Improved Objective Measurement of Meat Tenderness using Generation Two MIRINZ Tenderometer

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the requirements for the degree of
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STATEMENT OF STUDENT CONTRIBUTION

- I carried out the literature survey in order to contribute to the design and construction process of prototype tenderometer
- An initial design was created by Arthur Pitt, Fix All Services Ltd.
- I constructed the prototype tenderometer in collaboration with Arthur Pitt over three weeks in Hamilton, New Zealand
- I carried out the experiments at Carne Technologies over two weeks in Hamilton, New Zealand, in conjunction with Nicola Simmons, and Tracey Cummings
- I carried out the analysis. The conclusions are my own, and largely independent of my supervisor or industry partners

The above represents an accurate summary of the student's contribution.

Signed …………………. ……………………..

Student - Justin Kaye Supervisor - Jane Liu

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ABSTRACT

Tenderness has been established as the most important factor in determining consumer's perception of meat palatability. Toward the goal of improving meat quality and reducing its variation, the meat industry has placed a high priority on the development of instrumentation for measurement that accurately and reliably predicts cooked meat tenderness. A *Generation Two Tenderometer* (G2) has been developed to provide an objective assessment of meat tenderness using a direct shear force measurement. This device offers the significant advantage of providing a useful force-deformation trace and improved mobility over its predecessor, the *Generation One Tenderometer (G1).* A series of experiments were conducted to evaluate the performance of the prototype tenderometer. Firstly, shear force measurements using the G1 and G2 on two different muscles and packaging treatments were obtained and found to be highly related. Sensory taste panel tenderness scores also were shown to bear a significant relationship with the shear force tenderometer measurements. A recommendation for an operating protocol to optimise the precision of tenderness prediction is presented for subsequent commercial and research applications.

ACKNOWLEDGMENTS

Completing this thesis has provided me with valuable experiences and opportunities to gain exposure to meat science and engineering. It would not be possible without the financial assistance of Meat and Livestock Australia (MLA) to complete the experimental work in New Zealand with Carne Technologies and Fix All Services. I devote particular thanks to Dr Nicola Simmons at Carne Technologies for being so welcoming in providing access to meat samples and the existing tenderometers. Further thanks are directed to Dr Dean Gutzke at MLA for coordinating the opportunity and initiating the first research collaboration with Sydney University Biomedical Engineering. Arthur Pitt of Fix All Services, whose practical expertise and design provided the basis of generating the prototype tenderometer, must be acknowledged as indispensable in assisting my progress. Guidance from my supervisor, Dr Zizhen Jane Liu, has been valuable throughout the process and is greatly appreciated.

1. INTRODUCTION

Beef industries throughout Australia and the United States have been subject to increasing competition and pressures in retaining market share [1]. As a result, the beef industry has become increasingly interested in strategies for reducing the variation and improving the quality of meat. Juiciness, tenderness, and flavour are the dominant factors that contribute to a consumer's perception of meat palatability or the satisfaction derived from consuming beef. Of these factors, tenderness has been established as the most important in determining beef palatability [2]. Toward that goal of improving meat quality and reducing its variation, the beef industry has placed a high priority on the development of instrumentation for carcass measurement that accurately and reliably predicts cooked meat tenderness.

A means for predicting tenderness on the hanging carcass of raw meat samples, or even a means to predict the tenderness of cooked beef samples would be of substantial benefit for the improvement in beef quality and its consistency. It is of importance for the beef industry to satisfy consumer demands to be able to purchase guaranteed high quality, tender meat. Indeed, studies have shown that consumers can differentiate beef that varies in tenderness and are willing to pay some level of premium for guaranteed tenderness [3, 4]. Meat processing companies must acknowledge the potential for increased volumes as well as margins for meat products produced by offering a guarantee of meat quality.

Meat tenderness should be determined by an objective physical method, since organoleptic tenderness is ascertained by the physical chewing process. The overall impression of tenderness to the palate includes texture and involves penetration of meat by the teeth, the ease of fragmentation and the amount of residue remaining after chewing [5]. Consequently, the complexity of texture and tenderness is obvious, and the difficulty of measuring these properties is compounded when the changes occurring due to the cooking process are considered. Thus, the complexity of texture and tenderness from subjectively tasting does not allow any simple quantitative or accessible measurement. Objective mechanical technique to assess tenderness attempt to physically measure the force required to shear, penetrate, bit, mince, compress and or stretch meat.

1.1 DEFINING MEAT QUALITY

Meat quality can be defined in various ways from palatability to technological aspects to safety. A common definition of quality is that it is a ‘measure of traits that are sought and valued by the consumer. Hoffman (1990) described meat quality as the ‘sum of all quality factors of meat in terms of sensory, nutritive, hygienic and toxicological and technical properties’. Sensory properties which include tenderness, flavour and colour while nutritive factors include fat, protein and connective tissue content. Technological factors include parameters such as water-holding capacity, pH, water distribution etc. This study has primarily concerned itself with sensory properties and particularly tenderness.

Tenderness encompasses the ease with which the meat breaks into fragments and the amount and nature of residue remaining after mastication [6]. Determinants of meat tenderness are the content and state of the connective tissue and the structure and content of the myofibrils[7]. The two components are modified to some extent by intramuscular fat and sarcoplasmic proteins [6] which may be affected by the animal's genetics, the feeding regimen, and the physiological maturity of the animal at slaughter [8].

1.2 DIFFICULTIES FOR THE MEAT INDUSTRY

The variability of meat quality prevents the meat industry marketing its produce according to quality. Despite much work in understanding the scientific basis of quality attributes (tenderness, colour, water-holding capacity, juiciness) their evaluation, prediction, and control remain most elusive within the meat processing plant (ie within 48 hours post-slaughter). As a result meat produced today cannot be guaranteed to possess the best meat quality attributes as its quality can only truly be assessed after purchase. Therefore, the marketability of meat, the consistency of quality and the guaranteeing of set standards of product are made very difficult. The reasons for variability in meat quality are numerous, but they emanate from the fact that these quality attributes are altered from post-slaughter conditions, right along the production chain into the processing plant, the retail outlet and even in the purchaser's home.

1.3 WHY THE NEED FOR OBJECTIVE METHODS

Most of the laboratory-based methods require an expenditure of time, personnel and cost. Most procedures are generally not quick enough or adaptable enough for ‘on-line’ or ‘at-line’ situation. Ideally, the ultimate eating quality of meat needs to be predicted in the early post-mortem period. There is also a need for a method of assessing meat quality at the point of sale. Presently, routine methods of measuring meat quality, within a typical meat processing plant include measurements of both pH and temperature. Commercially available probes include hand held probes for the measurement of the electrical parameters of conductivity and impedance.

1.4 LABORATORY-BASED METHODS

Many objective and subjective, laboratory-based, methods for charactering meat quality have been developed to aid the comprehensive assessment of quality attributes. The whole area of sensory analysis provides a complex array of tools for deciphering details relating to meat quality. The sensory assessment depends on three principles considerations. Firstly, there are appearance characteristics including colour, form, size, shape, integrity, and viscosity. Secondly, textural characteristics including tenderness, firmness, mouthfeel, bite and chewability. The third principal consideration includes flavour factors such as taste, odour, off flavours. In general, the assessment of these sensory attributes requires trained panel of judges who can minimise subjectivity. In some circumstances, where untrained panellists are used, larger numbers of assessors may be required.

A wide range of objective tests are available for meat quality assessment. Some of the physical methods which have been developed to predict tenderness, as assessed by a sensory panel, include measuring the force required to shear, bite, mince, compress or stretch meat [9]. A detailed literature review outlines past and current standard techniques for assessing meat tenderness.

1.5 THESIS OBJECTIVES

The Meat Quality Science and Technology (MQST) is a cooperative research program supported by Meat and Livestock Australia (MLA) and Meat and Wool New Zealand (MWNZ) aiming to develop strategies and processes for enhanced meat quality. A program to improve methods for measurement of tenderness has been established to develop a technique and equipment to replace existing systems using the *MIRINZ tenderometer*. Implementation of this tenderometer design to commercial and research applications is presented for this undergraduate thesis. Specific tasks included the construction, validation, and documentation of an operating protocol. This report firstly presents an introduction to identify the nature of the problem and a literature review of objective tenderness measurement methods. Details of the improved prototype *generation two tenderometer* and existing *generation one tenderometer* are presented to show the progress in objective tenderness measurement. Experimental work to demonstrate the precision of tenderometer measurements was performed with reference to sensory panellists’ tenderness scores.

2. BACKGROUND AND LITERATURE REVIEW

2.1 MEAT QUALITY

2.1.1 MEAT COMPOSITION, STRUCTURE AND TENDERNESS

Meat is composed of lean tissue or muscle fiber cells, fat and connective tissue. Nervous tissue and components of the blood system are contained within meat but their total weight or proportional contribution to meat is small and will not be addressed. Additionally, bone is not be considered as part of meat due to the trend towards boneless meat cuts.

2.1.1.1 Fat Component

Fat can be deposited intramuscularly as marbling or contained between muscles (defined as seam fat) or it can be found as external fat or subcutaneous fat. The content of intramuscular fat or the degree of marbling has a great influence on the eating quality beginning when the consumers choose the meat in the supermarket. Many consumers will reject meat with a medium or high amount of visual marbling fat in beef even though they find it more palatable when eating without knowing the amount of fat [10].

There are conflicting results about the impact of intramuscular fat on tenderness. It is said to increase tenderness in some studies whilst others suggest a negative effect of intramuscular fat and tenderness exists.

Intramuscular fat affects palatability through the relationship between fat content and tenderness. This is explained using several theories [11]. The bulk moduls theory states that as fat is lower in density than heat-denatured protein in cooked meat, as the fat content increases, the overall density of the meat decreases. As bulk density decreases within a given bite of meat, the meat is tenderer. A Lubrication effect is also used to explain the relationship between intramuscular fat and tenderness. Triglycerides stored in adipose cells embedded in the perimysial tissue wall of muscles are released as meat is cooked and proceed to bathe and melt the muscle fibers. As meat is chewed the muscle fibers give or slide more easily resulting in an increased perception of tenderness. A third interaction between fat and tenderness proposes that fat provides protection against the negative effects of over-cooking or high heat protein denaturation. These meat proteins are involved in the binding water in the muscle. Their capacity to retain water is hindered when denatured, resulting in dry tough meat. Fat can act to insulate the transfer of heat or slow down the heat transfer so that protein denaturation is less severe and less moisture loss occurs during cooking. A final theory relates to the weakening of the perimysial connective tissue surrounding muscle bundles. Marbling deposits (of adipose cells) dispersed through the perimysial connective tissue weaken the connective tissue structure resulting in meat that is easier to separate and is perceived as tender [6].

2.1.1.2 Lean or muscle fiber component

The major component of meat is muscle fibers. Muscle fibers form the cellular structure that possesses the contractile apparatus of the muscle. Muscle proteins also are components in the muscle fiber that binds water and interacts with water to hold it in the muscle fiber. The structural integrity and the ability of the muscle proteins to bind water affect meat tenderness.

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Cold-induced toughening, or cold shortening, occurs during the onset of rigor mortis when muscle is chilled rapidly. It is caused by a process that begins when the sacrcoplasmic reticulum loses its ability to bind calcium to increase calcium concentrations. With ATP available and the contractile operations still functioning, the muscles contract more rigourously than normal and upon the inability to relax, yielding the muscle fixed in a shortened contractile state. The result is tougher meat.

The strength of the structural components within the muscle fiber has also been related to meat tenderness. The basic premise is that as the structural apparatus of the muscle is degraded and weakened, meat tenderness improves [12].

As a generalisation, connective tissue, which is dominated by collagen, defines the background toughness in meat [13]. This background toughness is not easy to change. In contrast tenderness due to the contractile apparatus can readily be modified by processing conditions.

Components related to the myofibrillar component, sacromere length and calpastain activity, and the connective tissue component, collagen amount and solubility, were not highly related to the Warner-Bratzler shear force values

2.1.1.3 Connective Tissue Component

Perimysium, connective tissue surrounding muscle bundling, and endomysium, connective tissue surrounding muscle fibers, provide structural support to muscles. High-use muscles used for work or major movements have higher connective tissue content than low-use muscles or muscles that provide structural support. Muscles with higher amounts of connective tissue are tougher [14]. This phenomenon is why muscles from the hindquarter of animals that are used for locomotion are inherently tougher than support muscles, such as those in the loin region. Another aspect of connective tissue is the type of cross-linking within connective tissue matrix. There are two classifications of bonds within connective tissues, heat-soluble bonds and heat-insoluble bonds. Collagen is the major fiber in the perimysium and endomysium connective tissue matrix. During heating and cooking, a proportion of the bonds can be solubilised and broken. As animals age, the percentage of insoluble bonds increases [15]. Increased toughness due to increased animal age is mainly attributed to the increase in heat-insoluble collagen bonds. Therefore connective tissue contributes to tenderness and overall meat quality through the total amount and proportion of heat-insoluble collagen cross-links.

In summary, the three major components of meat, fat, lean and connective tissue, contribute to meat quality with each uniquely contributing to meat juiciness, tenderness and flavour. While each of these components has been discussed separately, they are not independent components, but they are interconnected and interact biologically within the muscle and meat system. Therefore, ante-mortem and post-mortem factors that affect meat quality may affect any three components and subsequently affect meat quality.

2.2 ANTE- AND POST-MORTEM FACTORS AFFECTING THE QUALITY OF MEAT

A plethora of factors influence the tenderness of meat in many different levels. Some of the more significant influences on meat quality and especially tenderness are briefly presented.

As meat quality is affected by the lipid, muscle fiber and connective tissue components within an animal, animal genetics can play a major role in meat quality. It has been long understood that the unique genetic code for each animal regulates the production of proteins and that genetic variation exists within meat animal species for important meat quality attributes [6]. Biological type within *Bos taurus* cattle, British (Hereford, Angus and Shorthorn), exotic or continental and dairy breeds have been shown to influence tenderness nut mainly through differences in growth rates, weight at time of slaughter and fatness at slaughter [16-18]. As biological factors influences the growth rate, fatness, and body mass, these factors have a direct and indirect influence on meat tenderness, especially as carcass fatness and weight can influence cold-induced toughness and marbling levels [16-18].

Dietary influences on meat quality- In general, as the energy density of the diet increases, the growth rate of the animal increases, animals reach slaughter weight at younger ages, the resultant carcass is heavier and higher in overall fatness and marbling, the meat is juicier and species specific flavour is diluted by an increase in fat flavour.

The **rearing or housing of animals** prior to slaughter can affect meat quality. These effects are mainly due to the lack of stress or the level of stress inflicted on the animal due to the rearing environment and the subsequent impact on rates of gain.

Slaughter, the conversion of muscle to meat or the live animal to a carcass, can impact meat quality through the rigor mortis process. Long-term pre-slaughter stress results in reduced glycogen supplies at slaughter which prevents the pH decline during rigor to proceed at a normal rate. If pH does not fall sufficiently, meat becomes dark in colour, has a firm texture, and high water-holding capacity but attractive tenderness and juiciness properties.

The type of **stunning method** used to immobilise animals during the slaughter process can affect meat quality either through inducing short-term pre-slaughter stress or it can effect blood removal upon exsanguinations.

Storage of meat can affect quality positively and negatively. The positive effect of meat storage influences meat tenderness. The major factor responsible for post-mortem improvement in meat tenderness is degradation or proteolysis of muscle proteins. The negative effect is the result of microbial growth and/or lipid oxidation.

2.3 MECHANICAL TENDERNESS MEASUREMENT TECHNIQUES

Numerous attempts have been made to develop objective physical, chemical or visual methods to predict tenderness as assessed by sensory panels made up of consumers and trained experts. The following literature review encompasses a review of existing and former physical and mechanical testing techniques as well some relevant visual and non-invasive techniques.

2.3.1 ARMOUR TENDEROMETER

A type of puncture testing instrument that measures the force required to push a punch or probe into a food. The test is characterised by a) a force measuring instrument (b) penetration of the probe into the food causing irreversible crushing or flowing of the food and (c) the depth of penetration is usually held constant. A multiple probe maximum force instrument that applies a constant rate of force application

This simple primitive system utilises a group of probes designed to be inserted into the longissimus following carcass chilling. Measurements of the force required to penetrate the muscle are used to attempt to predict cooked meat tenderness. Researchers have shown different degrees of accuracy of evaluating meat tenderness [19]. Research has suggested that the Armour Tenderometer (AT) effectively categorises USDA Choice beef carcasses and USDA choice and Select Rib steaks into tenderness desirability groups [19, 20].

Subsequent research has suggested that AT provides minimal additional information beyond Warner-Bratzler shear force measurements [19-26]. Indeed, Huffman et al. (1974) investigated 192 carcasses of various USDA qualities to find that AT scores provided a strong correlation with Warner-Bratzler shear force scores (a standard tenderness testing procedure) but no statistically significant explanation of the variation in meat tenderness as adjudged by a trained sensory panel [25]. Harris *et al*. (1992), using data from the study by Smith *et al*. (1984), reported that Armour Tenderometer readings predicted sensory panel tenderness ratings and shear force values for steaks from 384 steer/heifer carcasses with less than 1% and less than 2% accuracy, respectively [24, 26].

Due to the low correlation to ultimate meat tenderness and palatability, and the apparent ineffectiveness of this technology [19, 20, 22-26], it has since largely been abandoned as a tenderness predicting tool. Tenderness prediction capabilities (accuracy) appear limited because of the inability to characterize the changes which occur in muscles during the cooking process[27].

The Armour Tenderometer is nonetheless worthy of mention to illustrate the difficulties in predicting tenderness from raw meat samples and provided a concept for development of further probe-based testing instruments.

2.3.2 TENDERTEC MARK III BEEF GRADING INSTRUMENT

Tendertec Mark III Beef grading Instrument (hereafter Tendertec) is a moderately-invasive mechanical penetrometer designed to measure the amount of connective tissue and other factors that contribute to the toughening of meat. The apparatus typically consists of a 14 cm piston and pause stops to control depth of carcass insertion at 4 cm and 6 cm. In total, the probe tip penetrates perpendicular to specified locations along the spinal cord, to a predetermined depth of 8 cm [27]. To initiate insertion, force is applied to the piston by a spring and a second piston is advanced by the trigger assembly. Scales associated with the first and second piston measure the depth of insertion and force required for penetration to produce plots of force-time and force-probe insertion distance similar to figure 1. Position-based and time-based recording systems have successfully overcome earlier complications associated with recoil influences caused by piercing strong connective tissue sheaths.

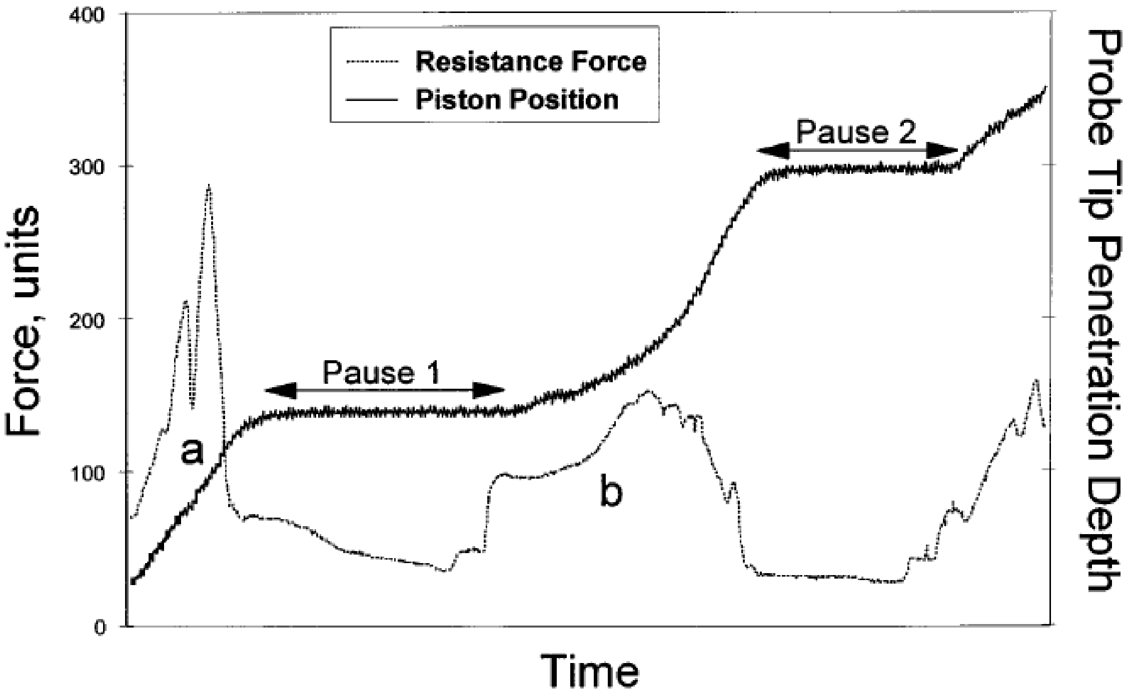

Figure 1. Schematic of a Tendertec generated force curve plotted relative to piston position (probe tip depth within the longissimus) and time. A represents measurement noise associated with penetration of the longissimus epimysial sheath. B represents the actual area under the curve used in analyses reported to generate Tendertec output variables. Pause 1 represents period probe tip remains stationary, following entry into the longissimus, and signifies the commencement of the force assessment period. Pause 2 represents the period probe tip remains stationary and signifies the end of the measurement period. (Source: George et al. 1997)

No statistical significance has been shown to exist between the Tendertec outputs and Warner-Bratzler shear force values [28]. But Tendertec output variables have been shown to be significantly correlated with sensory panel ratings for connective tissue amount and overall tenderness [27]. Therefore, Tendertec and Warner-Bratzler complimentary testing would be expected to provide explanation of meat tenderness beyond that associated with Warner-Bratzler shear force or Tendertec in isolation. Hence, Tendertec could become most important in the progress of objective tenderness evaluation.

More recent studies have verified that Tendertec outputs provide some explanation of meat tenderness perceived by a sensory tasting panel, without correlation with Warner Bratzler shear force, but only with very low coefficients and levels of significance [27, 29].

Measurement of tenderness perpendicular to the length of the longissimus provided by probe-based techniques (Tendertec and AT) have produced poor explanation of variation in tenderness [19, 20, 22-26][28]. To assess LM tenderness in an orientation perpendicular to the length of the muscle, the epimysium must be removed or the probe(s) must penetrate through the epimysium connective tissue before useful muscle measurements are taken. Stephens et al. (2004) suggest that this procedure is difficult to completely perform and that small outer pieces of connective tissue remain to affect measurements [30, 31]. The resulting uneven specimen surface results in needles not being in contact when testing commences to reduce measurement accuracy and ability to explain tenderness. Further, accurate tenderness prediction by the Tendertec appears limited due to the changes that occur in muscles during the cooking process.[27]

2.3.3 WARNER- BRATZLER SHEAR FORCE

Warner-Bratzler shear force (WBSF) has been the standard method for estimating tenderness from cooked meat samples for over fifty years [32]. Various apparatus setups apply a shear force perpendicular to the prepared cored meat samples using a cutting blade to determine the kilograms of shear force (KgF) required to penetrate and slice a piece of meat. Comparison to WBSF is the measure by which other objective measurements of meat quality are assessed. There is yet to be a method to surpass and replace Warner-Bratzler despite the best efforts of many pursuits.

The working part of the traditional apparatus consists of a stainless steel blade 0.040 inches thick in which a hole, consisting of an equilateral triangle circumscribed around a 1-inch diameter circle is cut and the edges rounded off to a radius of 0.02 inch. A sample of meat, usually a cylinder of 0.5 or 1.0 inch in diameter is placed through the hole and two metal anvils, one on each side of the blade, move down forcing the meat into the V of the triangle until it is cut through. A force gauge measures the maximum force encountered during this cutting action. This is a cutting action rather than a true shear.

Voisey and Larmond (1974) mounted the WB shear blade and various adaptions of the blade in the Instron and studied the effects of changing the dimensions of the blade using wieners as test material.

Following Wheeler et al. (1997) reporting that different methods for WBSF testing can result in increased variation in shear values among institutions, stringent procedures have been developed by researchers and meat processing companies to ensure valuable comparison of WBSF results [17]. These Standard procedures for sample preparation were established following the National (USA) Beef Tenderness Conference 1994. Warner-Bratzler shear force can be performed using a Warner-Bratzler shear machine or an automated testing machine (such as an Instron Universal Testing Machine) with a Warner-Bratzler shear blade attachment and crosshead speed of 200 or 250 mm/minute (Figure 2). Shear force is applied perpendicular to the orientation of the muscle fibers. Warner-Bratzler shear blade specifications include (see figure 1) [17]:

1. Blade thickness of 1.016 mm,
2. V-shaped (60° angle) cutting blade,
3. Cutting edge beveled to a half-round,
4. Corner of the ‘v’ should be rounded to a quarter-round of a 2.363 mm diameter circle,
5. Spacers providing the gap for the cutting blade to slide through should be 2.032 mm thick.

Cores of diameter 1.27 cm are extracted from cooked beef longissimus steaks of width 2.54 cm (1 inch). One steak per carcass is taken from between the 12th rib and 5th vertebra. Cores should be removed parallel to the longitudinal orientation of the muscle fibers so that the shearing action in perpendicular to the longitudinal orientation of the muscle fibers. Further sample preparation procedures including timing and temperature of storage, and cooking procedures are outlined in the *Standardised WBSF Procedures* [17].

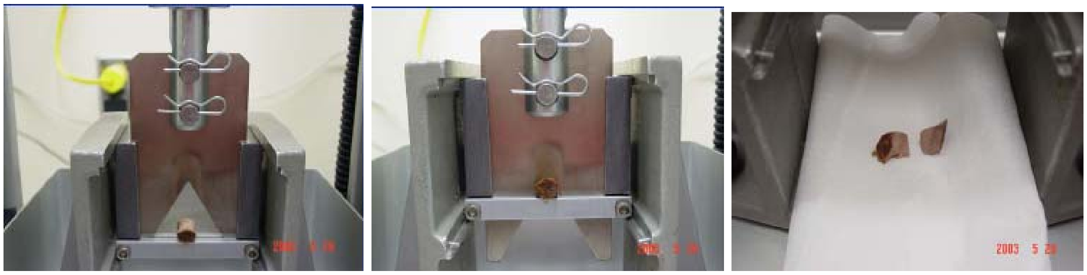

Figure 2. The Warner-Bratzler shear force is a simple method of objective tenderness measurement achieved by a blade applying a shear with measurement of force required to penetrate the cored meat sample

The Warner-Bratzler shear force has been the most popular method of measuring the tenderness of meat over a long period since its development by Warner and Bratzler in the 1930’s [33]. However, some authors have questioned the accuracy of the method [34, 35]. The procedure is time-consuming and expensive and requires cooked sample testing but maintains it position as the benchmark for testing and predicting meat tenderness.

Attempts have been made to evaluate different parts of the force-distance curve achieved in the Warner-Bratzler shear measurement. However, peak load is usually found to be the best predictor of tenderness and the use of additional characteristics obtained from the curve does not substantially improve the prediction of tenderness [36].

2.3.4 SLICE SHEAR FORCE TESTING

Modifications of the cumbersome Warner-Bratzler protocol have been developed as a means for more rapidly estimating tenderness based on measuring cooked longissimus shear force [37]. Slice shear force (SSF) testing requires subsample slices from cooked meat are sheared with a flat, blunt-end blade using an electronic testing machine (such as a universal testing machine).

A protocol for SSF testing, similar to that developed for WBSF testing, has been developed by researches at U.S. Meat Animal Research Centre (MARC). Test specimens are rapidly cooked with 1 cm thick and 5 cm long slices removed from a steak parallel to the muscle fibers and sheared perpendicular to the muscle fibers. The slice shear force blade has the same thickness and (1.016 mm) and degree of bevel (half-round) as the shearing edge as Warner-Bratzler shear blades. Consistent with the attempt to reduce testing time required, crosshead speeds are set to 500 mm/min and specimens are belt grilled rather than cooked with open-hearth electric broilers.

Scientists at the Meat Animal Research Center (MARC) in Clay Center, Nebraska advocate measurement of slice shear force of steaks removed from carcasses can categorise meat into groups described as “tender”, “intermediate” or “tough”. They proclaim that SSF provides greater explanation of the variation in tenderness than explained by WBSF. Shackelford et al. (1999) characterised this system using 204 A-maturity carcasses and showed it was effective in categorising meat tenderness with a high repeatability (0.89) and accuracy of correct categorisation (93%). These results exceeded tenderness predictions provided by WBSF to explain the sensory panel rating [37]. Similar experiments have shown slice shear force value at 3 d post-mortem accounted for a much higher proportion of the variation in trained sensory panel tenderness and ease of fragmentation than Warner-Bratzler shear force.

Meat packers and processing companies have rejected the SSF tenderness system due to the invasive nature of the technology. It is deemed removal of a steak from each carcass is too costly to a packing plant that processes in excess of 5000 carcasses a day. However, slice shear force is a more rapid, more accurate, and technically less difficult technique than WBSF [38]. Use of the slice shear force technique could facilitate the detection of treatment differences with reduced numbers of observations and reduced time requirements, thereby reducing research costs [39]. Since SSF is technically less difficult than WBSF it is less operator dependant and could allow more useful comparison of values derived to assess tenderness.

2.3.5 MIRINZ TENDERNESS PROBE

The tenderness probe developed by Meat Industry Research Institute of New Zealand (MIRINZ) has been shown to have the potential for analysing raw and cooked samples and quantifying tenderness [32]. Attempts to reliably forecast tenderness from raw samples is a focus for improved efficiencies in meat quality testing. Current specimen preparation and cooking procedures are rigorous in order to comply with standards to allow comparison. These costly, time-intensive procedures can detract from the benefit derived from tenderness classification. It is hoped that MIRINZ can develop machinery to accurately predict from raw samples.

The instrument consists of two sets of pins on which meat samples are impaled. Tension is applied to the muscle fibres by one set of pins which rotate relative to a static set of pins. Torque required to rotate the inner (rotating) pin set is measured by use of a torque arm pressing against a load cell, and the torque signal is recorded against the angle of rotation (Figure 3).

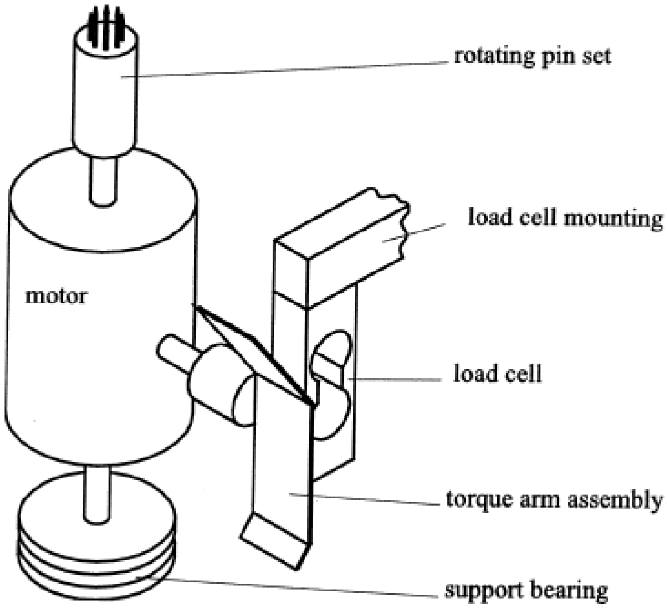

Figure 3. Mechanics of the MIRINZ Tenderness Probe

Two configurations have been developed for the inner and outer pins sets: shear and tension configurations. The tension configuration attempts to transmit a tension load, whilst the shearing configuration provides shear as well as tension loads. This is achieved by basic geometry (see figure 4 and 5). A significant gap between the rotating and static pins exists in the tension configuration. Contrastingly, the shear head has only about 0.5 mm of clearance between the pin sets.

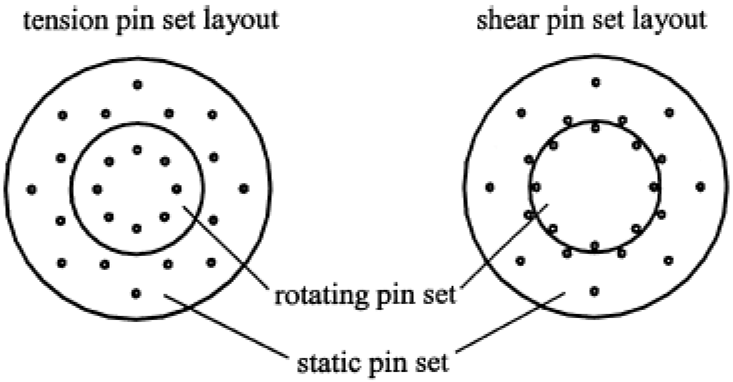

Figure 4. Tension and shear pin set configurations of MIRINZ Tenderness Probe

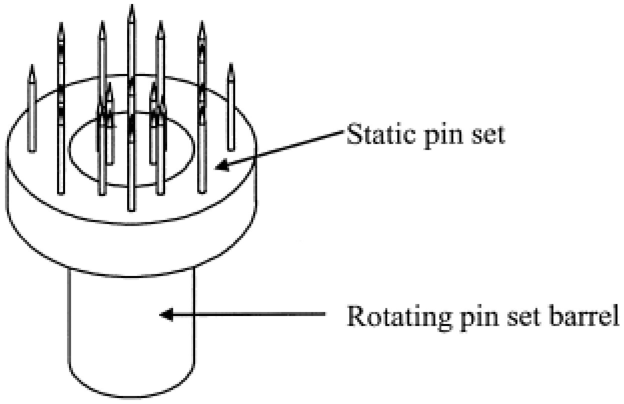

Figure 5. Pin set for tension and shear head configurations of MIRINZ Tenderness Probe

The torque/rotation angle trace (Figure 6) of individual instrument readings are analysed to produce characteristics to describe the trace:

1. Peak torque value
2. Maximum slope before the peak
3. Torque at 50 degrees rotation
4. Area under the trace before peak (area 1)
5. Area under the trace before 50 degrees of rotation (area 2)

6. Area under the whole trace (area 3)

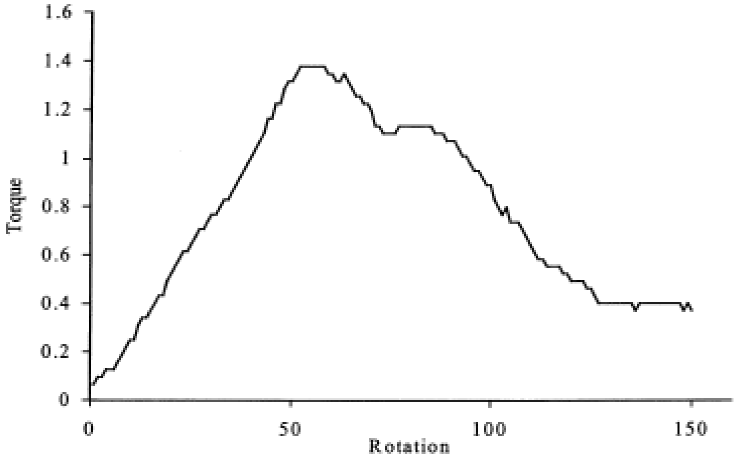

Figure 6. A typical MIRINZ tenderometer torque/rotation response trace [Torque= KgF^{-1} (Kilograms of force); rotation= degrees]

Selecting probe value and head configuration to provide the most statistically significant explanation of meat quality as determined by a sensory panel is not a simple statistical or experimental exercise. Jeremiah and Phillips (2000) considered which configuration and trace characteristics provides the most reliable and accurate prediction of meat tenderness from cooked and raw samples [32]. They investigated the level of explanation of variation in tenderness provided by objective measurement (Warner-Bratzler and MIRINZ tenderometer) compared with trained sensory panel and consumer properties perceptions of tenderness. Their research proposes that the MIRINZ tenderometer provides the most useful explanation from raw samples when applying the tension head configuration and examining the area under before 50 degrees. For cooked samples, the shear head was shown to be more effective and total area under the trace was the most efficient characteristic [32].

The MIRINZ tenderometer compares favourably to the Warner- Bratzler shear force objective measurement for analysis of cooked beef samples [32]. The shear head configuration with area 3 probe value provides between 30 and 73% explanation of variation in selected sensory and consumer traits of tenderness of cooked samples. Warner-Bratzler shear force provides between 28 and 53% of explanation of the variation in the same tenderness traits. However, when raw samples are considered Warner-Bratzler retains its superiority, accounting for 30 to 44% of the variation compared to only 8 to 13% of variation being explained using the D50 probe value and tension head.

2.4 NON-INVASIVE TECHNIQUES

2.4.1 CONNECTIVE TISSUE PROBE

The Connective Tissue probe (CT Probe) is a non-invasive system utilising an optical fibre probe that measures the reflectance of initially polarized light to predict the palatability of beef. The reflectance and transmission of light waves characterise the connective tissue properties of the muscle [40].

Testing specifications to measure reflectance at 460 nm, fluorescence peak 3 and mean length disorder with optical-electromechanical probe accounted for 34% of the variation in perceived tenderness of 21 d aged longissimus steaks [41]. Despite promising results in the laboratory, by Swatland et al., the CT probe has been criticized for its lack of durability and reliability in the packing environment and inability to reliably predict meat tenderness. This elementary, innovative design solution has inspired a development of spectroscopy based techniques.

2.4.2 NEAR INFRARED SPECTROSCOPY

The development of fast, non-destructive, accurate, and on-line techniques for tenderness prediction is strongly desired. Near infrared (NIR) spectroscopy could form the basis for such techniques due to the speed, ease of use, and minimal interferences from moisture or color of meat samples.

NIR has been used in the meat industry to analyse the fat, moisture and protein composition to develop models of meat tenderness. The ability of NIR to detect changes in the state of water and hydrogen bond interactions in foods has been observed. Since such changes evidently occur in meat during tenderisation and ageing, a relationship exists between NIR measurements and meat quality attributes. Indeed, Hildrum et al. (1994) reported that the near infrared reflectance (NIR) spectra of beef muscles changed during aging [42]. Given that a variation in the rate of aging causes most of the variation in tenderness of longissimus steaks [43], NIR spectroscopy may be able to predict variation in tenderness of longissimus steaks.

The concept underlying this technology is that light reflected from muscle on the visible and to near infrared portion of the spectrum contains important information related to quality attributes such as beef tenderness.

NIR equipment has included a contact probe with a built-in tungsten-halogen light source to supply broad-band light to the ribeye surface. A scanning monochromators collect reflectance readings over the applied wavelength range. Literature reports useful wavelength range between 450 and 2500 nm, although a smaller span of reflectance values are regularly utilised [44]. Two pairs of lead sulfide detectors collect the reflectance spectra. The absorbance spectrum recorded as log(1/R) for each meat disk is gathered on a spectrophotometer equipped with a rotating drawer. Reflected energy readings are referenced to corresponding readings from a ceramic disk. A reference scan is collected and stored to computer memory before each sample is scanned. The spectra from the three or four circular slices of each steak are averaged to produce one spectrum per steak for the development of chemometric models to predict meat tenderness.

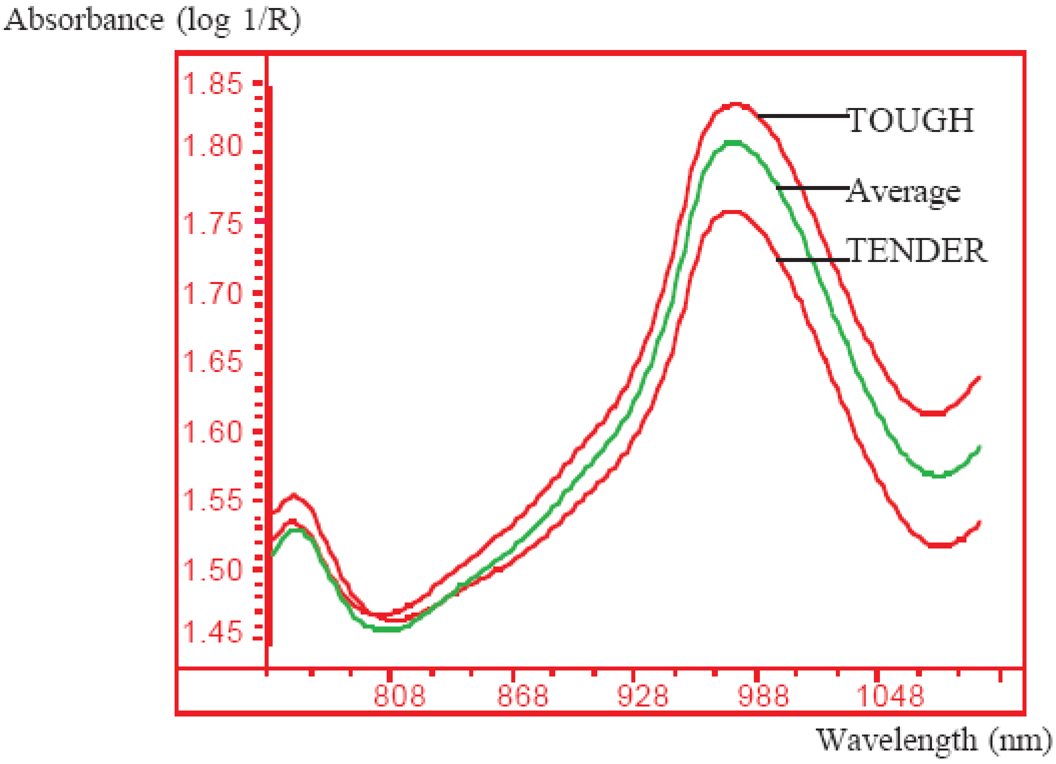

Figure 7. Sample mean spectra obtained from demonstration ‘tough’ and ‘tender’ meat specimens

The above figure show a representative sample of the spectra collected. The major features are two broad peaks and a large offset between the individual spectra. The sample with high WBSF values has a higher overall absorbance at all wavelengths measured than that with low WBSF values and predicted tenderness [42, 45-49].

A high degree of explanation of variation in tenderness of beef samples has been demonstrated by Rødbotten et al. (2001). Spectra were used to predict tenderness of the meat samples from two prediction models either based on NIR spectra alone or NIR spectra in combination with information about post slaughter treatments. Prediction models from NIR spectra alone gave correlation coefficients to the reference method (WBSF) in the range 0.52–0.83, but when variables for post slaughter treatments were included in the models the correlation coefficients were in the range 0.71–0.85. Based on these prediction models the beef samples were classified into two or three tenderness groups. When the beef samples were classified into two groups, 73–98% of the samples were correctly classified, while there were 63–75% correct classified samples when they were allocated into three groups [50].

High levels of accuracy have been demonstrated by Park et al. (1998) using NIR and developing partial least squares and multiple linear regression models to predict tenderness of beef longissimus thoracis steaks from 119 carcasses. Among his prediction set (39 samples) 48.7, 87.7 and 97.4% of the samples were predicted within 1.0, 2.0 and 3.0 kg of the observed WBSF value. When classified into a ‘tender’ (WBSF< 6 kg) and ‘tough’ (WBSF > 6 kg) groups 89 % of samples were correctly categorised.

Several further studies have shown that NIR offers promising results for prediction of beef tenderness [42, 44-50]. An accurate, reliable, rapid, non-invasive testing regime may provide meat processors to automate tenderness classification to enhance their procedures in order to provide consumers with guaranteed quality, tender meat.

2.5. OTHER NON-INVASIVE TECHNIQUES OF MEAT QUALITY MEASUREMENT

2.5.1 PH MEASUREMENT

Knowledge of pH and its importance in the quality of meat is an essential element in meat quality measurements. Postmortem glycolysis results in the accumulation of lactic acid and a decline in pH of the muscle from about 7.2, at death, to roughly 5.5 after rigor mortis onset.

The relationship between pH and temperature up to 24 hours post-mortem is an important factor when considering ultimate meat quality. [51]

2.5.2 COLOUR

The colour of raw meat is a combination of the content of myoglobin and the reflection from the protein denaturisation. During storage the colour might further change but it depends on both the packaging material and on the packaging and storage conditions. The amount of myoglobin in the raw meat might therefore be an indicator of the raw meat quality with respect to further processing. The hem-group of both myoglobin and traces of haemoglobin can be quantified spectrophotometrically.

2.5.3 WATER HOLDING CAPACITY

Drip Loss

Water losses originate from volume changes of myofibrils induced by pre-rigor pH fall and the attachment of myosin heads to actin filaments at rigor where myofibrils shrink owing to pH fall. Denaturation of proteins may also contribute to a reduction in WHC particularly in conditions of rapid pre-rigor pH and cold shortening. The fluid thus expelled acculculates between the fibre bundles. When a muscle is cut, the fluid will drain from the surface under gravity if the viscosity of the fluid is low enough and capillary forces do not retain it.

Cooking Loss

During heating, the different meat proteins denature at varying temperatures (37-75^{o}C). Denaturation causes structural changes such as the destruction of cell memebranes, transverse and longitudinal shrinkage of muscle fibers, the aggregation of sarcoplasmic proteins and shrinkage of the connective tissue. These events, particularly the connective tissue changes result in cooking losses in meat

3. PROTOTYPE TENDEROMETER

3.0 INTRODUCTION

Sensory assessment of tenderness or toughness is based on different elements that occur during the eating. These are the initial severing of meat portions as they are bitten and the ease with which the food is then compressed and torn apart during mastication to form a bolus suitable for swallowing [52]. No laboratory analysis exists that can approximate all the actions of biting and chewing and amalgamate these into a single measure of tenderness. Rather, these actions are simplistically mimicked by a series of objective tests. It is important for research and industry purposes that any correlated with sensory assessment of these criteria.

3.1 DESIGN OBJECTIVES

Existing objective tenderness measurement techniques throughout Australia and New Zealand rely on the generation one MIRINZ tenderometer measurement of shear force to penetrate meat samples. Although this familiar procedure provides satisfactory correlation with sensory tenderness scores and other measurement techniques (such as Warner-Bratzler shear force) the procedure is inadequate for more thorough analysis of the force-deformation curve as well as flexibility and mobility in its use. A prototype tenderometer has been developed with the following purpose for an objective tenderness measurement system:

- simple to perform
- rapid
- suitable for routine work
- strong correlation with sensory tenderness evaluations
- closely duplicates mastication
- complete texture measurement
- know exactly what is measured
- sample preparation considerations [30]

Following these requirements, a design concept was developed and executed as part of this thesis with designing engineer, Arthur Pitt, and Carne Technologies. Specific responsibilities included prototype construction, validation and testing, data acquisition procedures and documentation. This section outlines the features of the first generation (G1) and second generation (G2) tenderometers, a recommended operating procedure and documentation of the testing process for prototype validation.

Applications for a tenderness measurement device is

1. As a quality assurance (QA) tool within a processing operation
2. As an assessment of the effectiveness of production and processing treatments where there may be an interest in being able to compare results between laboratories or countries
3. as a research too, in fundamental structural studies of muscle and meat

Initial applications and implementation will involve the replacement of existing G1 tenderometers used by Carne Technologies and Meat and Livestock Australia researchers. Long-term, it is anticipated that, these tenderometers may be useful in commercial environments including abattoirs and meat processing plants but also supermarkets and bulk meat retailers and butchers.

3.2 THEORY OF SHEAR FORCE

Applying and measuring the force required to penetrate the myofibrillar is a concept that has long been utilised to measure the tenderness of meat [37, 38, 53, 54]. Indeed, the generation one tenderometer adopts a similar approach to the slice shear force of Shackelford et al [38]. However, whereas the slice shear force applies a load through a blunt flat, the existing tenderometer penetrates the meat sample with a v-shaped blade in order to simulate a biting action. The prototype design does not add on previous approaches in its theoretical justification of legitimacy to replicate mastication and biting but attempts to find a more practical, robust approach. This section outlines the existing tenderometer features in order to demonstrate its limitations and requirements for the improved G2 tenderometer.

3.3 DESIGN CONCEPTS

3.3.1 GENERATION ONE: A NOVEL IDEA

Meat science research conducted by MLA and Meat and Wool New Zealand (MWNZ) have utilised the meat tenderometer developed by MIRINZ (now AgResearch), which will be referred to as the generation one (G1) tenderometer. The concept is similar to the Slice Shear Force technique developed by Shackelford et al. at the US Meat Animal Research Center (MARC).

This tenderometer provides a means to measure tenderness based on force required to shear meat samples. A mechanical load is applied to the meat sample from pressure employed from an air compressor that manoeuvres a driving arm with a ‘cutting’ attachment (see figure 8). A v-shaped (60 degrees), eight millimetre wide attachment is utilising to apply a shear force. Compression based tenderness testing employs a flat one centimetre square attachment.

The pressure applied to the loading arm increases as it endures greater resistance from tougher meat samples. As a result, loading does not occur at a fixed rate and could not be analysed as a force (pressure) - time curve to derive a force-deformation curve. The force-deformation curve can illustrate useful meat properties, beyond the measured force to shear, to predict meat quality and tenderness. However the first generation machine is not capable of displaying any measurements other than the max pressure required to complete its cycle. Indeed, current data acquisition procedures require manual recording of peak pressures by the operator using paper and pen and later entry into a excel spreadsheet to calculate force measurements and further. analysis.

Significant drawbacks are derived from the implementation of air compressor and pneumatic components to apply load to meat sample. Measurement of the peak pressure encountered whilst penetrating the meat sample is presented on a simple display on the tenderometer. From calibration at the time of production an iteration equation is developed to transform the pressure measurement to a force to shear. Each machine encounters different internal resistances largely from friction forces of pneumatic components.

Air compressors are widely available in meat processing plants as is the required 240 Volt power supply required. However, these pressure and power constraints yield a bulky machine that is fixed and rigid. A mobile tenderometer is desired for tenderness measurement applications outside a laboratory or processing plant.

Figure 8. G1 Tenderometer apparatus includes a primitive display of the maximum pressure required to penetrate a cooked meat sample. A v-shaped blade is forced to penetrate the meat sample which is loaded into the fitted cavity.

3.3.2 GENERATION TWO: A PROTOTYPE TENDEROMETER

The development of a second generation tenderometer provides a more functional objective measurement device for the tenderness of meat. Significant improvements include

- reduced size and weight results in improved mobility
- improved data acquisition procedures captures a complete force-deformation trace
- reduced time and labour costs in operation

Most importantly, the newly developed tenderometer provides a satisfactory objective measurement of the tenderness qualities of meat products. This section outlines the design concepts and features, validation and operating protocol developed from my efforts in construction and preparation of the tenderometer for laboratory use.

3.3.2.1 Summary

A meat sample experiences a shear force applied to it from a linear actuator that drives the specimen platform towards a static shearing blade attachment connected to a load cell which measures the force encountered. The system utilised in the constructed prototype G2 tenderometer provides a more direct method of measurement of force to shear. The load cell provides an accurate live force measurement as the specimen is penetrated and released throughout the loading cycle. A force-time plot provides the opportunity for data analysis beyond peak force to shear in future applications of this device.

Figure 9. The G2 Tenderometer provides a convenient method for the objective measurement of meat tenderness by direct streaming of force-time data to attached PC and instrument display.

3.4 DESIGN AND CONSTRUCTION

3.4.1 COMPONENTS

3.4.1.1 Linear Actuator

The implemented actuator (Hiwin LAS-1-1-50-24) satisfies all specifications expected meat samples and other potential testing may require.

A maximum force expected to be encountered in penetrating meat with a v-shearing attachment is approximately 20 KgF (200 N) and in excess of 40 KgF (400 N) using a compression-based technique [37]. Regardless, the actuator only exerts this peak force for a short amount of time and is well within the manufacturers recommended maximum force of 1200N.

A force-deformation curve can be interpolated from the force-time data when the loading rate is constant throughout the loading cycle. Specifications provided by the manufacturers (see figure 10) show that, the speed is relatively constant at 12 mm/s at 24 volts when forces do not exceed 400 N. When attempting to validate these specifications is became apparent that the power provided by our two 12 volt rechargeable lead-acid batteries to the actuator dropped when required applying an increased load. However, a voltage regulator ensures that the power source provides a constant (adjustable) voltage to the actuator. Following the addition of the regulator, loading rate was shown to be constant when the motor was required to work harder. The manufacturers' specification regarding operating performance was confirmed by recording the stroke time under a variety of loading conditions. Stroke time was shown to remain constant.

This will mean that force-displacement analysis may not be available for tough samples when using a compression attachment. Tough samples are likely to require more than 40 KgF for penetration which may result in a non-uniform loading rate. Using the v-shaped shearing attachment and tender cuts, such as sirloin and rump, forces greater than 40 KgF have not been encountered in G2 validation and testing.

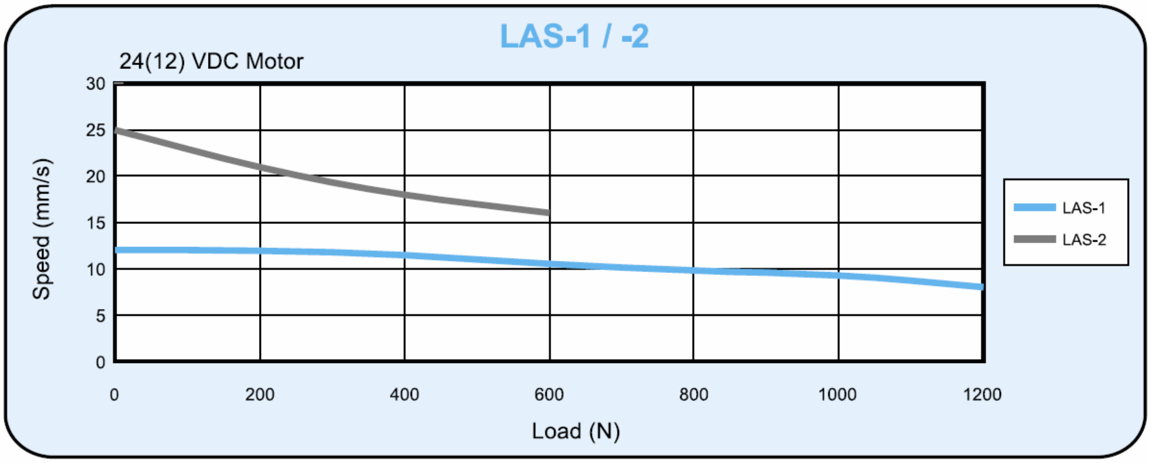

Figure 10. The HIWIN LAS-1-1 actuator operates at a constant speed in the expected operating environment of meat tenderness testing (<400N). This component drives the specimen platform up and down from the static shearing attachment.

The stroke length was selected at 40 mm to provide an acceptable cavity to manoeuvre a tray containing samples whilst reducing inefficiency of wasted space that increases cycle time and size of tenderometer. Default stroke length is determined by an internal limit switch and was reduced from 50 millimetres to 40 millimetres. This provides a sufficient gap for loading and removing meat specimens stuck to the shearing attachment.

3.4.1.2 Voltage Regulator

A simple voltage regulator was produced to ensure voltage supplied to the actuator and the speed at which it operated was constant. The applied voltage was set at 15.6 Volts in order to operate at a similar speed to that of SSF [37] who operate at 500 mm/min (or 8.33 mm/s). A constant operating speed was achieved.

3.4.1.3 Display

The Rinstrum R320 is a precision digital indicator using Sigma-Delta A/D technology to ensure fast and accurate weight readings. The setup and calibration are digital, with a non-volatile security store for all setup parameters.

This instrument is fitted with rin-LINK communications as standard. This allows a temporary isolated communications link to be established with a PC and enables software upgrades and the use of computerised setup and calibration via the rin-VIEW software.

3.4.1.3 Load Cell

The load cell is a miniature bending beam (Celtron MBB-100) type load cell that functions as a low profile platform scale for this low capacity scale application. It provides long term high performance and is sealed for protection of the cell from water and moisture damage.

3.4.1.4 Power Supply

Two rechargeable lead-acid batteries, each supplying 1.3 ampere hours and 12 volts, are connecting in series to provide power to the display unit, load cell and actuator. The voltage regulator will maintain a constant voltage to ensure the actuator operates at a constant speed and have sufficient current available when forced to work harder and draw more current. Batteries are only recommended for use when mobility is required. Routine operation in a laboratory testing environment will rely on power from mains line which is transformed from the 240 Volt down to approximately 15.6 Volts. The voltage regulator still maintains a constant voltage supply to the actuator.

3.5 DATA ANALYSIS AND PROCESSING

Extracting and processing measurement provided by the load cell and Rinview digital indicator system was performed with a serial port direct connection between the tenderometer and PC using Rinview software. Time-force data is streamed at a sampling frequency of 0.1 seconds and saved as a .csv file. Microsoft excel is required to execute all data analysis in order for future consumers not to require additional software. A configuration of logic statements extracts the useful peak shear force to penetrate each meat sample in the set of ten for each steak. The high degree of variability in tenderness within a given specimen requires that an average is used for its measurement. These ten peak values are extracted and then averaged by the user in Excel for sample data analysis.

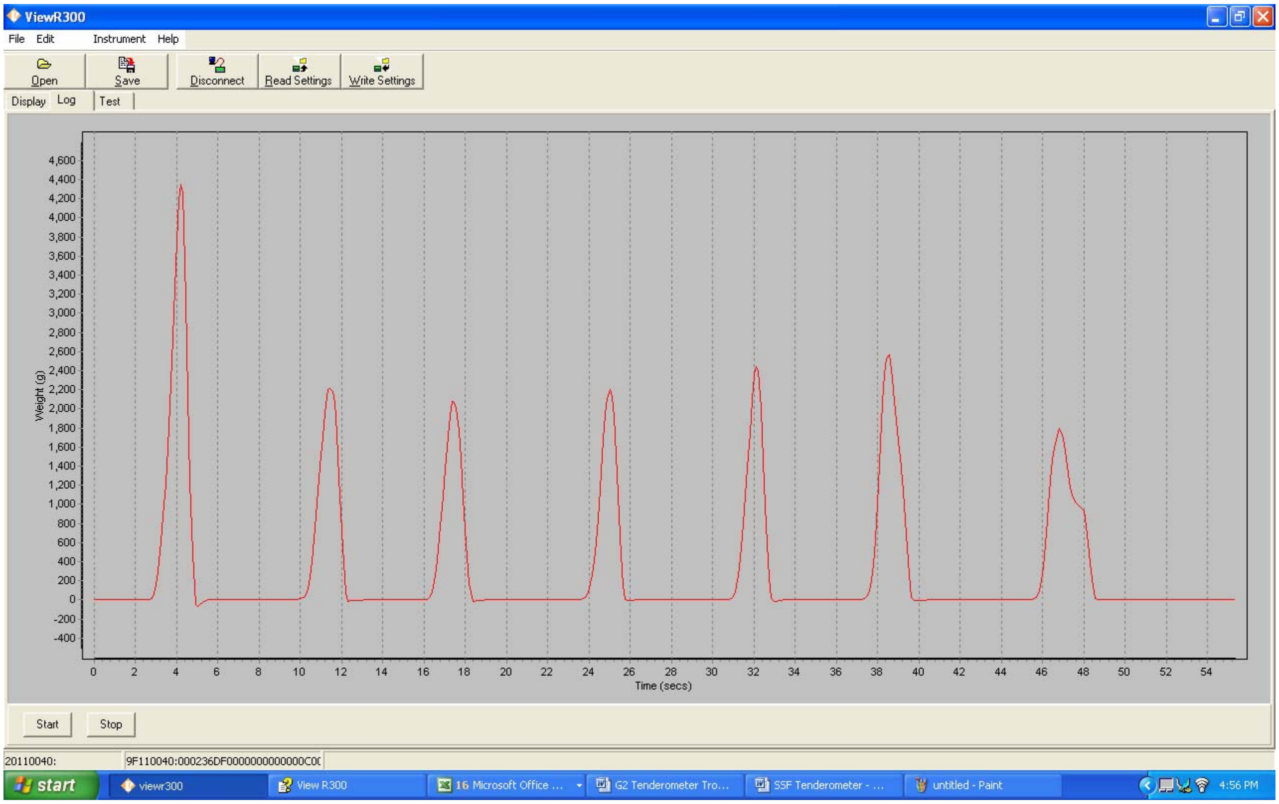

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Figure 11. A real-time force-time trace is illustrated using RinView software in association with the load cell. The variation in tenderness (shear force measurement) within each steak is large. Ten sample bites are required for averaging of tenderness measurements.

3.6 DIFFERENCES BETWEEN TENDEROMETER APPROACHES

The G1 tenderometer relies on a moving shear force/compression blade and a static restrained meat sample. Contrastingly, the G2 tenderometer operates with a dynamic meat sample and a static load cell. However, the applied forces onto the meat bites are not affected by which components actually move.

Further differences in the loading process are the rate of loading: the G1 tenderometer relies on the air compressor to provide a uniformly increasing pressure to move the drive arm. The resulting time required to complete the cycle to fully penetrate the meat sample is determined by the toughness of the specimen. Hence, a force-deformation curve could not be derived from the force-time curve even if streaming of that data were available. Alternately, the G2 tenderometer linear actuator provides a constant rate of travel throughout the loading and instantaneously adjusts the force accordingly. This permits the extrapolation of a force-deformation curve which may provide for more versatile and useful applications.

A subtle difference in the blade attachment for shear force measurement has been observed between the prototype and existing tenderometer. Specifications of the v-shaped blade attachment have changed since the G1 tenderometer were first produced. The machine used at Carne Technologies throughout this project employed a cutting attachment with a larger radius of curvature and rounded apex than newly-manufactured generation one tenderometers. The prototype generation two tenderometer is fitted with an attachment identical to recently produced tenderometers. This sharper attachment may contribute to lower shear force measurements for the newly developed tenderometer. A sharper blade will obviously require less force to sever the muscle fibers compared to the traditional rounded attachment.

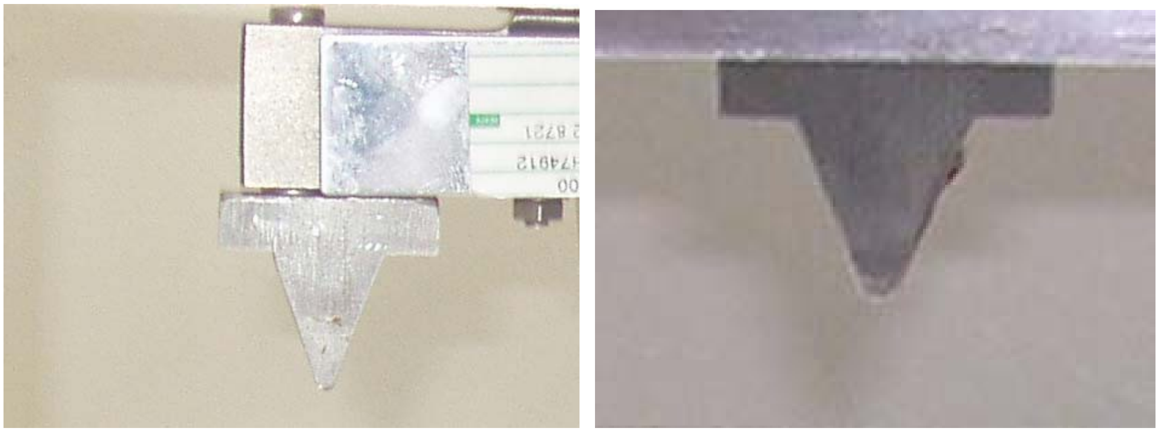

Figure 12. The G2 tenderometer shear force attachment (left) is shown to have a sharper tip than the G1 tenderometer at Carne Technologies. Recently manufactured generation one type tenderometer are manufactured with identical blades as the prototype tenderometer.

The pressure required to completely penetrate the meat sample and trigger the drive arm limit switch provides the measurement which is transformed into a force measurement by a calibration equation.

3.7 INITIAL VALIDATION AND PRACTICAL OPERATION

An initial investigation into the operation of the prototype tenderometer commenced soon after completing its construction during the first trip to New Zealand (June 28- July 15, 2006). Construction was completed with the design engineer, Arthur Pitt (Fix-All Services) in his workshop, and meat testing was completed with Carne Technologies, Hamilton, New Zealand. The initial testing process offered a valuable opportunity to assess the performance of the tenderometer in an environment likely for it to encounter as a completed product. However, the results were of limited use since modifications were being made throughout the testing period and sample availability was limited. Regardless, a brief summary of this testing process is documented in the following section.

Purpose

Carne Technologies required tenderness measurements as they investigated a combination of packaging and storing technique to optimise meat quality. This provided an opportunity to compare the objective measurements of tenderness provided by the two tenderometers. Relatively wide ranges of sample tenderness are expected to be encountered and provide statistically valid regression model fitting to calculate a r-squared to measure the extent of variation in tenderness measured by G1 explained by G2.

Method

Standard operating protocol is described in detail in the following section to outline the experimental method for principal validation. A brief description of the procedure carried out is presented to offer some context for the recognition of required modifications and the results acquired.

SAMPLE PREPARATION

Experiments conducted during this trial involve the testing of exclusively cooked meat samples. Cooked beef steaks are prepared into thin strip ‘bites’ of dimensions approximately 10 mm by 10 mm by up to 50 mm. It is imperative that muscle fibres are longitudinally aligned in order for the shearing force to always be applied perpendicular to the muscle fibers. Accordingly, sample preparation was completed with accuracy and care.

Sensory taste panellists consume grilled meat samples but tenderometer based assessment may test with waterbath or grilled cooked specimens. Analysis conducted at Carne Technologies in Hamilton, NZ was performed on chilled and hot samples cooked by broiling and grilling. Attempts were made to ensure that each steak was of similar thickness and hence cooking time and procedure. However, cooking times varied quite extensively (although this was not recorded). Consistency of the extent/degree of cooking using a grill and waterbath was achieved by measuring and ensuring once an internal temperature of 70^{o}C was attained, meat samples were removed from the cooking apparatus and placed into plastic bags and into an ice bath.

Cooking in a water bath is widely employed to provide a consistent cooking of meat samples. The experiments conducted utilised a water bath with a temperature of 100^{o}C and cooking of meat to an internal temperature of 75^{o}C. Cold samples were placed in ice immediately to cease the cooking process that may continue if allowed to cool at room temperature. The procedures follow those prescribed by the AMSA research guidelines for cookery, sensory evaluation and instrumental tenderness measurements of meat [55].

Grilling was conducted using an electric grill with a stable temperature throughout the grill. Samples were scheduled to be turned once after cooking for ten minutes and then cooked for another five minutes and turned every two minutes until an internal temperature of 70 degrees was achieved. This temperature represents the AMSA recommended temperature for cooking of all meat species for palatability research [55]. This attempts to limit misinterpretation of results when comparing between institutions by aligning preparation and cooking techniques. This temperature represents a high level of ‘doneness’ which corresponds to a worst case scenario for tenderness implications. Further, the tendency for consumers to cook their beef to a ‘well-done’ status is common throughout the US [56]. Meat samples must be cooked from a thawed (not frozen) state.

Results

Complete data is only available for limited parts of the total experiment. However, the r-squared are shown in the table below.

Cooking Technique	**Testing Temperature**	**Observed R-squared**
Grill	Hot	0.353
Grill	Hot	0.072
Grill	Cold	*Not available*
Grill	Cold	*Not available*
Water Bath	Hot	*Not available*
Water Bath	Hot	0.394
Water Bath	Cold	*Not available*
Water Bath	Cold	0.686

Table 1. Initial testing was performed to assess the tenderometer functionality rather than validation of the shear force concept. These results do not provide evidence of an effective tenderness measurement.

Discussion

This trial provided an opportunity to assess the performance of the G2 tenderometer prototype in conditions it will expect to encounter in meat testing. Valuable insights and modifications were made throughout the testing period of almost one week and data acquisitions procedures were fine-tuned. Modifications including ensuring correct alignment of the meat loading tray and shearing attachment and altering the shearing attachment to match the G1. These improvements were valuable in developing the G2 into a more useful machine to replace the G1. However, these modifications may explain the poor correlation of G1 and G2 tenderness measurements.

Further, the quality of meat samples provided for G2 were potentially inferior to those assigned for G1 testing. The primary objective for Carne Technologies was to conduct its experiment using existing objective tenderness measurement technique and thus G2 was not necessarily allotted quality or a full sample quota of ten. Homogenous specimen allocation and testing is essential for a legitimate comparison of G2 and G1 tenderometer performance. Following the design refinements of the prototype, an additional validation trial has been conducted.

Figure 13. Meticulous preparation of specimen bites to prescribed dimensions with consistent alignment of muscle fibers bears great importance in maintaining uniformity of samples to allow useful comparison of tenderness measurements.

Figure 14. Meat specimens are prepared into ‘bites’ with cross section dimensions 10mm by 10mm and up to 50 mm long with all muscle fibers oriented in the longitudinal direction. ‘Bites’ are confined within an aluminium loading tray which is projected upward to the static load cell and shear/compression attachment.

4. OPERATING PROTOCOL

It is necessary to document procedures for sample preparation and conduct for implementation of the generation two tenderometer. This will ensure that comparisons across different institutions will retain value and tenderness measurements are not impacted by differing operating protocols.

4.1 GENERAL PRINCIPLES

The origin and husbandry of the live animal, slaughtering procedures and the post-mortem handling of the carcass should be described as precisely as possible. The description can include species, breed, sex, age, feeding regime, transport and pre-slaughter handling, slaughter conditions, chilling and ageing regime. The rate of pH and temperature decline post mortem, together with the final pH of the muscle should be reported. The history of the animal should preferably be known, although it is not always important. If it is known it should be reported for tenderness measurement testing. [55, 57]

4.2 MUSCLE ORIGIN

Differences in tenderness exist among muscles differing in location and function in the live animal. These differences are largely attributed to differences in collagen content and

and/or differences in the contraction or stretching during rigor mortis. Obviously, the origin of meat for tenderness testing must be clearly considered and documented.

The muscle most widely used muscles in meat tenderness testing are derived from the loin region where the muscles are not in high use and required for strenuous actions such as locomotion. For tenderness testing, uniform alignment of muscle fibers is desirable and is explicitly related to the degree and type of cross-linking [6]. Muscles such as the *longissimus thoracis et lumborum* are regularly used for testing since they exhibit the most uniform alignment of muscle fiber direction. The sampling location should be clearly described eg between 12th to 13th thoracic rib in reporting testing.

4.3 STORAGE OF SAMPLES

Ideally, assessment should be performed immediately after sampling. Storage and aging treatments provide important methods for improving meat tenderness. Such aging treatments and storage conditions such as freezing conditions must be specified. The conditions of must be specified as these will affect the tenderness measurement. In such cases, samples should be packaged and frozen quickly and stored at -18^{o}C or below and the storage period should not exceed three months [58].

4.4 COOKING

A relationship among factors implicated in determining myofibrillar tenderness and how cooking rates affect these different muscles and cooking rates exists. Sacromere length, connective tissue content and heating rate in proteolysis influence the tenderness of beef [59]. Slower cooking rates have been shown to improve tenderness [60]. The myobirilar contribution to shear force is influenced by the heating rate up to 80°C. However, the tenderising effect of slow cooking is commonly attributed to the solubilisation of collagen [61] and connective tissue contribution to shear force was primarily influenced by a heating temperature between 60°C and 80°C. That is, at cooking temperatures up to 60°C connective tissue influences predominate and above that myofibrillar components are more important. Therefore end-point temperatures of cooking in the centre need to be defined and measured accurately [56, 58].

Cooking methods are varied throughout institutions across the world [62]. Processing including broiling, grilling, immersion in a heated water bath and oven-based methods provide different strategies to attempt to provide a uniform degree of cooking throughout the meat sample in a practical and efficient manner. Water bath and grilling methods have been performed prepare meat samples for assessment of meat tenderometers in this investigation are acknowledged as both being valid methods [58].

The water bath method involves preparing individual steaks of about 25 mm thick and of constant weight and placing them in a continuously boiling water bath inside a thin plastic bag with the bag opening extending above the water surface. Samples should be cooked to a predetermined internal temperature, with $70^{o}C$ recommended [55]. When the end-point temperature is attained, samples should be removed from the water bath, cooled in ice slurry and then chilled until equilibrated. Under chilling conditions ($1\text{-}5^{o}C$), samples are stable for four days, when stored without cooking.

Alternate cooking techniques such as belt grill and grilling to end-point temperature are also implemented throughout the meat science research industry although not recommended in an attempt to standardise assessment of meat characteristics.

End-point temperature has been shown to possess a negative relationship with tenderness as assessed by Warner-Bratzler shear force [56]. Wheeler et al. showed that beef longissimus tenderness decreases as end-point cooking temperature increases. Recent studies have shown that the degree of doneness to which beef is cooked varies considerably among US consumer and that 64% and 82% of beef consumers cook their beef medium to very well done. Yet, it is not known whether degree of doneness and inherent tenderness interact to effect tenderness

4.5 SHEAR TESTING PROCEDURE

The sample should be cut from a block of cooked meat and taken to avoid damage. Sample strips should be cut with 100 mm^2 (10x10) cross-section with the fibre direction parallel to a length dimension of at least 30 mm. The sample should be sheared perpendicular to the fibre longitudinal axis. Units of measurement are kPa or often KgF

Remove a 1cm thick, 5 cm long slice from each cooked sample parallel to the muscle fibres [37].

4.6 EVALUATION

The principal parameter to be measured from the force deformation curve is the peak force recorded for complete sample penetration. Total energy and initial yield may be useful in future applications of textural analysis but will not always provide any additional explanation of tenderness as explained by trained sensory panellists. [12].

4.7 SENSORY PANELLIST

Sensory assessment of tenderness or toughness is based on different elements that occur during the eating. These are the initial severing of meat portions as they are bitten and the ease with which the food is then compressed and torn apart during mastication to form a bolus suitable for swallowing [52].

Sensory assessment of meat quality is obtained by use of either trained taste panels or untrained consumer panels. Both of these can assess the separate components of tenderness, juiciness and flavour. In a consumer panel these sensory dimensions are highly correlated, whereas trained panellists score the attributes independently. Consumer panels are essential to obtain feedback on consumer preferences but are expensive and time consuming. When knowledge of preferences is not essential, the use of trained taste panels offer a more cost effective alternative which has been shown to be well correlated with scores given by consumer panels [63].

Panellist have conducted sensory evaluation of many meat quality components using a continuous 100 mm line scale anchored at each end by the extreme terms for example extremely tough (0) and extremely tender (9) for tenderness testing.
The subjective testing of meat by trained sensory taste panellists is the optimal measure of tenderness. The practicality of testing is obviously prohibitive, but provides a comparison for objective techniques such as tenderometer to be measured against.

Taste panellists conducted a analysis based on the following criteria

- Stage 1: initial bites; assessed during the first 2-3 bites
    - Firmness/ softness- force to bite through the sample
    - Initial juiceness- amount of moisture during the initial bites
    - Denseness- the compactness of the meat (density). Airy/loose vs compact/solid (dense)
- Stage 2: Mastication; (Chewing bites) assessed during mastication, 4-7 bites
    - Tenderness- the amount of force required to chew the sample. The force which is required to disintegrate the sample
    - Cohesiveness- how well the sample holds together during mastication.
      Loose and falls apart= non cohesive
      Tight and held together= cohesive

    - Fibrousness- strands and fibres perceived during breakdown of meat (the type and arrangement of the fibres)
- Stage 3
    - Cohesiveness of mass- degree to which chewed sample holds together in a mass after mastication
    - Sustained juiciness- amount of moisture remaining- dry vs juicy
    - Chewiness/ duration of chews- amount of work required to get sample to state ready to swallow- (number of chews required)= effort/work required

Of principal relevance for tenderness assessment is the tenderness measure in stage 2 and firmness in stage 1.

5. EXPERIMENTAL WORK

The developed prototype relies on the principle of applying a shear load to meat muscle structure to provide an objective tenderness measurement. This similar concept has been applied in developing the generation one tenderometer as well as the Warner-Bratzler shear force [17] and Slice Shear Force techniques [38]. An initial investigation into the accuracy of the prototype in describing the variation in tenderness was performed by comparing G2 shear force measurements against G1 tenderometer shear force measurements. These trials proved useful in assessing the performance of the G2 in a challenging environment likely to be encountered during laboratory testing and identifying required modifications before handing over to Carne Technologies. This second set of experimental work was a thorough investigation to demonstrate the precision of the prototype G2 tenderometer in providing a useful objective measure of tenderness. Operating parameter of cooking technique and testing temperature have been investigated to help develop an optimal operating protocol for objective tenderness evaluation.

5.1 RELATIONSHIP BETWEEN OBJECTIVE MEASUREMENT AND TASTE PANEL ASESSMENT OF BEEF QUALITY

The relationship between objective measurement (shear force) and sensory evaluation of tenderness and juiciness of samples of *loin* and *rump* was examined using data from two experiments which imposed packaging and post mortem aging treatments. Differences in sensory and objective measures of tenderness were measured with trained sensory panellist and mechanical shear force measurement devices. The relationships were tested in separate models for each of the two objective measurement devices, that is, the existing generation one tenderometer and prototype generation two tenderometer. Results show a strong positive relation between G1 and G2 tenderometer shear force measurement. A less powerful explanation of the variation in sensory tenderness scores is provided by the two tenderometers. Nonetheless, a significant negative relationship is shown to exist between objective measurements and sensory tenderness scores using both tenderometers.

5.1.2 MATERIALS AND METHOD

Data was acquired from a Carne Technologies investigation as part of their Meat Quality Science and Technology (MQST) testing program co-supported and funded by Meat and Livestock Australia (MLA) and Meat and Wool New Zealand (MWNZ). Specifically, the experiment examined the impact of aging meat with foodcap and vacuum packaging treatments. Comprehensive testing of pH, drip loss, water-holding capacity, and other visual and textural elements were performed to characterise the technological and textual component of total meat quality. These textural and visual meat quality measurements are largely peripheral to the analysis of tenderometer performance and tenderness measurements.

This investigation provided a large variety of meat samples with varying tenderness quality attributes for comparison of two objective tenderness measuring devices, the G1 tenderometer and G2 tenderometer and their correlation with tenderness as assessed by a trained sensory panel.

5.1.2.1 Animals and meat samples

Ten pasture-fed crossbreed steers were subjected to electrical stimulation post slaughter, packaging and aging treatments to improve meat quality. Animals were slaughtered at Auckland abattoir using a captive bolt. Carcasses were chilled in cold storage fridge with temperature of 2^{o}C post-mortem and then vacuum packed or placed in the foodcap. The loin from each side was removed.

5.1.2.2 Sample Preparation

Specimens were prepared from cooked loin and rump sections from ten animals and tested when hot and chilled. It is contentious as to which cooking technique provides the most controlled uniform level of ‘doneness’. Although efforts were made to ensure consistency in the thickness of steaks of 25 mm, variability in the sample size is not avoidable and finely controlled cooking is necessary. Water bath and grilling cooking methods were employed for each treatment and cut.

Grilling was performed on a pre-heated (180^{o}C) electric grill to cook approximately 25mm thick steaks to an internal end temperature of 70^{o}C, as measured by an electric thermometer. Samples assigned for cold tenderometer measurement were placed in thin plastic bags in an ice bucket to prevent the cooking process continuing once taken off the grill. Hot samples were immediately cut into standardised bites, which entails aligning muscle fibres aligned in a single direction with cross-section 10mm by 10 mm and length up to 50 mm. Cold samples were allowed to cool for between 4 hours and 1 day to a temperature of 2-4^{o}C and cut into bites for objective tenderness measurement on each tenderometer. Each steak produced ten bites for the G1 tenderometer and up to ten bites for G2 tenderometer. The number of samples available for G2 tenderness assessment is contingent on each steak providing a sufficient number of high quality standardised bites.

SEE OPERATING PROTOCOL FOR MORE DETAILED SAMPLE PREPARATION PROCEDUERES

The waterbath-based operating protocol for the developed tenderometer is based on the similar procedures used for Warner-Bratzler shear force and the modified slice shear force method. The undertaken procedures consist of heating fresh meat samples inside a plastic bag in a heated water bath either for a control time period to an internal meat sample temperature of 70^{o}C. Tenderness measurements are made on samples either immediately after cooking for hot testing or chilled for later cooled testing. Time between cooking and bite preparation has little effect on shear force values [36], however, core orientation and cooking conditions, as expected significantly affected shear force values.

5.1.2.3 Sensory evaluation of meat tenderness

Five trained testing panellist conducted sensory evaluation over five sessions at the Carne Technologies laboratories in Hamilton (NZ). Selection from a pool of regular well-trained panellists provided reliable evaluation of a broad range of meat quality properties.

Sensory meat samples in the form of 25 mm steaks were cooked from an initial temperature of ~4^{o}C to a final temperature of 70^{o}C in a Domestic Grill set at a temperature of 180^{o}C monitored with a thermometer. After cooking, steaks were cut into 15 mm cubes, which were placed into labelled containers/plates. Panellists assessed nine meat quality categories as shown in table 7. Panellists were instructed to cleanse the palate between samples with a bite of an unsalted cracker and a sip of water.

Stage	Attribute	Definition	Scoring
Stage 1 **Initial Bites** assessed during first 2-3 bites	**Firmness/Softness**	Force required to bite through the sample	0 = soft 9 = firm
	Initial Juiciness	The amount of moisture released during the initial bites	0 = dry 9= juicy
	Denseness	The compactness of the meat (density) Dense=compact/solid, airy/loose=spaces/gaps	0 = airy/loose 9 = dense
Stage 2 **Mastication** (Chewing Bites) assessed during mastication, 4-7 bites	**Tenderness**	The amount of force required to chew the sample the force which is required to disintegrate the sample	0 = tough 9 = tender
	Cohesiveness	How well the sample holds together during mastication loose & falls apart = non cohesive tight & held together = cohesive	0 = non cohesive 9 = cohesive
	Fibrousness	Strands of fibres perceived during breakdown of meat (the type and arrangement of the fibres)	0 = non fibrous 9 = fibrous
Stage 3 **Prior to swallowing** assessed after 8-12 chews	**Cohesiveness of Mass**	The degree to which the chewed sample holds together in a mass after mastication	0 = non cohesive 9 = cohesive
	Sustained Juiciness	Amount of moisture still remaining	0 = dry 9= juicy
	Chewiness/ Duration of Chews	Amount of work required to get sample to a state ready to swallow (number of chews required?)= effort /work required	0 =easy/low 9 =chewy/high effort

Table 2. Sensory panellists assess nine meat quality categories throughout the three stages of meat sample consumption.

5.1.2.3 Taste panellist meat quality scores

A trained taste panel at the Carne Technologies assessed the meat quality based on nine criteria, including tenderness, using a continuous unstructured 100mm line scale anchored by extreme terms such as extremely tough (0) and extremely tender (9). Other meat quality criteria included firmness/ softness, initial juiciness, denseness, cohesiveness, fibrousness and chewiness provide explanation of meat quality that are not expected to be measured with any reliability by the designed tenderometers and will not be investigated. The average score of the five panellists was used as the tenderness for each steak sample.

5.1.2.4 Objective Measurements- Shear Force

The generation one and prototype tenderometers are used to record the peak shear force required to completely penetrate loin and rump sample bites. The average scores of the ten bites were used as the objective tenderness measurement for each steak sample. Force-time data for each sample is recorded for each sample subject to the G2 tenderometer. This provides more information than we are currently interested in. Peak pressure measurements are the extent to which the G1 tenderometer provides. Therefore, comparison is only possible between peak shear force values of the two machines.

5.1.2.5 Statistical Analysis

Sensory tenderness scores were not adjusted for tasting sessions, taster, order of presentation, animal etc as suggested by Perry et al [64]. Relationships between sensory tenderness scores and objective measurements of shear force were examined for each treatment, cooking method and as a single sample. The homogeneity of the slope of the relationship between sensory and objective measurements was tested for significant differences. Primary interest is level of explanation of variation in tenderness provided by the G2 tenderometer compared to the taste panel and the G1 tenderometer. Correlation coefficients from univarate simple linear regression models indicate the proportion of variation in tenderness explained by the G2 tenderometer. Perry et al (2001) suggest that a curvilinear relation between sensory tenderness scores and objective tenderness exist. A quadratic term for shear force is included in an alternate model for examination.

The relationship between the shear force measurements of the G1 and G2 tenderometers are investigated to show that they measure similar tenderness properties and force measurements.

5.1.3 RESULTS AND DISCUSSION

5.1.3.1 Objective measurements using G1 versus G2 Tenderometer

A large range of tenderness, from both objective and sensory measurements of meat samples, were observed. However, large differences in sample distribution were not seen within different cooking techniques and different packaging treatments. Correlations between objective measures of tenderness provided by the two tenderometers, as illustrated in table 4, shows a close and significant ($P<0.05$) relationship. The observed relationship between each of the treatments provides only moderate level of explanation.

Testing for differences in shear force mean measurements from the two tenderometers suggests that there is statistically significant difference in mean shear force when investigating the vacuum-packed, loin and rump samples. Observed differences for the vacuum-packed loin and vacuum-packed rump and foodcap rump were -0.110, -0.104 and 0.494 KgF respectively. The shear force measurements for foodcap packaged loin and rump samples do not result in different average measurements. This may be explained by a smaller sample size and inferior quality of samples available for G2 tenderometer measurements. The G1 tenderometer was provided the first access to samples. In cases of small steaks or irregular muscle fiber orientation, either incomplete testing or testing of inferior bites

Muscle	Packaging Treatment	Mean Shear Force (KgF)		Standard Deviation		Observations
		G1	G2	G1	G2	(bites)
Loin	Food Cap	3.7284	3.8383	1.1299	0.6530	201
Loin	Vacuum	3.1661	3.6259	0.6121	0.6850	118
Rump	Food Cap	5.3571	4.8635	1.6692	1.3448	163
Rump	Vacuum	4.3672	4.4716	1.1122	0.7278	110

Table 3. Descriptive statistics for G1 and G2 tenderometer measurements of rump and loin steaks with FoodCap and vacuum packaging treatments

More importantly, a strong relationship between the shear force measurements from the two tenderometers is demonstrated in table 4 and figure 15. This strong positive relationship is anticipated since the tenderometer designs are based on the same principles of applying a shear force to measure the force to penetrate the meat samples using a similar shearing attachment.

A simple linear regression model, with the G1 tenderometer shear force being the dependent variable and G2 tenderometer shear force as the explanatory variable, describes the data with a moderate goodness of fit ($r^2 = 0.724$). The coefficient of the explanatory variable, 1.186, suggests that, on average we expect the existing G1 tenderometer to measure a shear force 18.6% higher than the prototype G2 tenderometer. This offers some suggestion as to why the mean tenderness scores are not statistically similar. The coefficient is significant at all conventional levels of significance ($P<0.0001$) indicating a strong relationship. However, it is not obvious why the slope coefficient is different to the expected one-to-one relationship. This observed slope coefficient, 1.186, is inconsistent with noted differences between the two tenderometers and their cutting attachments in section 6.6. The prototype tenderometer has been fitted with a slightly sharper cutting attachment than its precursor. Ceteris paribus, a more rounded blade would be expected to require a greater force to entirely penetrate any specimen. That is, the differences in cutting attachments would be expected to result in lower shear measurements provided by the G2 tenderometer.

A prototype tenderometer that consistently measures lower shear force does not present a major problem for the success of the G2 tenderometer since its function is to provide an explanation of tenderness rather than provide strong correlations with other measurements and machines. A shift in acceptability criteria for tenderness classifications would be a solution if underlying differences in measurements between the tenderometer were not identified. Current benchmark shear force measurements for acceptable tenderness are less than 8 KgF. The expected G2 shear force measurement would be approximately 6.74 KgF. At the current benchmark, there would be effectively a relaxing of tenderness acceptability criteria and lower levels of rejection.

Shear force measurements provided by the prototype tenderometer are a more direct approach compared to its predecessor. The G2 tenderometer records the force precisely applied to its load cell whilst the existing tenderometer measures shear force in a more roundabout manner by recording the maximum pressure to propel the drive arm downwards into the meat sample. Effects of friction inefficiencies from the pneumatic components of the G1 tenderometer are removed through a machine-specific calibration equation that transforms the pressure measurement into a shear force measurement.

Whilst it is impossible to know a ‘true’ value, the direct measurement by the G2 Tenderometer provides less opportunity for misreporting shear force of meat for meat tenderness measurement.

When a similar linear regression model for measured G1 and G2 shear forces is fitted to individual treatment and muscle data sets, there is a wide variation in quality of model fit. The loin vacuum-packed sample subset did not fit a linear model well, with a poor correlation coefficient ($r = 0.464$), coefficient of determination ($r^2 = 0.215$) and a regression coefficient only significant at a level of significance greater than 0.061 (p-value). However, the loin vacuum sample subset consisted of only 116 bites for G2 tenderness measurement, compared to 400 available to the G1 tenderometer. Data integrity is shown to be problem throughout this investigation with insufficient samples for G1 and G2 testing from many steaks due to size and irregular muscle fibre orientation. It is unusual to require twenty bites from a single steak and therefore the problem of inadequate samples is not likely to be encountered when using a single tenderometer. The remaining three treatments and muscle permutations demonstrated a strong positive relationship between the shear force measurements with the different tenderometer measurement techniques as shown in table 4.

Muscle	Packaging Treatment	Correlation Coefficient	Slope Coefficient	P-value of slope coefficient	Intercept
All Samples	All Samples	0.724	1.186	0.000	-0.902
Loin	Vacuum	0.215	0.489	0.061	1.425
Loin	Food Cap	0.620	1.362	0.000	-1.499
Rump	Vacuum	0.763	1.335	0.000	-1.602
Rump	Food Cap	0.721	1.054	0.000	0.232

Table 4. Linear regression models were fitted to model the shear force measurements to penetrate meat samples using the G1 tenderometer and G2 prototype tenderometer. This simple model was satisfactory in demonstrating a strong positive relationship in the rump vacuum, rump foodcap and loin food cap samples but not for the loin vacuum samples. Overall, the G1 and G2 tenderometer provided similar measurements of shear force.

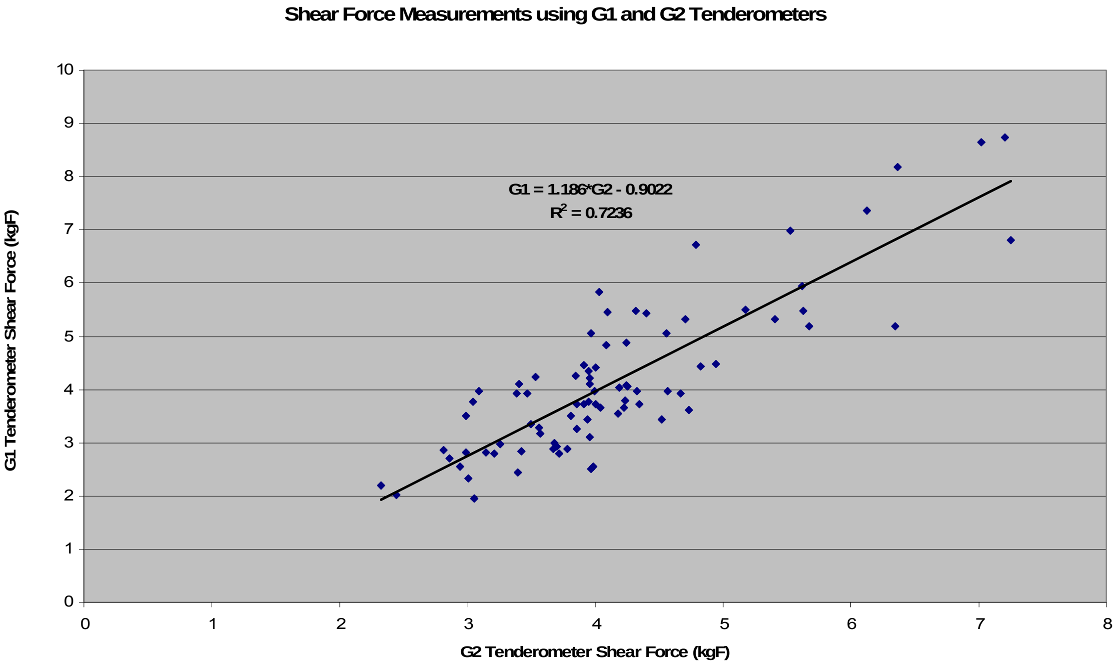

Figure 15. The use of different tenderness measurement techniques provides similar shear force values for a range of meat samples. A linear regression equation demonstrates that the G2 tenderometer measures similar

values of shear force to the existing G1 tenderometer. The strong relationship between shear force measurements of loin and rump beef samples with vacuum and foodcap packaging treatments is characterised by a positive relationship with a coefficient of determination, r^2= 0.732 and correlation coefficient, r= 0.851.

Previous investigations into the relationship between different shear-based objective tenderness measurements technique have provided strong correlation and that they apparently measure similar characteristics of the meat [65] and they account for a range of sensory quality attributes with tenderness being the most notable and possessing strongest correlation.

5.1.3.2. Sensory Tenderness and Objectives Measurements of G1 and G2

A negative relationship between sensory tenderness scores and shear force measurements provided by the G1 and G2 tenderometer has been shown to exist at moderate levels of precision. Overall correlations (r_{G1}= -0.581 and r_{G2} = -0.533) between sensory tenderness scores and generation one and generation two tenderometer shear force measurements were observed. The underlying relationship between shear force and sensory tenderness is demonstrated in figure 11 and figure 12 as a scattergram. The pattern, which is similar to that for other objective and sensory measures of tenderness, shows that with increasing shear force, sensory tenderness scores decreased in a linear fashion. Peachey et al (2002) demonstrated that measures of sensory tenderness (hardness, cohesiveness, toughness and chewiness) were closely correlated with each other, and that mechanical measures using a

Warner-Bratzler device, a MIRINZ tenderometer and a compression cell in an Instron device provided varying levels of correlation [66].

Curvilinear relationships have been reported for beef tenderness as assessed by trained panellist and objective shear force values. Specifically, a quadratic term for the shear force measurement has be used to develop a more useful prediction model for tenderness of young and old beef animals [66, 67]. In this investigation, a quadratic model provided a slightly more accurate model for prediction of sensory tenderness scores from shear force measurements from the G1 tenderometer and G2 prototype as shown in table 7. The experimental observations fit a quadratic model with 29% and 35% of the variation in sensory tenderness scores being provided by the G1 and G2 tenderometer shear force measurements respectively. These adjusted coefficients of determination reflect the variation in sensory tenderness scores explained by objective measurements, correction for the second explanatory variables introduced in the quadratic model. A direct comparison of the adjusted-r-squared of for the quadratic models and linear models suggest that a quadratic model is more appropriate as it provides a more powerful explanation (higher adjusted r-squared). The coefficients of quadratic term (shear force squared) are not significantly different from zero at a five percent level of significance. However, they still provide improved explanation of sensory tenderness.

G1 Vs Sensory

Muscle	Packaging Treatment	Coefficient of Determination (R^2)	Pearson Correlation Coefficient (r)	Slope Coefficient	P-value of slope coefficient	Intercept	Observations (bites)
All Samples	All Samples	0.339	-0.582	-0.832	0.000	9.143	592
Loin	Vacuum	0.521	-0.721	-0.439	0.001	6.105	201
Loin	Food Cap	0.411	-0.644	-1.466	0.000	12.989	118
Rump	Vacuum	0.011	0.104	0.186	0.711	3.349	163
Rump	Food Cap	0.212	-0.461	-0.641	0.036	8.808	110

G2 Vs Sensory

Muscle	Packaging Treatment	Coefficient of Determination (R^2)	Pearson Correlation Coefficient (r)	Slope Coeffecient	P-value of slope coeffecient	Intercept	Observations (bites)
All Samples	All Samples	0.339	-0.533	-0.532	0.000	8.215	592
Loin	Vacuum	0.521	-0.384	-0.665	0.128	9.077	201
Loin	Food Cap	0.411	-0.634	-0.480	0.000	8.158	118
Rump	Vacuum	0.011	0.079	0.068	0.779	5.163	163
Rump	Food Cap	0.212	-0.393	-0.351	0.078	7.088	110

Table 6 and 7. Linear models were fitted to describe the explanation in tenderness provided by the G1 and G2 tenderometer and sensory taste panellists. Observed levels of explanation provided by G1 and G2 tenderometers for rump vacuum treatments are not significant. Our two tenderness measurement devices provide satisfactory description when the entire data set is considered.

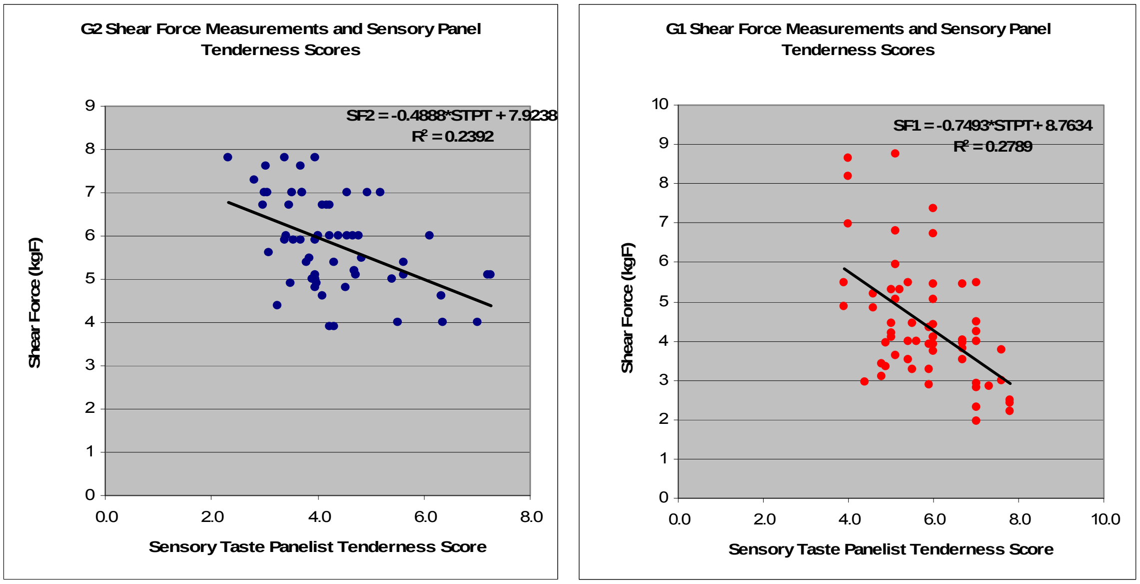

Figure 16 & 17. Objective shear force (tenderness) measurements provided by the G1 and G2 tenderometer provided modest correlation with sensory taste panel tenderness scores.

Regardless of the model of choice, both shear force measurements can not account for relatively large amounts of the underlying tenderness as determined by taste panellists. It is common practice to measure other properties to assess meat quality which may complement shear force measurement by a tenderometer. However, as an objective principal tenderness measurement, both tenderometers can only account for a small portion of meat quality variation. This is contrast to previous general practice and unpublished investigations into the effectiveness of the G1 tenderometer. The G1 tenderometer has shown strong correlations with Warner-Bratzler shear force measurements as well as trained sensory panellists at AgResearch and recently with Carne Technologies.

A variety of objective tenderness measurement techniques have reported an extremely large range of significant correlations between sensory tenderness and their objective measurements.

Shear Force Measurement	Fitted Model	Adjusted coefficient of determination (r^2_{adj})	Coefficient of linear term (β_1)	p-value of linear term	Coefficient of quadratic term (β_2)	p-value of quadratic term
G2 Tenderometer	Linear	0.27	-0.53	0.00	*n/a*	*n/a*
G2 Tenderometer	Quadratic	0.29	-1.42	0.02	0.09	0.14
G1 Tenderometer	Linear	0.33	-0.41	0.00	*n/a*	*n/a*
G1 Tenderometer	Quadratic	0.35	-0.99	0.00	0.06	0.06

Table 8. Linear and quadratic models were fitted to shear force measurements from the two tenderometers to attempt to explain sensory taste panel tenderness scores. There is some evidence that a curvilinear relationship exists between sensory and objective tenderness measures.

The MIRINZ tenderness probe accounted for only 4 to 13% of the variation in cooked tenderness of the longissimus with correlations of only -0.15 to -0.30 [32]. Clearly the G1 and G2 tenderometers provide a more useful objective method of estimating cooked meat tenderness.

Why the low levels of correlation between sensory and objective measures?

Tenderness is well acknowledged as a complex element of meat quality to measure since it is influenced by a plethora of factors. The non-linear relationship between sensory and mechanical assessments can be due to the non-linearity in sensory evaluation. That is, when meat is very tender or very tough meat tends to be difficult for sensory panellists to differentiate between the samples at extreme end of the tenderness spectrum.

Muscle fiber orientation is easier to control in instrumental testing using the tenderometers than in sensory evaluation. Structural changes of the meat occurring during rigor development are both longitudinal and lateral contraction of the myofibrillar mass.

Other factors responsible for the relatively weak predictability of tenderness by the instrumental tenderometer shear force measurements are the repeatability of the taste panel, the repeatability of the tenderometer shear force measurement [62], the variation in tenderness over the striploin (*longissimus lumborum)* and rump, the composite (muscle fibers and connective tissue) and anisotropic nature of meat and the intrinsic differences between shearing of standardised ‘bite’ and the biting of grilled meat.

Bouton et al. (1975) suggested that the lack of a closer relationships between objective and subjective measures of tenderness could be explained by sampling variation and the fact that stress and strain patterns developed in the mouth, during chewing and mastication of meat can not adequately represented by instrumental techniques.

Waterbath versus grilling cooking methods

Table 9 shows the number of samples, mean and standard deviation of the different tenderometer shear force measurements under varying cooking and sample testing protocols. These results indicate that the tenderometers provide similar measurements, given cooking method, muscle origin and testing temperature. That is, the tenderometers measure the same properties. More importantly, table 9 and 10 allows us to compare the effects of cooking method (grill or waterbath) and testing temperature. Grilling of raw meat instead of heating in water resulted in a decrease in the average tenderometer shear force value ranging from 8.1-18.7%. Overall, the average grilled samples recorded 13.9% lower tenderometer shear force measurements.

Steaks cooked in the water bath required longer cooking time to reach the endpoint temperature [68], which result in more myofibrillar toughening, collagen shrinkage, and cooking losses. Collagen is theorized to solubilise more with holding time at certain temperatures (especially between 60 and 64 °C) so it would be expected that with water-bath cooking more collagen would be solubilised resulting in tougher meat. These observed differences result in difficulties in interpretation and categorising samples as tender or tough when standards are imposed, such as the current benchmark for acceptable tenderness of 8 KgF.

Cooking Method	Testing Temperature	Muscles	G1 Mean Shear Force ± Standard Deviation (KgF)	G2 Mean Shear Force ± standard Deviation (KgF)	Observations (bites)
Grill	Cold	Loin	3.66 ± 1.00	3.79 ± 0.61	103
Grill	Cold	Rump	4.75 ± 1.52	4.60 ± 0.93	78
Grill	Hot	Loin	2.96 ± 1.12	3.25 ± 0.58	88
Grill	Hot	Rump	4.34 ± 1.08	4.08 ± 0.70	65
Grill	**Hot and Cold**	**Rump and Loin**	**3.86 ± 1.33**	**3.89 ± 0.83**	**342**
Water Bath	Cold	Loin	4.03 ± 0.88	4.13 ± 0.62	57
Water Bath	Cold	Rump	5.38 ± 1.36	5.12 ± 1.34	65
Water Bath	Hot	Loin	3.51 ± 0.78	3.84 ± 0.51	77
Water Bath	Hot	Rump	5.34 ± 2.05	4.99 ± 1.36	65
Water Bath	**Hot and Cold**	**Rump and Loin**	**4.51 ± 1.51**	**4.49 ± 1.12**	**264**

Table 9. Descriptive statistics show the impact of different cooking methods on tenderness of the cooked meat samples

Muscle	Testing Temperature	G1 Shear Force Difference (Waterbath- Grill), kgf	Percentage Difference	G2 Shear Force Difference (Waterbath- Grill), kgf	Percentage Difference
Loin	Cold	0.37	9.3%	0.34	8.1%
Rump	Cold	0.63	11.6%	0.52	10.2%
Loin	Hot	0.54	15.5%	0.59	15.4%
Rump	Hot	1.00	18.7%	0.92	18.4%
Rump and Loin	**Hot and Cold**	**0.65**	**14.5%**	**0.60**	**13.3%**

Table 10. The waterbath cooking method resulted in higher shear force measurements using both tenderometers

A linear regression model was fitted to the sensory scores and tenderometer shear force measurements to demonstrate the variation in precision of tenderness classification under different cooking regimes. Table 11 shows that the different tenderometer shear force protocols and tenderness scores give similar variation coefficients of 25-47%. It is difficult to conclude whether grilling provides improved precision in estimation of tenderness with contrasting results for cold and hot sampling. Overall, the variation in tenderometer measurements of grilled samples provided explanation of 35.3% of the variation in sensory scores compared to a 33.5% explanation by waterbath-cooked samples. This is not a significant difference at a 5% level of significance.

Cooking Method	Testing Temperature	Coefficient of determination (R-squared)		
		G1 Tenderometer	G2 Tenderometer	Average
Water Bath	Cold	0.254	0.228	0.241
Water Bath	Hot	0.473	0.408	0.440
Water Bath	**All**	**0.346**	**0.324**	**0.335**
Grill	Cold	0.290	0.308	0.299
Grill	Hot	0.397	0.341	0.369
Grill	**All**	**0.383**	**0.323**	**0.353**

Table 11. A linear model for sensory scores and tenderness shear force measurements applied to sub-samples based on operating protocol.

Samples that were tested using the tenderometer immediately after cooking (whilst still hot) provided improved accuracy in explaining variation in sensory tenderness compared to samples that were stored and chilled to approximately 4°C before testing. Hot sampling provided improved coefficients of determination for each of the four combinations of tenderometers and cooking method. When using the waterbath cooking method, the effects of temperature of samples at testing is particularly significant with almost twice the coefficient of determination with the G1 tenderometer ($r^2_{Hot} = 0.473$ and $r^2_{Cold} = 0.254$) and G2 tenderometer ($r^2_{Hot} = 0.408$ and $r^2_{Cold} = 0.228$). Indeed, the optimal operating procedure is to test waterbath cooked immediately after they have been cooked. The reduced accuracy of tenderness prediction from chilled samples is derived from the impacts of additional storage time.

Cooking Method	**Testing Temperature**	**Coefficient of determination (R-squared)**		
		G1 Tenderometer	**G2 Tenderometer**	**Average**
Water Bath	Cold	0.254	0.228	0.241
Water Bath	Hot	0.473	0.408	0.440
Water Bath	**All**	**0.346**	**0.324**	**0.335**
Grill	Cold	0.290	0.308	0.299
Grill	Hot	0.397	0.341	0.369
Grill	**All**	**0.383**	**0.323**	**0.353**

Therefore, in an attempt to mimic the way consumer evaluate meat tenderness meat samples grilled before tenderometer shear force evaluation provided improved precision of tenderness prediction compared to waterbath cooking [69].

6. CONCLUSION

Results of this series of experiments indicate that the *generation two tenderometer* provides a quick, viable alternative to the existing *generation one tenderometer* for obtaining an objective estimate of cooked meat tenderness. The design and construction for the prototype G2 tenderometer successfully reproduces the shearing loading conditions of the G1 tenderometer and results in a more direct measurement of the required force to penetrate the meat sample.

A strong positive relationship between the shear force measurements of the G1 and G2 tenderometers was demonstrated over a range of levels of meat toughness. Our prototype provided similar precision in evaluation of tenderness when observed shear force values were compared to sensory tenderness scores. Finally, a recommended operating protocol is proposed based on the accuracy of objective tenderness measures provided by the two tenderometer. The recommended procedure features cooking by a waterbath and testing hot samples.

Our prototype tenderometer has begun to replace the existing G1 tenderometer at Carne Technologies for routine tenderness measurement and we anticipate its application to expand into other research environments and beyond.

7. FUTURE IMPROVEMENTS

DISADVANTAGES OF THE G2 TENDEROMETER

This prototype provides limited advancement on previous attempts Warner-Bratzler and Slice Shear Force with respect to the underlying concept of applying a linear shear force. Alternate approaches, such as the MIRINZ tenderness probe and the Tendertec, attempt to provide increased levels of explanation of tenderness through innovative mechanical measures. For example, the MIRINZ tenderness probe, attempt to apply a torque to meat sample to break down the myofibrillar muscle components in tension as well as shear provided some degree of precision in estimating palatability attributes [32]. Regardless, a simple application of a shear force applied perpendicular to muscle fibers continues to most closely simulate a biting action which bears strong relation to tenderness [9]

Sample preparation continues to be key factor in determining repeatable and reliable tenderness measurement. As with slice shear force, the repeatability is highly dependent on the angle at which muscle fibers are sheared [62]. It is critical that the samples be obtained in a manner such that the shearing action is perpendicular to the longitudinal orientation of muscle fibres. As a result, most testing is performed on longissimus meat samples [70]. Procedures may be more complicated by other specimen origins [35, 71]. But since most variation among carcasses in tenderness of LM than any other muscles group, most research is performed using LM samples. User-dependence in operation of the tenderometers is not substantial but correct preparation of the sample bites continues to of utmost importance.

The ultimate goal of objective meat quality measurement is for rapid online measurement devices that can be incorporated into the processing chain within the meat processing plant. Tenderness measurement with this tenderometer technique provides a means for testing in a variety of environments due to its mobility but will not be suitable for online testing since it still requires cooking and meticulous preparation of meat samples. Testing of raw samples for the prediction of tenderness is not likely to provide strong explanation based on the disappointing precision of past attempts to characterise raw meat samples using mechanical testing methods [2, 51, 67, 72, 73]. However, testing of raw samples and specifically, properties other than peak shear force from a force-deformation chart and data provide promise [51].

FURTHER DEVELOPMENTS

In order to simplify operation of the tenderometer so that there is limited user dependence it is necessary to automate the loading cycle. This will reduce the probability of occurrences causing incomplete and unreliable measurements. Simple examples include ensuring that the actuator does change its direction of operation before the meat sample is completely penetrated. Current operation requires the user toggle a control switch to reverse the polarity of the power supply to alter the movement of the specimen platform from up to down and requires. This assumes that the user does not prematurely reverse the switch and that they recognise that the bites are completely penetrated only once the limit switch is triggered to stop the motor. There are a variety of features that will be addressed and modified for widespread implementation beyond the current uses in the Carne Technologies laboratories.

Force-Deformation Curve and Textural Attributes

A substantial contribution from the development of a new tenderness measuring device has been the desire to further characterise the behaviour of meat samples under compression and shear loading. It is anticipated that the force-deformation curve derived from the force-time trace provided by the G2 tenderometer will provide new means of predicting meat quality attributes other than tenderness. Specifically, textural properties including fibrousness and cohesiveness may be objectively determined from features such as area under trace up to inflexion at 20% of max load.

Apply control systems to replicate (program) loading conditions to simulate mastication

  - Automated repetition of cycle
  - Sinusoidal, square wave, sawtooth etc

In a study of the masticatory pattern of meat, using strain gauges attached to a prosthetic appliance, the number of chewing cycles, not the maximum load, was the best single indicator of the sensory impression of meat texture [74]. An even higher, significant correlation with toughness was achieved, when loading rates of the recordings were included. If one approximates the strain-time recordings as the force-deformation curves of the material studied, the loading rate should reflect a mean of complex moduli obtained during the deformation and fracturing of meat.

If toughness is to be more strictly defined in physical terms, not only should the work of deformation and failure be considered but also the types of forces involved and the anisotropy of the whole muscle. The mechanical forces acting on meat can include shear, compressive and tensile forces and they should be defined in the mechanical test in use. As meat is a composite, it is important to study in which structural elements failure takes place, and where cracks propagate, to be able to understand its mechanical properties.

COMPRESSION AND SHEAR

Future studies will look into the tenderness prediction capabilities and further textural aspects of to indicate meat quality using a blunt compression attachment. The measurements obtained by compression action tend to be more indicative of the connective tissue contribution to meat tenderness while the shear forces reflect mainly the myofibrillar contribution [75]. By cooking at lower temperatures for the compression measurements it is possible to increase the probability of detecting the differences in connective tissue characteristics and their impact on tenderness.

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