20	3.9	2.51
39	45.1	3.52	0.8	0.2	5.8	1.61

[1]Maximum bite force was the highest peak on the bite force curve collected using the bite force apparatus.
[2]Duration was calculated as the time from the start of the bite until the force was removed.
[3]The area under the curve was calculated using the integration function in the Chart4 software.

Appendix M: Predicting crispness using physiological measures

Equation #	Crisp (y) =	r^2 [1]	MSE[2]
[1]	$6.57 - 0.53(x2)^3$	0.004	2.70
[2]	$12.04^{**} - 4.28(x3)^4$	0.006	2.69
[3]	$5.28^{***} - 1.0.x10^{-4}(x4)^5$	0.007	2.64
[4]	$5.33^{***} + 3.6x10^{-4}(x5)^6$	0.006	2.64
[5]	$12.39^{*} - 0.23(x2) - 4.25(x3)$	0.002	2.69
[6]	$6.83 - 0.99(x2) + 1.0x10^{-4}(x4)^{*}$ [7]	0.008	2.68
[7]	$6.19 - 0.64(x2) - 6.3x10^{-4}(x5)^{*}$	0.01	2.67
[9]	$13.36 - 0.69(x2) - 4.76(x3) + 1.4x10^{-4}(x4)^{*}$	0.01	2.67
[8]	$14.85^{**} - 0.22(x2) - 6.40(x3)^{*} - 7.9x10^{-4}(x5)^{**}$	0.03	2.64

[1] r^2 is the coefficient of determination calculated from the responses collected from 39 panelists evaluating 2 samples in duplicate (n=156).
[2] MSE is mean square error calculation.
[3] x2=air-conducted fractal dimension
[4] x3=bone-conducted fractal dimension
[5] x4=maximum force
[6] x5=area under the curve
[7] * $0.01 \leq p \leq 0.05$
** $0.001 \leq p \leq 0.01$
*** $p \leq 0.001$

Appendix N: Publications

Duizer, L.M., Campanella O. and Barnes, G.R.G., (1998). Sensory, textural and acoustic characteristics of extruded snack food products. *Journal of Texture Studies*. 29, 397-411.

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

Duizer, L.M. (2003). Chapter 8: Sound input techniques in Texture in Solid Foods, D. Kilcast (Ed). Woodhead Publishing, United Kingdom

Chapter 6: Sound input techniques

L. M. Duizer, Massey University, New Zealand

6.1 Introduction

Acoustic emissions are an important aspect of food texture perception. Quality and acceptability of food products are often assessed based on the sounds produced during crushing or biting of the food. For crisp food products in particular, when the sound is not appropriate, the food may be considered unacceptable and of poor quality (Szczesniak, 1990)

Two acoustic emission techniques exist in the literature for measuring the sounds produced by manipulation of a food product. The first is destructive testing, which, as the name implies refers to the permanent deformation of the food such that it can no longer be used for further texture research. The second, in which sound is transmitted through a food product to obtain the natural resonant frequencies of the product, is predominantly used for the assessment of fruit ripeness and quality. Consumers subjectively evaluate fruit ripeness and quality by tapping products and listening to the sounds they make in order to assess their texture. This approach has led to the development of objective instrumental techniques for collecting the same information.

This chapter will focus on the destructive and non-destructive acoustic measures of food products. The equipment required for each test will be discussed and important factors to consider will be addressed. Various applications of these tests will be presented. The chapter will conclude with a brief discussion on the types of equipment most often used as well as books referenced to aid in the understanding of the contribution of sound to textural properties of foods. Key to understanding acoustic measurements is the physics of sound and the sensation of hearing. These topics will be discussed prior to explanation of the acoustic techniques.

6.2 What is sound?

Sound originates due to the vibration of a sound source moving through its surrounding medium. During eating or compressing food, the sound source is the product being crushed. During non-destructive testing, the sound source is a signal generator attached to the food being tested. The medium through which the sound wave travels is typically air, however, in the case of non-destructive testing the sound medium is the flesh and skin of the fruit which the sound is being transmitted through.

The vibrations from the sound source cause a disturbance in the surrounding medium, setting particles in motion, and thereby transporting energy through the medium. This motion is produced due to the vibration around the equilibrium of one molecule displacing others around it. This then causes a pressure wave to be produced. The pressure wave is composed of periods of rarefaction (regions of low air pressure due to decreased particle density) and compression (regions of high air pressure due to increased particle density) (Speaks, 1999). It is this pressure wave that is detected by the ear for the perception of sound and also what is detected by microphones during recording of bite sounds.

All elastic objects vibrate best at natural frequencies. A natural frequency is defined as the characteristic frequency at which an elastic structure is free to vibrate (Speaks, 1999). An object can have more than one natural frequency and this natural frequency has significant implications during both destructive and non-destructive testing. Resonance occurs when a forced frequency, such as that occurring during non-destructive testing, coincides with a natural frequency, resulting in amplification of sounds at that frequency. The resonant properties of an object are dependent on the density of the object, as well as its shape and size (Abbott et al, 1997).

6.3 The detection of sound

Within humans, sound detection occurs via two mechanisms; bone-conduction or air-conduction. Air-conducted sound is detected via the movement of sound waves throughout the auditory system. There are three sections to the auditory system; the outer ear, the middle ear and the inner ear. The auditory canal in the outer ear functions as a funnel for incoming sound waves (Stevens and Davis, 1938). At the end of the outer ear is the tympanic membrane, or eardrum. Internal to the tympanic membrane is the middle ear. This portion of the auditory system contains the ossicles which are three small bones called the malleus, incus and stapes (commonly referred to as the hammer, the anvil and the stirrups)(Kiang and Peake, 1988). The major function of the middle ear is to ensure the efficient transfer of sound from the air to the fluid in the cochlea within the inner ear (Moore, 1982). The last section of the auditory system, the inner ear, lies within the temporal bone of the skull. Located within the inner ear, is the cochlea which contains the oval and round windows, the helicotrema, the basilar membrane and the organ of corti. The cochlea is the most important part of the auditory system. It is here that the sound pressure variations are transformed into neural impulses (Rossing, 1990).

During air-conduction, sound waves enter the auditory canal and cause the tympanic membrane (eardrum) to vibrate. The ossicles transmit the vibrations through the middle ear. The movement of the foot-plate of the stapes vibrates the membranous covering of the oval window, causing pressure changes in the cochlear fluids. The inward movement of the oval window causes a flow of fluid around the helicotrema and an outward movement of the round window. This flow of fluid causes the basilar membrane to move in waves from the base of the cochlea toward the apex or end of the cochlea. The waves build slowly, increasing in amplitude as they move down the cochlea. Upon reaching maximum amplitude, the magnitude of the waves decreases abruptly.

Sounds of different frequencies produce maximum amplitude at different places along the basilar membrane. High frequency sounds produce maximum intensity displacement near the oval window with little activity further along the membrane. Low frequency sounds produce vibrations along the entire membrane, with maximum amplitude near the apex of the cochlea (Moore, 1982). Resting on the basilar membrane is the organ of corti. This organ is responsible for converting mechanical activity into neural activity. Hair cells within the organ of corti translate the wave motions of the basilar membrane into nerve impulses.

Sound waves are also transmitted to the inner ear via bone-conduction. For bone-conduction, the vibrations of the sound source do not enter the auditory system via the auditory canal. Instead they are picked up by the bones of the skull around the middle ear. These vibrations trigger the movement of the endolymphatic fluid and the basilar membrane within the inner ear similar to the movement triggered by air-conducted sounds (Stevens and Davis, 1938)

6.4 Destructive techniques for collecting acoustic information

Sound is produced due to the application of a force on the food product. The cell walls of the product snap and energy is released. It is this energy moving through the air (or other sound medium) which is detected and recorded. Destructive testing has been conducted in two ways; via recording the sounds produced by the application of a force on the product by either the teeth (during biting and chewing) or by instrumental shear or compression probes (the instrumental element).

To record the sound emission produced via destructive means an experimental setup such as that shown in Figures 8.1 and 8.2 is required. Requirements for this setup include; a means of crushing the food product (either by eating as shown in Fig. 8.1 or by crushing as shown in Fig. 8.2), a microphone interfaced with an amplifier and sometimes a filter. Attached to the amplifier and filter is a computer or other data acquisition system (such as a strip chart recorder). Data analysis software or equipment is then required to analyse the collected data. Each of these pieces of equipment will be discussed in turn.

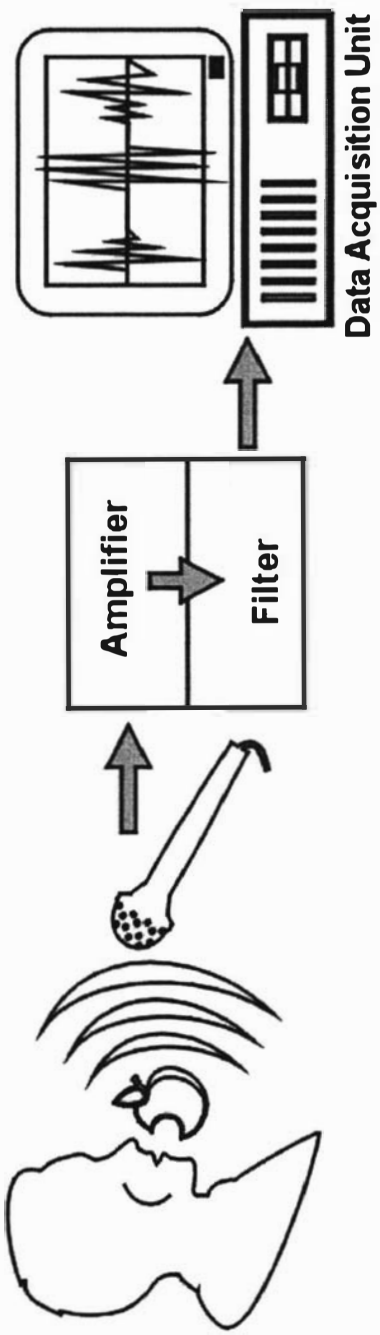


Figure 6.1 Example of acoustic apparatus used for destructive testing when biting with teeth

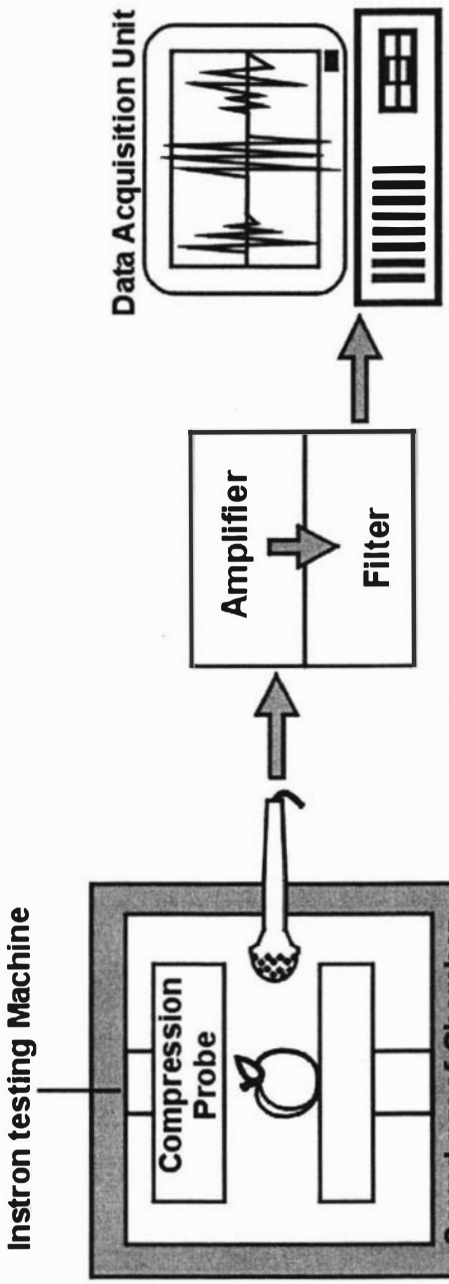


Figure 6.2 Example of acoustic apparatus used for destructive testing by instrumental compression

The microphone selected for use should be able to detect frequencies within the audible frequency range (20–20 000Hz). The microphone acts to convert the acoustic energy of the sound wave produced during crushing of the food into electrical voltage. The voltage signal is then amplified and filtered. Amplification increases the signal in order to process the information while filtering reduces noise and gives a smoother signal for processing. In some systems, preamplifiers and amplifiers are interfaced with the microphone for this purpose and the data is processed prior to storage. However, it is also possible to use a data acquisition unit where the amplification and filtering may be done automatically. One such system that can be used is the Powerlab system developed by ADInstruments Pty Ltd (Castle Hill, Australia). Others have developed their own proprietary data acquisition systems (Seymour and Hamann, 1984).

Once the signal has been amplified (and possibly filtered) the data is stored on either audio tape (Drake, 1963; Drake 1965; Kapur, 1971; Vickers, 1987; Dacremont et al, 1991; Dacremont, 1995) or as a data file on a computer (Lee et al, 1990; Duizer et al, 1998). If saved onto tape, Fourier transformation of the data takes place using fast Fourier transformation (FFT) signal analysers (Dacremont et al, 1991; Dacremont, 1995; Lee et al, 1988) or audio spectrometers (Drake, 1963; Kapur, 1971). FFT determines the important frequencies (in Hertz (Hz)) of the sound wave. If stored on a computer, the saved data can be analysed using computer programs for determining the FFT of the sound wave (Seymour and Hamann, 1984; Bouvier et al, 1997; Liu and Tan, 1999; De Belie et al, 2000). This experimental setup can be used for recording data during testing with individuals biting and chewing samples as well as during instrumental compression and puncture. However, there are factors specific for each type of testing situation which must be considered.

6.4.1 Recording of sounds produced during physical biting of samples

In order to fully record all vibrations produced during biting of foods, both air-conducted and bone-conducted sounds must be recorded. The location of the microphone for the recording of air-conducted sounds has included placement directly in front of the mouth (Drake, 1963; Lee et al 1988; Lee et al 1990) or beside the ear canal (Dacremont et al, 1991; Dacremont, 1995; De Belie et al, 2000).

The majority of research into bone-conducted sounds has used a contact microphone as the sound detector. However, Kapur (1971) first devised a system for measuring bone-conducted vibrations where a very fine stainless steel needle was inserted on the bone under the skin in three areas of the face; the forehead, the mastoid process and the lower border of the mandible (Kapur, 1971). This needle was attached to a phonograph cartridge for picking up the signals from the bony surfaces. Although this is an invasive approach to collecting the information, it was felt that a needle placed on the bone was the only means of measuring bone conducted vibrations. The vibrations were recorded onto magnetic tape and the amplitude of the vibrations plotted against frequency.

Now, bone-conducted sounds are recorded via a contact microphone attached to the skin above the facial bones of subjects. This is a much less invasive technique than the needle used by Kapur (1971). A contact microphone detects vibrations at the location to which it is attached and no airborne sounds are detected. The frequency range of a contact microphone for recording bone-conducted sounds does not have to be as broad as that for air-conducted sounds, as bone-conducted sounds are lower in frequency than air-conducted sounds (Dacremont, 1995). Sounds have been recorded from contact microphones placed on the cheek of the subject near the maxillar angle of the jaw directly in front of the ear (Dacremont et al, 1991) or attached to the mastoid bone directly behind the ear of the subject (Dacremont, 1995).

The eating technique employed during testing has an effect on recorded acoustic signals. High-frequency air conducted sounds are most prominent during biting of samples with the front teeth. The physiological tissue of the cheeks will dampen air-conducted sounds produced during chewing food with the back molars (Dacremont et al, 1995). Also, open mouth chewing results in louder sound recordings than close mouthed chewing during recording of both air-conducted sounds and bone-conducted sounds as vibration transmission through the bone

increases when biting with an open jaw (Lee et al, 1990; Hashimoto and Clark, 2001). When recording bone-conducted sounds, care must be taken to ensure that only the bite sounds are being recorded. When the teeth come into contact with each other during biting, an increase in the recorded sound amplitude has been noted (Hashimoto and Clark, 2001). It is important when evaluating physiological acoustic responses that the placement of the microphone and the eating technique (bite vs chew, open vs closed mouth) be carefully considered for correlating acoustic results with sensory measures.

When analysing bone-conducted sounds, it is important to note that the acoustic properties of this sound may be altered due to the resonant frequency of the mandible. Kapur (1971) showed that the jaw resonates at 160 Hz meaning that recordings at this frequency may be louder than what is actually heard during chewing. This has been further supported by Dacremont et al (1991) who noted that when bone and air-conducted sound recordings are combined to match what is heard by an individual during chewing, the bone-conducted sounds are attenuated at 160 Hz.

6.4.2 Recording of acoustics produced during mechanical testing

One of the stated advantages of recording an acoustic signature by mechanical testing is the reproducibility and consistency of mechanical tests (Mohamed et al, 1982; van Hecke et al, 1998). However, it is important that the instrumental test selected simulates the conditions to which a food is subjected during chewing (Mohamed et al, 1982). Factors such as the type of probe used and the speed of the cross head during testing must be carefully considered to ensure that the instrument adequately mimics the sensation occurring in the mouth during chewing.
Various instruments and probes have been used for the production of acoustic signatures via mechanical crushing. These have included the Instron Universal Testing Machine with a compression probe (Roudaut et al, 1998) or a Kramer shear cell (Seymour and Hamann, 1988), the Steven's testing machine with a compression probe (Tesch et al, 1995) as well as other proprietary instruments (Mohamed et al , 1982; Al Chakra et al, 1996; Liu and Tan, 1999). Researchers have argued that mechanical tests such as puncture and compression are similar to tooth impact and molar action during mastication (Liu and Tan, 1999; Van Hecke et al, 1998). However, more recent debates point out that there is a difference between strain that occurs during chewing compared to that possible in instrumental tests (van Vliet, 2002).

In order to remove extraneous noise from the collected signature during testing, the samples and the probe should be placed in an insulated chamber, as shown in Figure 8.2 (Mohamed et al, 1982; Seymour and Hamann, 1988; Tesch et al, 1995; Roudaut et al, 1998). This prevents the noise of the machine from interfering with the acoustic signal of the sample. This noise appears to originate from the electronic drive control as well as the toothed belts and drive mechanism required to move the probe into the sample. Additionally, background noise present in the room can be eliminated by using the insulated chamber.

In order to ensure that instrumental acoustic recordings are similar to the acoustics produced during biting, a similar rate of fracture should occur. Sharp cracking sounds occur due to the high energy sound waves produced when a material fractures rapidly and is broken (Bruns and Bourne, 1975). On average, a human compression rate is 20 $mm.s^{-1}$ (Bourne, 1982), whereas instrumental compression varies between 0.3 $mm.s^{-1}$ (Roudaut et al, 1998) to 3.33 $mm.s^{-1}$ (Seymour and Hamann, 1988) depending on the instrument used. When allowing the sample to break at its own rate, Mohamed et al (1982) observed that a Malteser fractured at a rate of 83.3 $mm.s^{-1}$. The fracture rates may have an impact on the resulting acoustic properties of the sample and care should be taken to ensure that consistency in the rate of compression or shear occurs.

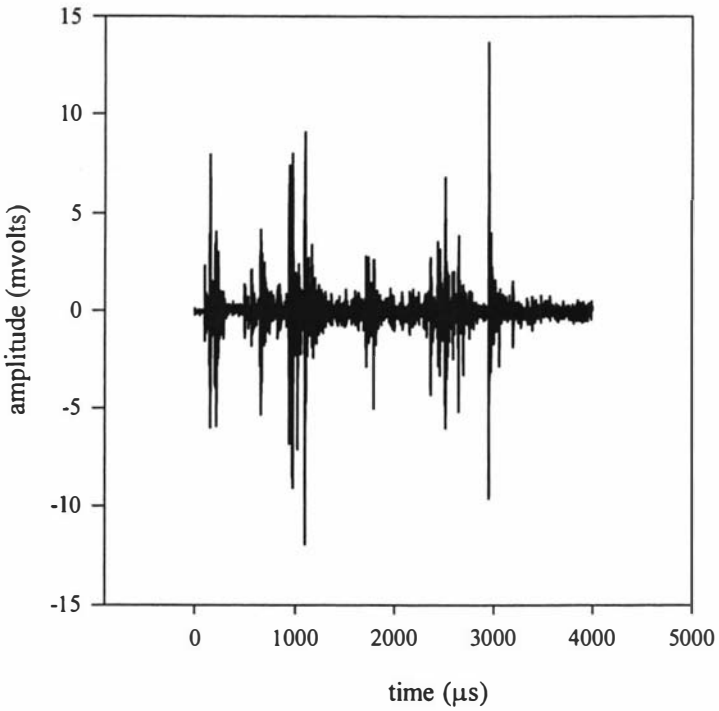
6.4.3 Analysis of sound waves produced during destructive testing

The sound wave recorded during destructive testing is presented as a plot of amplitude versus time. An example of an amplitude-time plot of sounds produced during biting of an extruded snack product stored at water activities of 0.11 and 0.44 is shown in Figure 8.3. The sound

wave from the 0.11 water activity sample represents the sounds made when biting a crisp product and the sound wave from the 0.44 water activity sample represents the sound made when biting a less crisp product. There are visual differences apparent between the two curves. The crisp product in Figure 8.3(a) has more peaks as well as having peaks of a higher amplitude than the less crisp product in Figure 8.3(b).

Figure 6.3 Sound waves produced while biting extruded corn based samples stored at water activities of (a) 0.11 and (b) 0.44

(a)



(b)

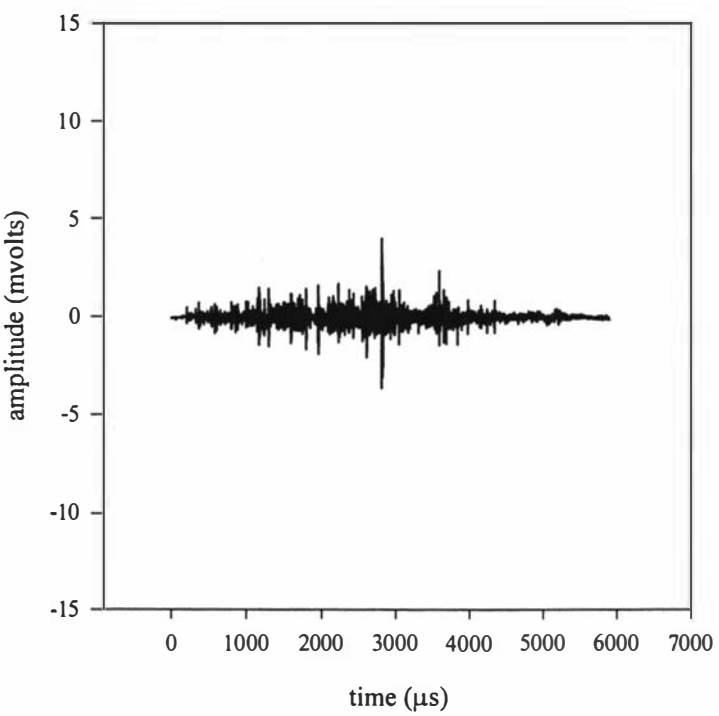
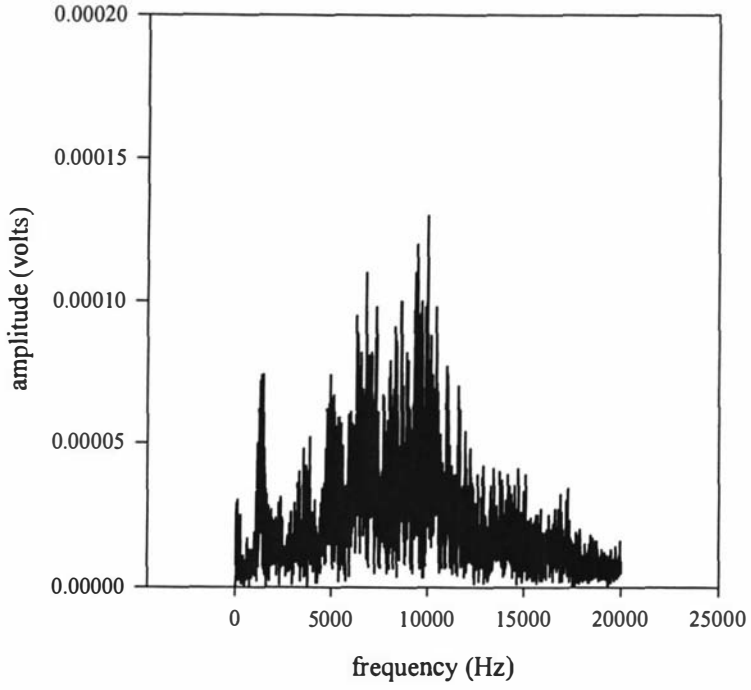
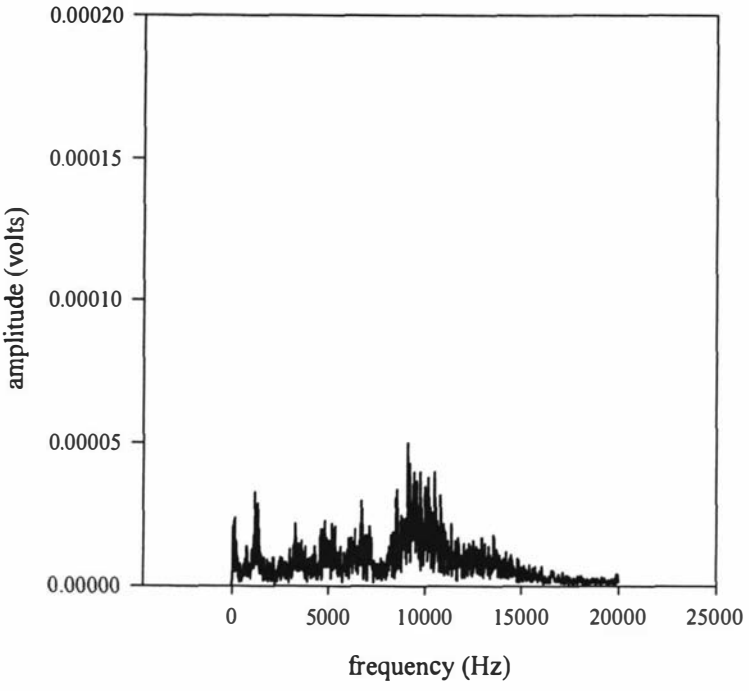


Figure 6.4 Power spectrum analysis of sound waves produced while biting extruded corn based samples stored at water activities of (a) 0.11 and (b) 0.44

(a)



(b)



Many different properties of sound waves have been measured and correlated with sensory properties and a list of these acoustic parameters published in food literature is shown in Table 8.1. The amplitude of the sound wave refers to the amount of energy the sound source produces. A high amount of energy is reflected in a high amplitude wave and a low amount of energy is reflected in a low amplitude wave. The amount of energy transported across a given area per unit of time is known as the sound intensity (measured in decibels or dB) (Speaks, 1999). This measure, and its related measure, sound pressure level (also measured in dB) are related to the perceived loudness of the sound, a more subjective measure than the measured sound intensity and sound pressure (Rossing, 1990). There is a great deal of variability between individuals in terms of how loud a sound is perceived. In general, for one individual, the more intense the sound, the louder it is perceived. This will vary between individuals due to differences in ability to detect sounds because of age as well as other physiological variables inherent to a person. Additionally, different frequencies of sounds are perceived to be louder or softer than other frequencies (Rossing, 1990).

The amplitude-time plot of sounds collected during destructive testing has been described as a jagged curve (Vickers and Bourne, 1976). And in fact, some of the measures of the amplitude-time curve can be used to characterize the jaggedness of the curve (such as number of peaks, and mean height of the peaks). A technique which can characterise the jaggedness of peaks, and has recently been applied to food research, is fractal analysis (Barrett et al, 1992; Barrett et al, 1994; Duizer et al, 1998). Fractal analysis has been defined as a quantitative technique for assessing the overall ruggedness or jaggedness of irregular objects (Barrett et al, 1992). Briefly, fractal analysis involves the use of mathematical algorithms to determine the degree of jaggedness of a line in order to give a fractal dimension of the line. An area around the line is measured and through various iterations of the algorithm, the space occupied by the line within that area is determined. This space is plotted against the measured area and the slope of the linear relationship is determined. The resulting number is the fractal dimension. The fractal dimension of a jagged line can range from one, which is a smooth line, to two, which occurs when the line is so jagged that it occupies the entire area being measured by the algorithm.

Although there are many different algorithms which can be used for fractal analysis, the algorithm most often used for acoustic research is the Kolmogorov algorithm. This algorithm is a box counting technique that involves dividing the signature into a grid and counting the number of squares which contain a part of the object. The size of the boxes of the grid is halved and again the occupied squares are counted. This process continues for numerous iterations. The size of the boxes cannot be smaller than the resolution of the object (Russ, 1994). The slope of a log: log plot of the number of filled boxes versus the size of the box gives the Kolmogorov fractal dimension.

Table 6.1: Acoustic parameters used to define crisp products

Author	Parameter	
Drake (1965)	Mean frequency Bite time Sound level at 1200 c/s	
Mohamed et al (1982)	Equivalent continuous sound level (Leq)	
Edmister and Vickers (1985); Vickers (1987)	Mean height of the peaks (mhp) Duration of sound Number of peaks (NP)	
Seymour and Hamann (1988)	Mean sound pressure (N/m2)	Averaged over frequency ranges of: 0.5-3.3
	Mean sound pressure level (dB)	Averaged over frequency ranges of: 0.5-3.3
	Acoustic intensity (watts/m2)	Sum over frequency ranges of: 0.5-3.3
Lee et al (1998, 1990)	Amplitude	
Dacremont (1995)	Frequencies	
Duizer et al (1997)	Fractal analysis	

For an object to be truly fractal, it must be self-similar. This means that any part of the object cannot be distinguished from the whole object or another part of the object (i.e., it has the same scaling factor in all directions). In the case of an acoustic signature, it is not possible to achieve self-similarity due to restrictions in sampling rate. Despite this, Barrett et al (1992) and Tesch et al (1995) concluded that it was possible to use fractal analysis as an objective measure of the degree of jaggedness of acoustic signatures. In this instance, the fractal dimension must be termed 'apparent' rather than 'true'

Frequency is an integral part of an acoustic signature. The frequency of the vibratory motion of the sound wave is the rate at which the particles in the medium vibrate as the wave moves through the surrounding medium. It is measured in Hertz (Hz) where one hertz equals one vibration per second (Speaks, 1999). The particles within the sound medium vibrate at the same frequency at which the sound source vibrates. The objective frequency measurement of a sound corresponds with the subjective measure of pitch (Rossing, 1990). A high frequency sound source is perceived to have higher pitch than a low frequency sound source.

The frequency of the sound is determined using fast Fourier analysis (FFT). During Fourier analysis, the original data points are transformed into underlying frequencies. These frequencies are then plotted as amplitude versus frequency. From the plot, it is possible to identify special or important frequencies as these are characterised by higher amplitude on the plot. FFT plots of the sound waves shown in Figure 8.3 are shown in Figure 8.4. The sample stored at a water activity of 0.11 which is a more crisp sample shows more high frequency peaks (Figure 8.4(a)) than the sample stored at a water activity of 0.44, a less crisp sample (Figure 8.4(b)).

The frequencies of sound have been used to compare to various textural properties in order to obtain a better understanding of how the characteristics are perceived (Mohamed et al, 1982; Dacremont, 1995).

6.5 The transmission of sound via non-destructive testing

Non-destructive sonic transmission tests measure the dynamic resonant behaviour in the audio-frequency range of the products. This is based on the principle of resonance, where the object vibrates vigorously at a particular frequency. For each resonant frequency there is one (and sometimes more than one) vibration mode. This mode and the frequency can provide information regarding the mechanical properties of the food.

In the sonic transmission test developed by Abbott et al (1968) the signal generator produces a pulse signal of uniform amplitude over a variety of consecutive frequency ranges. This is interfaced with an acoustic driver which imparts vibrational energy through the fruit, supported on a pedestal. An accelerometer attached on the opposite side of the fruit detects the vibrations which are converted to a signal and analysed via FFT. Due to the time consuming nature of the test, the acoustic impulse technique has been developed (Yamamoto et al, 1980). In the experimental setup for the acoustic impulse technique, a microphone replaces the accelerometer. The microphone does not require attachment to the fruit, thereby eliminating the effect of detector placement on resonant frequencies. Additionally, in place of a signal generator, a ball pendulum is swung into the fruit at an equatorial location, thereby producing the sounds which are picked up by the microphone and analysed for resonant frequencies. Recently, a number of commercial bench top machines for non-destructive testing of fruit (such as the Acoustic Firmness Sensor™ by Aweta BV, The Netherlands) have been produced and high speed machines for grading of fruit on packing lines are imminent.

The test location around the fruit and the holding position of the fruit does not have an effect on the resonance frequencies but does affect their amplitude (Chen et al, 1992). Additionally, the hitting strength and location of the microphone do not have an effect on the peak frequency recorded during testing (Yamamoto et al, 1980). Fruit shape will have an effect on resonance and it has been recommended that three measurements be recorded and averaged in order to reduce the error due to variance in fruit shape (Chen and Baerdemaeker, 1993).

6.5.1 Analysis of data collected during non-destructive testing

The resonant frequencies resulting from the sound input signal have been used to calculate a stiffness factor of the fruit (equation 8.1). Abbott et al (1968) found the second resonant frequency to be related to changes in the apple texture. This frequency was found to be the most reproducible, being less affected by the position of the driver and pickup than the other natural frequencies. The inclusion of mass in this stiffness coefficient equation compensates for the effect of the size of the apple on the resonant frequencies recorded.

[equation 8.1]

$$S = f^2 m$$

Where f^2 is the second frequency squared and m is the mass of the sample in grams.

Others (Cooke and Rand, 1973) have modified this equation to that shown in equation 8.2. However, Abbott et al (1997) indicate that this stiffness coefficient equation is designed for fruit with a large variation in sizes and may not provide any more useful results for fruit with small variations in size than the original equation.

[equation 8.2]

$S=f^2m^{⅔}$

Where f^2 is the second frequency squared and m is the mass of the sample in grams.

6.6 Application of sound measurement techniques

Both destructive and non-destructive acoustic results have been applied to various food products in order to gain an understanding of the texture and quality of these products. In particular, destructive testing has provided key information regarding the perception of various textures of food while non-destructive testing has allowed for the determination of stiffness, leading to the evaluation of fruit quality.

6.6.1 The use of acoustics for understanding crispness

The fact that crushing sounds might have an effect on the perception of texture was first suggested by Drake (1963). He proposed that when correlated to sensory data, vibrations produced during compression of foods could be helpful in the area of texture research. In 1976, Vickers and Bourne first published a psychoacoustical theory of crispness that led to numerous research publications exploring the use of acoustics and their relationship to the perception of crispness, crunchiness and crackliness of food products. All of the tests conducted have resulted in non-recoverable damage to the tested food samples.

Structurally, crisp foods have a tendency to be cellular (Brennan et al, 1974). When a force is applied to such a cellular product, each cell ruptures, creating a sound and the overall rupture pattern produces an irregular frequency and amplitude signature (Vickers and Bourne, 1976; Vickers and Christensen, 1980; Vickers, 1981; Vickers, 1987). Crisp food products can be classified into two general categories based on their structure; wet crisp (those which have water in their cells such as carrots, apples, water chestnuts and cabbage) and dry crisp (those which contain air within their cells such as toast, biscuits, extruded products and potato chips). The sound pattern generated by foods in these product categories is similar, and can be best characterised by the loudness of the sound and the number of sound occurrences. This is shown by the significant correlations between crispness and the log (number of peaks x mean height of the peaks) for wet and dry crisp products ($r=0.89$ for wet and dry together, $r=0.95$ for wet alone and $r=0.88$ for dry alone (Edmister and Vickers, 1985).

Acoustics have been applied much more for understanding the textural properties of dry crisp products than wet crisp products and the majority of published literature has been in the area of crispness perception of dry snack foods such as potato chips or extrusions (Mohamed et al, 1982; Vickers, 1987; Seymour and Hamann, 1988; Duizer et al, 1998). One reason for this is

that dry crisp products have a texture which is easy to manipulate, usually through modifying the water activity, while keeping the structural properties of the samples constant.

Mohamed et al (1982) suggested that crispness of potato chips could be understood through combining acoustical results with force-deformation results. Various instrumental parameters have been applied to regression equations in order to test this theory. These instrumental parameters include the ratio of work done during fracture to total work (Mohamed et al, 1982), the total work to fracture (Seymour and Hamann, 1988) and peak force (Vickers, 1987). The regression equations developed by these authors, and the products studied are shown in Table 8.2.

Each of the three regression equations shown in Table 8.2 have strong predictive ability, with r^2 values of greater that 0.85, indicating that a measure of force as well as the acoustic element is important for prediction of crispness. The negative relationship between crispness and peak force indicates that the hardness or toughness of the potato chip samples studied must counteract the auditory sensation of crispness, leading to the belief that crispness must have a vibratory component and a non-vibratory component and the non-vibratory component is counteracting crispness (Vickers, 1987).

Table 6.2: Regression equations used for predicting crispness of dry crisp products

Author	Foods tested	Regression equation	r^2 value
Mohamed et al (1982)	Sponge fingers, wafer biscuits, crisbakes, ice cream wafers, Maltesers varying in water activity	Log Crispness=0.59+0.49log (L_{eq})+0.50(W_F/W_T)	r^2=0.85
Vickers (1987)	Potato chips	Oral crispness = -15.6 +5.35(np) + 133(mhp) – 6.21(peak force)	r^2=0.98
Seymour and Hamann (1988)	Pringles potato chips	Crispness=9.904-0.134(work)+0.025(mean sound pressure 2.6-3.3kHz)	r^2 =0.95
	Crunch twists:	Crispness=16.47-0.064(force)-0.110(sound pressure level 0.5-1.2kHz)	r^2 =0.95

Note: L_{eq} is continuous sound level; W_F/W_T is the ratio of work done during fracture to total work; np is number of peaks and mhp is mean height of peaks

6.6.2 The use of acoustics to differentiate between crispness, crunchiness and crackliness

In addition to developing an understanding of the sensation of crispness, acoustic techniques have been used to differentiate between the sensation of crispness and those of crunchiness and crackliness. Crunchiness has been shown to be strongly related to crispness (Vickers and Wasserman, 1979; Vickers, 1981) and various definitions indicate their close association. Recently, Fillion and Kilcast (2002) proposed that the crispness of fruit and vegetables can be defined as 'a light and thin texture producing a sharp clean break with a high-pitch sound when a force is applied'. Crunchiness was associated with products with hard, dense textures producing a repeated loud, low-pitched sound (Fillion and Kilcast, 2002). During sensory evaluation of apples, crispness has been defined as 'the amount and pitch of sound generated when the sample is first bitten with the front teeth' and crunchiness as 'the amount of sound generated when chewing with the back teeth' (Harker et al, 1997). Vincent et al (2002) differentiated between crispness and crunchiness based on the amount of force applied to the samples, with crisp products fracturing after the application of a lower force than that required for crunchy products. Certainly, there appears to be an association between the two textures.

To differentiate between crispness and crunchiness, Vickers (1984a) asked judges to bite various crisp and crunchy foods and to indicate whether they were crisp or crunchy and then in a separate experiment, to indicate which sample in a pair of crisp-crunchy samples was higher in pitch during biting. Foods which were classified as more crisp than crunchy nearly always produced a higher pitched sound than those which were classified as more crunchy than crisp. This was later confirmed by Dacremont (1995) who, through FFT of acoustic data produced during biting of food products, determined the actual frequencies of the sounds produced. Amongst the food products tested were extruded flat breads (crisp), carrot (crunchy) and dry biscuits (crackly). Crisp foods generated high pitched frequencies (between 5–12.8 kHz) and these sounds were predominantly air-conducted. In contrast, crunchy foods produce low frequency sounds when bitten, with frequencies within the frequency range of 1.25–2 kHz (Dacremont, 1995).

Crackliness is not a texture term found frequently in sensory evaluation literature. Vickers (1984b) stated that a crackly product could be characterized by the number of sharp repeated noises produced when a food is bitten and chewed. This could be judged using either oral tactile or auditory cues. Dacremont (1995) showed that crackly food products produce a great deal of low frequency sounds, similar to crunchiness and can be differentiated from crunchiness because of the high level of bone-conducted sounds generated during biting.

6.6.3 The use of acoustics for the determination of fruit quality

Both destructive testing and non-destructive acoustic testing has been used to determine the textural properties of fruit, predominantly firmness and crispness. Both of these properties have been related to the quality and ripeness of the fruit. For apples, texture is an important characteristic that directly influences consumer preferences for crisp, juicy fruit (Liu and King, 1978). However, for many other fruits changes in hardness are used to follow the ripening process. As the fruit ripens, it becomes softer, starch converts to sugars, acidity is lost and flavour develops. In these cases, consumers tend to have distinct preferences for softer and riper fruit (Jaeger et al, 2003). The different consumer needs from apples (crisp and hard texture) and other fruit (ripe and flavourful) explain the different research approaches. In apples, both destructive and non-destructive approaches have been used to investigate the properties of fruit. However, for most other fruit, the focus has been on the use of non-destructive measurements to monitor the softening/ripening process. There has been a concentration of this type of research in fruit but not in manufactured foods due to the fact that fruit are subject to high levels of biological variability (Dever et al, 1995). Therefore, there is commercial interest in methods that can sort for products that are more homogenous in quality. Manufactured foods do not face this high level of product variability.

Using destructive acoustic techniques, a method for classifying apples based on crispness has been suggested (De Belie et al, 2000). Cox's orange pippin apples were stored under various conditions to modify the texture. The apples were grouped into mealy and crisp categories and

the sounds produced during biting were recorded. Crisp apples produced sounds which were higher in frequency than mealy apples. Through the use of principle components analysis of the analysed frequencies, the two groups of fruit could be separated based on frequencies, indicating that acoustics can be useful for the determination of fruit texture and therefore quality. The authors stated that with more extensive experiments, including sensory panels, the acoustic technique could be used to develop a method for objective crispness evaluation of apples, removing the necessity for trained sensory panels for the determination of crispness of apples. Others, however, have concluded that chewing sounds were no better than other instrumental tests (in particular, puncture testing) for measuring apple texture (Harker et al, 2002).

The stiffness coefficient calculated from results of the non-destructive acoustic tests has been related to firmness and ripeness measurements of fruit. The relationship between the stiffness coefficient and sensory firmness/ripeness has been determined for Starking Delicious apples (r=0.66) (Yamamoto et al, 1980), Golden Delicious apples (r=0.6) (Abbott et al, 1992), Red Delicious apples immediately after picking (r=0.84) (Finney, 1971a). Although different sensory scales have been used for the sensory portion of the research, each of these tests showed a strong relationship between the stiffness coefficient and sensory scores. Acceptability has also been related to the stiffness coefficient. Van Woensel et al (1987) showed that the acceptability of Golden Delicious apples could be related to the stiffness coefficient, stating that it was important to find a relationship between the stiffness coefficient and the acceptability of the fruit for the consumer.

While apples are a relevant subject to review in terms of methodologies for measuring crispness, other fruit are perhaps not so relevant. Research on measuring firmness as a method to follow ripening has involved kiwifruit (McGlone and Shaane, 1993), avocado (Peleg et al, 1990) and stonefruit (Finney, 1971b; Landahl et al, 2000). Furthermore, a number of studies have compared the ability of non-destructive acoustic testing to grade for quality with that of trained inspectors used to assess fruit against official standards for tomatoes (Schotte et al, 1999) and apples (Abbott et al, 1992). Schotte et al (1999) found that graders from different fruit auction houses showed a large amount of variability in the use of the scale. All results had to be rescaled prior to comparison with the stiffness data. The stiffness score was related to tomato firmness (r^2=0.79) and the authors felt that it was a more objective technique than grading and could be used without requiring a rescaling of data.

6.7 Future trends

The area of acoustic research shows a promising future. Crispness perception has been studied from a mechanical and acoustical perspective and the contribution of the acoustic properties to the perceived crispness has largely been addressed. Now the focus can shift to the relationship between the structure and how it affects the acoustic properties of the products and therefore the perceived crispness of the product. Acoustics will play a large role in furthering the understanding of crispness and how manipulating various structural properties of the food product can alter the acoustic properties of the product and therefore its perceived crispness.

Additionally, the use of acoustics during processing is an emerging trend. One area where this is receiving attention is in the acoustic emissions produced during extrusion of food products (Francis et al, 1998). The motor output of an extruder produces certain sounds when extruding samples. The output changes as the texture of the product changes. This is due to the amount of work that the extruder must do in order to produce the samples. An experienced extruder operator can tell by listening to the machine if it is making the correct noises during production and then modify the settings on the extruder (screw speed, feed rate) in order to ensure that the machine is making the correct noise. Extruder sounds have been recorded and related to the physical properties of the final extruded product (Francis et al, 1998). Quantifying these noises and analysing their frequencies can be a useful tool for predicting the quality attributes of the processed food product.

6.8 Sources of information and advice

Following is a list of equipment commonly used for recording of chewing sounds. It is compiled from published research papers and is not exhaustive. Inclusion in this list is by no means indicative of the quality of the equipment. It is an indication that it has been used for acoustic recordings.

6.8.1 Microphones

Condenser microphones used to record air-conducted sounds include the AKG C414EB or Bruel and Kjaer 4133. These microphones have a suitable frequency range for recording air-conducted sounds (within the audible frequency range).

Contact microphones for recording bone-conducted sounds include AKGC401B and the Shadow 4001. These microphones do not have as broad a frequency range as the condenser microphones; however, such a broad range is not required for bone-conducted sounds

6.8.2 Data acquisition equipment for recording and analysis of sound waves

Various amplifiers have been interfaced with the microphones. Most often this amplifier is a Bruel and Kjaer. These amplifiers must be interfaced with either signal conditioners or to a computer with appropriate software.

For recording and analysis of acoustic sound waves, one software package which has been mentioned is Soundedit (Macromedia, San Fransisco, California). This software can be used to set up the testing situation as well as for analysis of the data by FFT. Another means for recording the data is to use a Powerlab (ADInstruments, Castle Hill, Australia) with associated software (Chart4) for analysis of data. This data acquisition unit has built in amplifiers and filters therefore the microphone can merely be plugged into the system for data collection.

6.8.3 Data analysis

FFT can be analysed using any number of data programs. SigmaPlot (SPSS Inc, Chicago, Illinois) and MATLAB (The MathWorks Inc, Natick, Massachusetts) can be used to convert incoming signals into frequencies.

There are also many books which can be of use for gaining an understanding of hearing, and the physics of sound. Two books which this author has found quite useful are; 'The science of sound' by Rossing (1990) and 'An Introduction to Sound' by Speaks (1999).

6.8.4 Useful references

For further understanding of fractal dimensions, the book 'Fractal Surfaces' by Russ (1994) provides an overview of fractal analysis. This book also contains a computer program which can be used for calculating fractal dimensions. Additionally, the fractal dimension of a sound wave can be calculated by using MATLAB (The MathWorks Inc, Natick, Massachusetts).

References

Abbott J A, Affeldt H A and Liljedahl L A (1992), 'Firmness measurement of stored 'Delicious' apples by sensory methods, magness-taylor, and sonic transmission', *J Amer Soc Hort Sci*, 117(4), 590-595.

Abbott J A, Bachman G S, Childers R F, Fitzgerald J V and Matusik F J (1968), 'Sonic techniques for measuring texture of fruits and vegetables', *Food Technol*, 22, 635-645.

Abbott J A, Lu R, Upchurch B L and Stroshine R L (1997), 'Technologies for non-destructive quality evaluation of fruits and vegetables', *Hort Reviews,* 20, 1-120.

Al Chakra W, Allaf K and Jemai A B (1996), 'Characterization of brittle food products: Application of the acoustical emission method', *J Text Studies*, 27, 327-348.

Barrett A H, Cardello A V, Lesher L L and Taub I A (1994), 'Cellularity, mechanical failure, and textural perception of corn meal extrudates', *J Text Studies,* 25, 77-95.

Barrett A M, Normand M D, Peleg M and Ross E (1992), 'Characterization of the jagged stress-strain relationships of puffed extrudates using the fast fourier transform and fractal analysis', *J Food Sci,* 57(1), 232-235.

Bouvier, J.M., Bonneville, R., and Goullieux, A. (1997). Instrumental methods for the measurement of extrudate crispness. *Agro. Food Industry Hi Tech.* Jan/Feb, 16-19.

Bourne, M C (1982), *Food texture and viscosity,* Academic Press, New York.

Brennan J G, Jowitt R and Williams A (1974), 'Sensory and instrumental measurement of brittleness and crispness', *Proceedings of the IV International Congress of Food Science and Technology,* 2, 130-143.

Bruns A J and Bourne M C (1975), 'Effects of sample dimensions on the snapping force of crisp foods', *J Text Studies*, 6, 445-458.

Chen H and De Baerdemaeker J (1993), 'Effect of apple shape on acoustic measurements of firmness', *J Agric Eng Res,* 56, 253-266.

Chen P, Sun Z and Huarng L (1992), 'Factors affecting acoustic responses of apples', *Trans of the ASAE,* 35(6), 1915-1920.

Cooke J R and Rand R H (1973), 'A mathematical study of resonance in intact fruits and vegetables using a 3-media elastic sphere model', *J Agric. Eng Res,* 18, 141-157.

Dacremont C (1995), 'Spectral composition of eating sounds generated by crispy, crunchy and crackly foods', *J Text Studies,* 26, 27-43.

Dacremont C, Colas B and Sauvageot F (1991), 'Contribution of air- and bone-conduction to the creation of sounds perceived during sensory evaluation of foods', *J Text Studies* 22, 443-456.

De Belie, N., De Smedt, V., and De Baerdemaeker, J., (2000). Principal component analysis of chewing sounds to detect differences in apple crispness. Postharvest biology and technology, 18, 109-119.

Dever M C, Cliff M A and Hall J W (1995), 'Analysis of variation and multivariate relationships among analytical and sensory characteristics in whole apple evaluation', *J Sci Food and Agric,* 69 (3), 329-338.

Drake B K (1963), 'Food crushing sounds. An introductory study', *J Food Sci*, 28, 233-241.

Drake B K (1965), 'Food crushing sounds: Comparisons of objective and subjective data', *J. Food Sci,* 30, 556-559.

Duizer L M, Campanella O and Barnes G R G (1998), 'Sensory, textural and acoustic characteristics of extruded snack food products', *J Text Studies,* 29, 397-411.

Edmister J A and Vickers Z M (1985), 'Instrumental acoustical measures of crispness in foods', *J Text Studies*, 16(2), 153-167.

Fillion L and Kilcast D (2002), 'Consumer perception of crispness and crunchiness in fruits and vegetables', *Food Qual Pref*, 13, 23-29.

Finnney E E (1971a), 'Dynamic elastic properties and quality of apple fruit', *J Text Studies,* 2, 62-74.

Finney E E (1971b), 'Random vibration techniques for non-destructive evaluation of peach firmness', *J Agric Eng Res*, 16(1), 81-87.

Francis G, Sellawaha J and Chessai C (1998), 'Use of acoustic emissions as a novel on-line sensor to evaluate the quality of extruded products', Presented at the 3rd Annual Smart Extrusion Seminar, Sydney, Australia.

Harker F R, Maindonald J, Murray S H, Gunson F A, Hallett I C and Walker S B (2002), 'Sensory interpretation of instrumental measurements 1.Texture of apple fruit', *Postharvest Biology and Technology*. 24, 225-239.

Harker F R, Redgewell R J, Hallett I C, Murray S H and Carter G (1997), 'Texture of fresh fruit', *Hort Reviews,* 20, 121-224.

Hashimoto K and Clark G T (2001), 'The effect of altering jaw position on the transmission of vibration between the skull and teeth in humans', *Arch Oral Biol,* 46, 1031-1038.

Jaeger S R, Rossiter K L, Wismer W V and Harker F R (2003), 'Consumer-driven product development in the kiwifruit industry, *Food Qual Pref*, 14, 187-198.

Kapur K K (1971), 'Frequency spectrographic analysis of bone conducted chewing sounds in persons with natural and artificial dentitions', *J Text Studies,* 2, 50-61.

Kiang N Y S and Peake W T (1988), 'Physics and physiology of hearing', in Atkinson R C, Herrnstein R J, Lindzey G and Luce R D, *Stevens' handbook of experimental psychology, 2nd ed,* New York, John Wiley and Sons, 277-326.

Landahl S, De Belie N, De Baerdemaeker J, Peirs A and Nicolaï B M (2000), 'Non-destructive and destructive firmness measurements on apples and peaches', *Agricontrol 2000: IFAC International Conference on Modelling and Control in Agriculture, Horticulture and Post-Harvest Processing*, Wageningen, The Netherlands, 315-320.

Lee W E, Deibel A E, Glembin, C T and Munday E G (1988), 'Analysis of food crushing sounds during mastication: Frequency-time studies', *J Text Studies,* 19, 27-38.

Lee W E, Schweitzer M A, Morgan G M and Shepherd D C (1990), 'Analysis of food crushing sounds during mastication: Total sound level studies', *J Text Studies,* 21, 165-178.

Liu F W and King M M (1978), 'Consumer evaluations of McIntosh apple firmness, *Hortsci*, 13, 162-163.

Liu X and Tan J (1999), 'Acoustic wave analysis for food crispness evaluation', *J Text Studies,* 30, 397-408.

McGlone V A and Shaane P N (1993), 'The application of impact response analysis in the NZ fruit industry', *Am Soc Agr Eng* Paper#93-6537.

Mohamed A A A, Jowitt R and Brennan J G (1982), 'Instrumental and sensory evaluation of crispness: I – In friable foods', *J Food Eng*, 1, 55-75.

Moore B J (1982), *An introduction to the psychology of hearing, 2nd ed,* London, Academic Press.

Peleg K, Ben-Hanan U and Hinga S (1990), Classification of avocado by firmness and maturity, *J Text Studies*, 21, 123-139.

Rossing T D (1990), *The Science of Sound, 2nd ed,* Massachusetts, Addison-Wesley Publishing Company.

Roudaut G, Dacremont C and Le Meste M (1998), 'Influence of Water on the Crispness of Cereal-Based Foods: Acoustic, Mechanical, and Sensory Studies', *J Text Studies,* 29(2), 199-213.

Russ J C (1994), *Fractal surfaces,* New York, Plenum Press.

Seymour S K and Hamann D D (1984), 'Design of a microcomputer based instrument for crispness evaluation of food products', *Trans of the ASAE,* 27(4), 1245-1250.

Seymour S K and Hamann D D (1988), 'Crispness and crunchiness of selected low moisture foods', *J Text Studies.* 19, 79-95.

Schotte S, De Belie N and De Baerdemaeker J (1999), 'Acoustic impulse-response technique for evaluation of modelling of firmness of tomato fruit', *Postharvest Biol and Tech,* 17, 105-115.

Speaks C E (1999), *Introduction to sound: Acoustics for the hearing and speech sciences, 3rd ed,* San Diego, Singular Publishing Group.

Stevens S S and Davis H (1938), *Hearing: Its Psychology and Physiology*, New York, John Wiley and Sons.

Szczesniak A S (1990), 'Texture: Is it still an overlooked food attribute?' *Food Technol,* 44(9), 86-95.

Tesch R, Normand M D and Peleg M (1995), 'On the apparent fractal dimension of sound bursts in acoustic signatures of two crunchy foods' *J Text Studies,* 26, 685-694.

Van Hecke E, Allaf K and Bouvier J M (1998), 'Texture and structure of crispy-puffed food products: Part II Mechanical properties in puncture', *J Text Studies*, 29, 617-632.

van Vliet T (2002), 'On the relation between texture perception and fundamental mechanical parameters for liquids and time dependent solids', *Food Qual Pref,* 13, 227-236.

Van Woensel G, Wouters A and De Baerdemaeker J (1987), 'Relation between mechanical properties of apple fruit and sensory quality', *J Food Process Eng,* 9, 173-189.

Vincent J F V, Saunders D E J and Beyts P (2002), 'The use of critical stress intensity factor to quantify 'hardness' and 'crunchiness' objectively'. *J Text Studies,* 33, 149-159.

Vickers Z M (1981), 'Relationships of chewing sounds to judgements of crispness, crunchiness and hardness', *J Food Sci,* 47(1), 121-124.

Vickers Z M (1984a), 'Crispness and crunchiness – A difference in pitch?', *J Text Studies,* 15(2), 157-163.

Vickers Z M (1984b), 'Crackliness: Relationships of auditory judgments to tactile judgments and instrumental acoustical measurements', *J Text Studies,* 15(1), 49-58.

Vickers Z M (1987), 'Sensory, acoustical, and force-deformation measurements of potato chip crispness', *J Food Sci,* 52, 138-140.

Vickers Z M and Bourne M C (1976), 'A psychoacoustical theory of crispness', *J Food Sci,* 41, 1158-1164.

Vickers Z M and Christensen C M (1980), 'Relationships between sensory crispness and other sensory and instrumental parameters' *J Text Studies,* 11(3), 291-307.

Vickers Z M and Wasserman S S (1979), 'Sensory qualities of food sounds based on individual perceptions', *J Text Studies,* 10(4), 319-332.

Yamamoto H, Iwamoto M and Haginuma S (1980), 'Acoustic impulse response method for measuring natural frequency of intact fruits and preliminary applications to internal quality evaluation of apples and watermelons', *J Text Studies,* 11, 117-136.

REFERENCES

Ablett, S., Attenburrow, G. E., & Lillford, P. J. (1986). The significance of water in the baking process. In J. M. V. Blanshard, P. J. Frazier, & T. Galliard (Eds.) *Chemistry and Physics of Baking* (pp. 30-41). London: Royal Society of Chemistry.

Agrawal, K. R., Lucas, P. W., Bruce, I. C., & Prinz, J. F. (1998). Food properties that influence neuromuscular activity during human mastication. *Journal of Dental Research,* 77(11), 1931-1938.

Ahlgren, J., & Öwall, B. (1970). Muscular activity and chewing force: A polygraphic study of human mandibular movements. *Archives of Oral Biology,* 15, 271-280.

Anderson, D. J. (1956). Measurement of stress in mastication. I. *Journal of Dental Research,* 35(5), 664-670.

Andersson, Y., Drake, B., Granquist, A., Halldin, L., Johansson, B., Pangborn, R. M., & Åkesson, C. (1973). Fracture force, hardness and brittleness in crisp bread, with a generalized regression analysis approach to instrumental-sensory comparisons. *Journal of Texture Studies,* 4, 119-144.

Anonymous. (2001). The "spectrum" chart extension. In *ADInstruments application notes.* Document number AEM07B. Australia: ADInstruments.

Arnold, G. M. & Williams, A. A. (1986). The use of generalised procrustes technique in sensory analysis. In J. R. Piggott (Ed.) *Statistical procedures in food research* (pp. 233-253). Essex: Elsevier Applied Science Publishers Ltd.

Ashby, M. F. (1983). The mechanical properties of cellular solids. *Metallurgical Transactions A.* 14(a), 1755-1769.

Atkinson, H. F. & Shepherd, R. W. (1967). Masticatory movements and the resulting force. *Archives of Oral Biology,* 12, 195-202.

Attenburrow, G. E., Davies, A. P., Goodband, R. M., & Ingman, S. J. (1992). The fracture behaviour of starch and gluten in the glassy state. *Journal of Cereal Science,* 16, 1-12.

Barrett, A. H., Cardello, A. V., Lesher, L. L., & Taub, I. A. (1994). Cellularity, mechanical failure, and textural perception of corn meal extrudates. *Journal of Texture Studies,* 25, 77-95.

Barrett, A. M., Normand, M. D., Peleg, M., & Ross, E. (1992). Characterization of the jagged stress-strain relationships of puffed extrudates using the fast fourier transform and fractal analysis. *Journal of Food Science,* 57(1), 227-235.

Barrett, A. H., & Peleg, M. (1992a). Cell size distributions of puffed corn extrudates. *Journal of Food Science,* 57(1), 146-148, 154.

Barrett, A. M., & Peleg, M. (1992b). Extrudate cell structure-texture relationships. *Journal of Food Science,* 57(5), 1253-1257.

Barrett, A. H., & Ross, E. W. (1990). Correlation of extrudate infusibility with bulk properties using image analysis. *Journal of Food Science*, 55(5), 1378-1382.

Bates, J. F., Stafford, G. D., & Harrison, A. (1975). Masticatory function - a review of the literature I. The form of the masticatory cycle. *Journal of Oral Rehabilitation,* 2, 281-301.

Bhattacharya, M., Hanna, M. A., & Kaufman, R. E. (1986). Textural properties of extruded plant protein blends. *Journal of Food Science,* 51(4), 988-993.

Bearn, E. M. (1973). Effect of different occlusal profiles on the masticatory forces transmitted by complate dentures. *British Dental Journal,* 134, 7-10.

Borges, A., & Peleg, M. (1996). Determination of the apparent fractal dimension of the force-displacement curves of brittle snacks by four different algorithms. *Journal of Texture Studies,* 27, 243-255.

Bourdiol, P., & Mioche, L. (2000). Correlations between functional and occlusal tooth-surface areas and food texture during natural chewing sequences in humans. *Archives of Oral Biology,* 45, 691-699.

Bourne, M. C., (1966). A classification of objective methods for measuring texture and consistency of foods. *Journal of Food Science*, 31, 1011-1015.

Bourne, M. C. (1994). Converting from empirical to rheological tests on foods. It's a matter of time. *Cereal Food World,* 39(1), 37-39.

Bourne, M. C. (2002). *Food Texture and Viscosity. Concept and Measurement.* San Diego: Academic Press.

Boyar, M. M. & Kilcast, D. (1986). Food texture and dental science. *Journal of Texture Studies,* 17, 221-252.

Brandt, M. A., Skinner, E. Z., & Coleman, J. A. (1963). Texture profile method. *Journal of Food Science,* 28, 404-409.

Brennan, J. G., Jowitt, R., & Williams, A. (1974). Sensory and instrumental measurement of "brittleness" and "crispness". *Proceedings of the IV International Congress of Food Science and Technology,* 130-143.

Cairncross, S. E. & Sjöstrom, L. B. (1950). Flavour profiles: a new approach to flavor problems. *Food Technology*, 4, 308-311.

Carlsson, G. E. (1974). Bite force and chewing efficiency. *Frontiers of Oral Physiology,* 1, 265-292.

Chang, C. S. (1988). Measuring density and porosity of grain kernels using a gas pycnometer. *Cereal Chemistry,* 65(1), 13-15.

Chen, J., Serafin, F. L., Pandya, R. N., & Daun, H. (1991). Effects of extrusion conditions on sensory properties of corn meal extrudates. *Journal of Food Science,* 56(1), 84-89.

Christensen, C. M. (1984). Food texture perception. *Advances in Food Research,* 29, 159-199.

Christensen, C. M., & Vickers, Z. M. (1981). Relationships of chewing sounds to judgments of food crispness. *Journal of Food Science,* 46, 574-578.

Civille, G. V., & Lawless, H. T. (1986). The importance of language in describing perceptions. *Journal of Sensory Studies,* 1, 203-215.

Civille, G. V., & Liska, I. H. (1975). Modifications and applications to foods of the General Foods sensory texture profile technique. *Journal of Texture Studies*, 5, 9-32.

Civille, G.V., & Szczesniak, A. S. (1973). Guidelines to training a texture profile panel. *Journal of Texture Studies*, 4, 204-223.

Climas, C. (1987). Focusing on powder characterization. *Food Processing (UK)*, 56, 29-32.

Cohen, S. H., & Voyle, C.A. (1987). Internal porosity of corn extrudate air cell wall. *Food Microstructure,* 6, 209-211.

Dacremont, C. (1995). Spectral composition of eating sounds generated by crispy, crunchy and crackly foods. *Journal of Texture Studies,* 26, 27-43.

Dacremont, C., Colas, B., & Sauvageot, F. (1991). Contribution of air- and bone-conduction to the creation of sounds perceived during sensory evaluation of foods. *Journal of Texture Studies,* 22, 443-456.

De Boever, J. A., McCall, W. D., Holden, S., & Ash, M. M. (1978). Functional occlusal forces: An investigation by telemetry. *Journal of Prosthetic Dentistry,* 40(3), 326-333.

Drake, B. (1965). On the biorheology of human mastication: An amplitude-frequency-time analysis of food crushing sounds. *Biorheology,* 3, 21-31.

Dullien, F. A. L. (1979). *Porous media Fluid transport and pore structure.* New York: Academic Press.

Dullien, F. A. L., & Mehta, P. N. (1971/2). Particle size and pore (void) size distribution determination by photomicrographic methods. *Power Technology* 5, 179-193.

Edmister, J. A. & Vickers, Z. M. (1985). Instrumental acoustical measures of crispness in foods. *Journal of Texture Studies,* 16(2), 153-167.

Faller, J. Y., & Heymann, H. (1996). Sensory and physical properties of extruded potato puffs. *Journal of Sensory Studies,* 11, 227-245.

Faller, J. F., Huff, H. E., & Hsieh, F. (1995). Evaluation of die swell and volumetric expansion in corn meal extrudates. *Journal of Food Process Engineering,* 18, 287-306.

Fløystrand, F., Kleven, E., & Øilo, G. (1982). A novel miniature bite force recorder and its clinical application. *Acta Odontological Scandinavica,* 40, 209-214.

Fontijn-Tekamp, F. A., Slagter, A. P., van 'T Hof, M. A., Geertman, M. E., & Kalk, W. (1998). Bite forces with mandibular implant-retained overdentures. *Journal of Dental Research,* 77(10), 1832-1839.

Garrett, F. A., Angelone, L., & Allen, W. I. (1964). The effect of bite opening, bite pressure and malocclusion on the electrical response of the masseter muscles. *American Journal of Orthodontics,* 50(6), 435-444.

Ghorpade, V. M., Bhatnagar, S., & Hanna, M. A. (1997). Structural characteristics of corn starches extruded with soy protein isolate or wheat gluten. *Plant foods for Human Nutrition,* 51, 109-124.

Gibbs, C. H., Mahan, P. E., Lundeen, H. C., Brehnan, K., Walsh, E. K., & Holbrook, W. B. (1981). Occlusal forces during chewing and swallowing as measured by sound transmission. *Journal of Prosthetic Dentistry,* 46(4), 443-449.

Gibbs, C. H., Mahan, P. E., Mauderli, A., Lundeen, H. C., & Walsh, E. K. (1986). Limits of human bite strength. *Journal of Prosthetic Dentistry,* 56(2), 226-229.

Gillespie, P. G., & Walker, R. G. (2001). Molecular basis of mechanosensory transduction. *Nature,* 413, 194-202.

Gomez, M. H., & Aguilera, J. M. (1984). A physiocochemical model for extrusion of corn starch. *Journal of Food Science,* 49, 40-43, 63.

Graf, H., Grassl, H., & Aeberhard, H. J. (1974). A method for measurement of occlusal forces in three directions. *Helvetica Odontologica Acta*, 18, 7-11.

Greenspan, L. (1977). Humidity fixed points of binary saturated salt solutions. *Journal of Research of the National Bureau of Standard A: Physics and Chemistry,* 81A(1), 89-96.

Guraya, H. S., & Toledo, R. T. (1996). Microstructural characteristics and compression resistance as indices of sensory texture in a crunchy snack product. *Journal of Texture Studies,* 27, 687-701.

Hair, J. F., Anderson, R. E., Tatham, R. L., & Black, W. C. (1998). *Multivariate data analysis.* (5th ed.). New Jersey: Prentice Hall International Inc.

Hagberg, C. (1987). Assessments of bite force: A review. *Journal of Craniomandibular Disorders: Facial and Oral Pain,* 1(3), 162-169.

Harker, F. R., Redgewell, R. J., Hallett, I. C., Murray, S. H., & Carter, G. (1997). Texture of fresh fruit. *Horticultural Reviews,* 20, 121-224.

Harper, J. M. (1986). Extrusion texturization of foods. *Food Technology,* 40(3), 70-76.

Harris, M. & Peleg, M. (1996). Patterns of textural changes in brittle cellular cereal foods caused by moisture sorption. *Cereal Chemistry,* 73(2), 225-231.

Hashimoto, K. & Clark, G. T. (2001). The effect of altering jaw position on the transmission of vibration between the skull and teeth in humans. *Archives of Oral Biology,* 46, 1031-1038.

Heath, M. R., & Lucas, P. W. (1988). Oral perception of texture. In J. M. V. Blanshard, & J. R. Mitchell (Eds.) *Food Structure: Its creation and evaluation* (pp. 465-481). London: Butterworths.

Helkimo, E., Carlsson, G. E. & Helkimo, M. (1977). Bite force and state of dentition. *Acta Odontologica. Scandinavica,* 33, 297-303.

Hiçşaşmaz, Z., & Clayton, J.T. (1992). Characterization of the pore structure of starch based food materials. *Food Structure,* 11, 115-132.

Hsieh, F., Peng, I. C., & Huff, H. E. (1990). Effects of salt, sugar and screw speed on processing and product variables of corn meal extruded with a twin-screw extruder. *Journal of Food Science,* 55(1), 224-227.

Huber, G. R. & Rokey, G. L. (1990). Extruded snacks. In R. G. Booth (Ed.) *Snack Food.* (pp. 107-138). New York: Van Nostrand Reinhold.

Iles, B. C., & Elson, C. R. (1972). Crispness. *BFMIRA Research Reports,* No. 190. October.

ISO., (1981). Sensory analysis vocabulary. Part 4: International Organization for Standardization. Geneva, Switzerland.

Jenkins, G. N. (1978). Mastication and deglutition. In G. N. Jenkins (Ed.) *The Physiology and Biochemistry of the Mouth* (pp. 501-541). London: Blackwell Scientific Publications

Jowitt, R. (1974). The terminology of food texture. *Journal of Texture Studies,* 5, 351-358.

Jowitt, R. & Mohamed, A.A.A. (1980). An improved instrument for studying crispness in foods. In P. Linko, Y. Mälkki, J. Olkku, & J. Larinkari (Eds.) *Food process engineering Vol 1: Food processing systems* (pp. 292-300). London: Applied Science Publishers.

Kapur, K. K. (1971). Frequency spectrographic analysis of bone conducted chewing sounds in persons with natural and artificial dentitions. *Journal of Texture Studies,* 2, 50-61.

Katz, E. E. & Labuza, T. P. (1981). Effect of water activity on the sensory crispness and mechanical deformation of snack food products. *Journal of Food Science,* 46, 403-409.

Kiang,Y. S. N. & Peake, W. T. (1988). Physics and physiology of hearing. In R. C. Atkinson, R. J. Herrnstein, G. Lindzey, & R. D. Luce (Eds.) *Stevens' handbook of experimental psychology. Volume 1: Perception and Motivation* (pp. 277-326). New York : John Wiley and Sons.

Lawless, H., & Heymann, H. (1998). *Sensory evaluation of food: Principles and practices*. New York: Chapman and Hall.

Lee, W. E., Deibel, A. E., Glembin, C. T., & Munday, E. G. (1988). Analysis of food crushing sounds during mastication: Frequency-time studies. *Journal of Texture Studies,* 19, 27-38.

Lee, W. E., Schweitzer, M. A., Morgan, G. M., & Shephard, D. C. (1990). Analysis of food crushing sounds during mastication: total sound level studies. *Journal of Texture Studies,* 21, 165-178.

Linderholm, H. & Wennström, A. (1970). Isometric bite force and its relation to general muscle force and body build. *Acta Odontologica Scandinavica,* 28, 679-689.

Liu, X., & Tan, J. (1999). Acoustic wave analysis for food crispness evaluation. *Journal of Texture Studies*, 30(4), 397-408.

Marklund, G., & Wennström, A. (1972). A pilot study concerning the relation between manifest anxiety and bite force. *Swedish Dental Journal,* 65, 107-110.

Meilgaard, M., Civille, G.V., & Carr, B.T. (1991). *Sensory evaluation techniques.* (2nd Ed.). Florida: CRC Press Inc.

Mioche, L., & Peyron, M. A. (1995). Bite force displayed during assessment of hardness in various texture contexts. *Archives of Oral Biology,* 40(5), 415-423.

Mohamed, A. A. A., Jowitt, R., & Brennan, J. G. (1982). Instrumental and sensory evaluation of crispness: I - In friable foods. *Journal of Food Engineering,* 1, 55-75.

Möller, E. (1966). The chewing apparatus. *Acta Physiologica Scandinavica,* 69 suppl. 280, 1-229.

Moore, B. J. (1982). *An introduction to the psychology of hearing.* London: Academic Press.

Moore, D., Sanei, A., van Hecke, E., & Bouvier, J. M. (1990). Effect of ingredients on physical/structural properties of extrudates. *Journal of Food Science,* 55(5), 1383-1402.

Muňoz, A. M. (1986). Development and application of texture reference scales. *Journal of Sensory Studies,* 1, 55-83.

Murray, J. M., Delahunty, C. M., & Baxter, I. A. (2001). Descriptive sensory analysis: past, present and future. *Food Research International,* 34, 461-471.

Neilson, R.G., & Zannoni, M. (1998). Progress in developing an international protocol for sensory profiling of hard cheese. *International Journal of Dairy Technology,* 31(2), 57-64.

Norton, C. R. T., Mitchell, J. R., & Blanshard, J. M. V. (1998). Fractal determination of crisp or crackly textures. *Journal of Texture Studies,* 29, 239-253.

Olthoff, L.W., van der Bilt, A., de Boer, A., & Bosman, F., (1986). Comparison of force-deformation characteristics of artificial and several natural foods for chewing experiments. *Journal of Texture Studies*, 17, 275-289.

O'Mahony, M. (1982). Some assumptions and difficulties with common statistics for sensory analysis. *Food Technology,* 36 (11), 75-82.

O'Mahony, M. (1986). *Sensory evaluation of food. Statistical methods and procedures*. New York: Marcel Dekker Inc.

Onwulata, C. I., Mulvaney, S. J., Hsieh, F., & Heymann, H. (1992). Step changes in screw speed affect extrusion temperature and pressure and extrudate characteristics. *Journal of Food Science,* 57(2), 512-515.

Owusu-Ansah, J., van de Voort, F. R., & Stanley, D. W, (1984). Textural and microstructural changes in corn starch as a function of extrusion variables. *The Journal of the Canadian Institute of Food Science and Technology*, 17(2), 65-70.

Paphangkorakit, J., & Osborn, J. W. (1998). Effects on human maximum bite force of biting on a softer or harder object. *Archives of Oral Biology,* 43, 833-839.

Peleg, M. (1993). Fractals and Food. *Critical Reviews in Food Science and Nutrition,* 33(2), 149-165.

Peyron, M-A., & Mioche, L. (1994). Oral assessment of hardness between elastic and plastic products. *Journal of Sensory Studies,* 9(2), 223-236.

Piggott, J. R., & Sharman, K. (1986). Methods to aid interpretation of multidimensional data. In J. R. Piggott (Ed.) *Statistical procedures in food research* (pp. 181-232). London: Elsevier Applied Science.

Powers, J. J., (1984). Using general statistical programs to evaluate sensory data. *Food Technology*, 38, 74-82,84.

Rahman, S. (1995). *Food Properties Handbook*. Florida: CRC Press.

Rainey, B. A. (1986). Importance of reference standards in training panelists. *Journal of Sensory Studies*, 1, 149-154.

Roos, Y. H., Karel, M., & Kokini, J. L. (1996). Glass Transitions in Low-Moisture and Frozen Foods: Effects on Shelf Life and Quality. *Food Technology,* 50(11), 95-108.

Rossing, T. D., (1990). *The Science of Sound.* Reading: Addison-Wesley Publishing Company.

Roudaut, G., Dacremont, C., & Le Meste, M. (1998). Influence of Water on the Crispness of Cereal-Based Foods: Acoustic, Mechanical, and Sensory Studies. *Journal of Texture Studies,* 29(2), 199-213.

Russ, J. C. (1994). *Fractal surfaces.* New York: Plenum Press.

Rutledge, K. P., & Hudson, J. M. (1990). Sensory evaluation: method for establishing and training a descriptive flavour analysis panel. *Food Technology,* 44 (12):78-84.

Ryu, G. H., Neumann, P. E., & Walker, C. E. (1993). Effects of some baking ingredients on physical and structural properties of wheat flour extrudates. *Cereal Chemistry,* 70(3), 291-297.

Sakada, S. (1983). Physiology of mechanical senses of the oral structure. *Frontiers of Oral Physiology,* 4, 1-32.

Sauvageot, F., & Blond, G. (1991). Effect of water activity on crispness of breakfast cereals. *Journal of Texture Studies,* 22, 423-442.

Scott Blair, G.W. (1958). Rheology in food research. *Advances in Food Research,* 8, 1-61.

Seymour, S. K., & Hamann, D. D. (1988). Crispness and crunchiness of selected low moisture foods. *Journal of Texture Studies,* 19, 79-95.

Sherman, P., & Deghaidy, F. S. (1978). Force-deformation conditions associated with the evaluation of brittleness and crispness in selected foods. *Journal of Texture Studies,* 9, 437-459.

Sinesio, F., Moneta, E., & Saba, A. (1991/2). Comparison of multivariate methods of analysis to evaluate panelists' performance. *Food Quality and Preference,* 3, 201-208.

Slade, L., & Levine, H. (1991). Beyond water activity: recent advances based on an alternative approach to the assessment of food quality and safety. *Critical Reviews in Food Science and Nutrition,* 30(2 - 3), 115-360.

Smolarz, A., Van Hecke, E., & Bouvier, M. (1989). Computerised image analysis and texture of extruded biscuits. *Journal of Texture Studies,* 20, 223-234.

Snedecor, G. W., & Cochran, W. G. (1989). *Statistical Methods.* (8th Ed.). Iowa: Iowa University Press.

Speaks, C. E. (1999). *Introduction to sound: Acoustics for the hearing and speech sciences.* San Diego: Singular Publishing Group Inc.

Spencer, M. A. (1998). Force production in the primate masticatory system: electromyographic tests of biomechanical hypotheses. *Journal of Human Evolution,* 34, 25-54.

Steiner, J. E., Michman, J., & Litman, A. (1974). Time sequence of the activity of the temporal and masseter muscles in healthy young human adults during habitual chewing of different test foods. *Archives of Oral Biology,* 19, 29-34.

Stevens, S. S., & Davis, H. (1938). *Hearing: Its Psychology and Physiology*. New York: John Wiley and Sons Inc.

Stone, H., & Sidel, J. L. (1998). Quantitative Descriptive Analysis: Developments, applications, and the future. *Food Technology*, 52(8), 48-52.

Stone, H., Sidel, J., Oliver, S., Woolsey, A., & Singleton, R.C. (1974). Sensory evaluation by quantitative descriptive analysis. *Food Technology*, 28(11), 24-34.

Szczesniak, A. S. (1971). Consumer awareness of texture and other food attributes. *Journal of Texture Studies,* 2, 196-206.

Szczesniak, A. S. (1988). The meaning of textural characteristics - crispness. *Journal of Texture Studies,* 19, 51-59.

Szczesniak, A. S. (2002). Texture is a sensory property. *Food Quality and Preference,* 13, 215-225.

Szczesniak, A. S., Brandt, M. A., & Friedman, H. H. (1963). Development of standard rating scales for mechanical parameters of texture and correlation between the objective and the sensory methods of texture evaluation. *Journal of Food Science,* 28:397-403.

Szczesniak, A. S., & Kahn, E. L. (1971). Consumer awareness of and attitudes to food texture I: Adults. *Journal of Texture Studies,* 2, 280-295.

Szczesniak, A. S., & Kleyn, D. (1963). Consumer awareness of texture and other food attributes. *Food Technology,* 17, 74-77.

Tesch, R., Normand, M. D., & Peleg, M. (1995). On the apparent fractal dimension of sound bursts in acoustic signatures of two crunchy foods. *Journal of Texture Studies,* 26, 685-694.

Tesch, R., Normand, M. D., & Peleg, M. (1996). Comparison of the acoustic and mechanical signatures of two cellular crunchy cereal foods at various water activity levels. *Journal of the Science of Food and Agriculture,* 70, 347-354.

Thexton, A. J. (1992). Mastication and swallowing: An overview. *British Dental Journal,* 173, 197-206.

Tornberg, E., Fjelkner-Modig, S., Ruderus, H., Glantz, P. O., Randow, K., & Stafford, D. (1985). Clinically recorded masticatory patterns as related to the sensory evaluation of meat and meat products. *Journal of Food Science,* 50, 1059-1066.

Troller, J. A. (1989). Water activity and food quality. In T. M. Hardman (Ed.). In *Water and Food Quality*. London: Elsevier Applied Science.

Trulsson, M. & Gunne, H. S. J. (1998). Food-holding and -biting behavior in human subjects lacking periodontal receptors. *Journal of Dental Research,* 77(4), 574-582.

Trulsson, M., & Johansson, R. S. (1996a). Forces applied by the incisors and roles of periodontal afferents during food-holding and -biting and tasks. *Experimental Brain Research,* 107, 486-496.

Trulsson, M. & Johansson, R. S. (1996b). Encoding of tooth loads by human periodontal afferents and their role in jaw motor control. *Progress in Neurobiology,* 49, 267-284.

Valles Pamies, B., Roudaut, G., Dacremont, C., Le Meste, M., & Mitchell, J. R. (2000). Understanding the texture of low moisture cereal products: mechanical and sensory measurements of crispness. *Journal of the Science of Food and Agriculture,* 80, 1679-1685.

van der Bilt, A., Weijnen, F. G., Ottenhoff, F. A. M., van der Glas, H. W., & Bosman, F. (1995). The role of sensory information in the control of rhythmic open-close movements in humans. *Journal of Dental Research,* 74(10), 1658-1664.

Van Hecke, E., Allaf, K., & Bouvier, J. M. (1998). Texture and structure of crispy-puffed food products. Part II. Mechanical properties in puncture. *Journal of Texture Studies,* 29, 617-632.

Vickers, Z. M. (1980). Food sounds: How much information do they contain? *Journal of Food Science,* 45, 1494-1496.

Vickers, Z. M. (1981). Relationships of chewing sounds to judgments of crispness, crunchiness and hardness. *Journal of Food Science,* 47, 121-124.

Vickers, Z. M. (1984a). Crackliness: Relationships of auditory judgments to tactile judgments and instrumental acoustical measurements. *Journal of Texture Studies,* 15(1), 49-58.

Vickers, Z. M. (1984b). Crispness and crunchiness - A difference in pitch? *Journal of Texture Studies,* 15(2), 157-163.

Vickers, Z. M. (1985). The relationships of pitch, loudness and eating technique to judgments of the crispness and crunchiness of food sounds. *Journal of Texture Studies,* 16(1), 85-95.

Vickers, Z. M., (1987). Sensory, acoustical, and force-deformation measurements of potato chip crispness. *Journal of Food Science,* 52(1), 138-140.

Vickers, Z. M. (1988). Evaluation of crispness. In J. M. V. Blanshard, & J. R. Mitchell (Eds.). *Food Structure: Its creation and evaluation* (pp. 433-448). London: Butterworths.

Vickers, Z., & Bourne, M. C. (1976). A psychoacoustical theory of crispness. *Journal of Food Science,* 41, 1158-1164.

Vickers, Z. M., & Christensen, C. M. (1980). Relationships between sensory crispness and other sensory and instrumental parameters. *Journal of Texture Studies,* 11(3), 291-307.

Vickers, Z. M., & Wasserman, S. S. (1979). Sensory qualities of food sounds based on individual perceptions. *Journal of Texture Studies*, 10(4), 319-332,

Waichungo, W. W., Heymann, H., & Heldman, D. R. (2000). Using Descriptive Analysis to Characterise the Effects of Moisture Sorption on the Texture of Low Moisture Foods. *Journal of Sensory Studies,* 15(1), 35-46

Waltimo, A., & Könönen, M. (1993). A novel bite force recorder and maximal isometric bite force values for healthy young adults. *Scandinavian Journal of Dental Research,* 101, 171-175.

Wang, J-S., & Stohler, C. S. (1990). Textural properties of food used in studies of mastication. *Journal of Dental Research.* 69, 1546-1550.

Wollny, M., & Peleg, M. (1994). A model of moisture induced plasticization of crunchy snacks based on Fermi's distribution function. *Journal of the Science of Food and Agriculture,* 64, 467-473.

Yoshikawa, S., Nishimaru, S., Tashiro, M., & Yoshida, M. (1970). Collection and classification of words for description of food texture I: Collection of words. *Journal of Texture Studies,* 1, 437-442.

Yurkstas A. A., & Curby, W.A. (1953). Force analysis of prosthetic appliances during function. *Journal of Prosthetic Dentistry*, 3, 82-87.

Zook, K., & Wessman, C. (1977). The selection and use of panelists for descriptive panels. *Food Technology,* 31(11), 56-61.

Massey University
COLLEGE OF SCIENCES

INSTITUTE OF FOOD, NUTRITION
AND HUMAN HEALTH
Private Bag 102 904
North Shore Mail Centre
Auckland
New Zealand
T 64 9 414 0800
F 64 9 443 9640
www.massey.ac.nz

CERTIFICATE OF REGULATORY COMPLIANCE

This is to certify that the research carried out in the Doctoral Thesis entitled "Physiological measures related to crispness perception of extruded snacks" in the Institute of Food, Nutrition and Human Health at Massey University, New Zealand.

(a) is the original work of the candidate, except as indicated by appropriate attribution in the text and/or in the acknowledgements;
(b) that the text, excluding appendices/annexes, does not exceed 100,000 words;
(c) all the ethical requirements applicable to this study have been complied with as required by Massey University, other organisations and/or committees which had a particular association with this study, and relevant legislation.

Ethical authorisation code: MUAHEC 01/010

Candidates Name: LISA DUIZER

Signature:

Date: 19/12/03

Supervisor's Name: R Winger

Signature:

Date: 19/12/03

Massey University
COLLEGE OF SCIENCES

INSTITUTE OF FOOD, NUTRITION AND HUMAN HEALTH
Private Bag 102 904
North Shore Mail Centre
Auckland
New Zealand
T 64 9 414 0800
F 64 9 443 9640
www.massey.ac.nz

CANDIDATES'S DECLARATION

This is to certify that the research carried out for my Doctoral thesis entitled "Physiological measures related to crispness perception of extruded snacks" in the Institute of Food, Nutrition and Human Health, Massey University, Albany Campus, New Zealand is my own work and that the thesis material has not been used in part or in whole for any other qualification.

Candidate's Name: LISA DUIZER

Signature: 

Date: 19/12/03

Massey University
COLLEGE OF SCIENCES

INSTITUTE OF FOOD, NUTRITION
AND HUMAN HEALTH
Private Bag 102 904
North Shore Mail Centre
Auckland
New Zealand
T 64 9 414 0800
F 64 9 443 9640
www.massey.ac.nz

SUPERVISOR'S DECLARATION

This is to certify that the research carried out for the Doctoral thesis entitled "Physiological measures related to crispness perception of extruded snacks" was done by Lisa Duizer in the Institute of Food, Nutrition and Human Health, Massey University, Albany Campus, New Zealand . The thesis material has not been used in part or in whole for any other qualification, and I confirm that the candidate has pursued the course of study in accordance with the requirements of the Massey University regulations.

Supervisor's Name: R Winger

Signature:

Date: 19/12/03