TENSILE PROPERTIES AND WARNER-BRATZLER TENDERNESS MEASUREMENT OF RAW AND COOKED BEEF

R. Lu, Y.-R. Chen, M. B. Solomon, B. W. Berry

ABSTRACT. *Tensile tests and Warner-Bratzler (WB) shear tests were performed to study the mechanical properties of beef and their relationship with WB tenderness measurement. Four bovine muscles, biceps femoris (BF), longissimus dorsi (LD), semimembranosus (SM), and semitendinosus (ST), were used. The experiment was conducted in a randomized complete block design where muscle type, cooking status, and aging were treatments and animals as blocks. Results showed that raw muscles exhibited all or some of the elastic, stress-yielding, and work-hardening behaviors in tension. The work-hardening behavior generally disappeared in cooked beef. Cooking resulted in a significant ($P < 0.05$) increase in the maximum tensile force, ranging from 65% for BF muscle to 144% for SM muscle. The strain energy at break did not change significantly for BF, LD, and SM muscles after cooking but increased significantly for ST muscle. Muscle type had a considerable effect on the relationship between tensile properties and WB shear measurements. The correlation between WB shear value and the maximum tensile force for cooked beef was significant for LD and SM muscles ($r = 0.65$ and $r = 0.48$, respectively) and was not for the other two muscles. There was also a significant correlation ($r = 0.64$) between WB shear value of cooked beef and the maximum tensile force of raw beef for LD muscle.*
Keywords. *Meat, Beef, Tenderness, Mechanical properties.*

Tenderness is one of the most important quality attributes of meat. A number of objective techniques have been investigated in the past to measure tenderness from raw or cooked meat, which include mechanical, chemical, ultrasonic, and optical (Chrystall, 1994). However, only mechanical techniques are currently used/recommended for measuring tenderness from cooked meat or its products. Among them, the Warner-Bratzler (WB) shear device is the most commonly used and has been recommended as a standard by the American Meat Science Association (AMSA, 1995).

During the WB measurement, a cooked meat specimen is placed in a triangular opening of the shearing blade whose edges are beveled to a semicircle. As the blade is pulled through the slot, the specimen is sheared into two parts. The maximum force recorded is considered to be a measure of meat tenderness. Due to the complex loading pattern and the difficult-to-characterize mechanical properties of meat, it is not clear how the meat specimen actually fails during WB shearing. The conventional interpretation, as the device's name indicates, is that shear forces are responsible for cutting the meat specimen. Other researchers (e.g., Voisey, 1976), however, argued that meat specimens primarily fail in tension during WB shearing. Validation of these interpretations has yet to be demonstrated, which is crucial for furthering our understanding of WB shearing process and, therefore, tenderness measurement. Apparently, the key to understanding WB tenderness measurement lies in understanding of the fundamental mechanical properties of meat.

Considerable research has been conducted with regard to mechanical properties of meat and their relationship with tenderness measurement (Chrystall, 1994; Lepetit and Culioli, 1994; Tornberg, 1996). Tensile tests have been used to study mechanical properties of raw and cooked beef in relation to muscle structures and their changes caused by post-mortem treatments and cooking process (Bouton and Harris, 1972; Bouton et al., 1975; Carroll et al., 1978; Dansfield et al., 1995; Locker et al., 1983; Mutungi et al., 1995; Penfield et al., 1976; Rao and Gault, 1991; Sacks et al., 1988). Several studies have been reported on how tensile properties of cooked beef are related to tenderness measurement. Bouton and Harris (1972) performed WB shear and tensile tests on cooked beef from *longissimus dorsi*, *semimembranosus*, and *deep pectoral* muscles. They reported that WB shear value was correlated with tensile strength of beef for each muscle and that the relationship was strongly influenced by muscle type. Davey and Gilbert (1977) reported that shortening treatments influenced the tensile force-deformation behavior of raw *stenomandibularis* muscle. They found that beef tenderness, as measured by the MIRINZ tenderometer, was correlated ($r = 0.81$) with the tensile strength of cooked meat.

For the purposes of quality control, it is important to be able to predict tenderness of cooked meat from raw muscle.

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Considerable effort has been made to develop methods or techniques to predict tenderness from raw meat and a review on recent developments in this area is given in Chrystall (1994). A number of mechanical devices have been reported (e.g., Hansen, 1972; Phillips, 1992; Smith and Carpenter, 1973), but none of them has been adopted commercially primarily due to the unsatisfactory results in predicting meat tenderness. There is still a lack of understanding of the relationship between mechanical properties and tenderness measurement, particularly for beef. Stanley et al. (1972) conducted a study on raw porcine *psoas* muscle to determine how tenderness, measured using both sensory evaluation method and WB shear device, was related to its tensile properties. They found that correlations between WB shear value and tensile properties were either low or insignificant. However, the tensile properties, including breaking strength and elongation at break, were significantly correlated with the sensory evaluation of tenderness. It is not clear whether the findings of Stanley et al. (1972) are also applied to beef since beef has different texture from pork. Furthermore, little is known about whether or how tensile properties of raw and cooked beef are related to each other and how they are related to tenderness as measured by WB shear device or sensory evaluation. Also, it is important to know whether WB shear value measured from cooked beef is related to that from raw muscle. Quantification of these relationships will help us better understand WB tenderness measurement and develop an effective method to predict tenderness from raw muscle.

Therefore, the objectives of this study were to:

1. Evaluate and characterize the tensile properties of four bovine muscles before and after cooking;
2. Determine the shear values of raw and cooked beef using the Warner-Bratzler shear device; and
3. Quantify the relationship of the tensile properties and WB shear measurements between raw and cooked beef, and the interrelationship between the tensile properties and WB shear measurements.

Materials and Methods

Materials

Four bovine muscles, *biceps femoris* (BF, bottom round), *longissimus dorsi* (LD, strip loin), *semimembranosus* (SM, top round), and *semitendinosus* (ST, eye of round), were used in this study. Ten intact pieces of each muscle were obtained from carcasses of ten animals (one piece per muscle per carcass) with unknown history from a commercial pack house within 48 h after slaughtering over a period of two months. All carcasses from which muscles were obtained had been graded as U.S. Select and Yield Grade 2. After the removal of excessive subcutaneous fat and visible connective tissue, the muscles were then divided into two or three sections, depending on their size. These muscle sections were further cut into two equal-size (symmetrical) samples; one would be tested raw and the other tested after cooking. The average weight of these muscle samples was about 815 g (± 248 g). All muscle samples were then vacuum packed and subjected to different aging treatments. All symmetrical pairs of samples were subjected to the same aging treatments before being tested in raw or cooked. About two-fifths of the samples were tested without aging; two-fifths were aged at 4°C for one week; and the remaining samples were aged for two weeks. Aging treatments were intended to obtain meat with various degrees of tenderness and not to study the aging effect on meat mechanical properties and tenderness. After completing the aging treatments, all samples were placed in a walk-in freezer at –20°C until cooking and/or mechanical tests.

Cooking

Cooking was conducted following the procedure recommended by AMSA (1995). The frozen samples were thawed at 4°C for 36 h to allow their internal temperature to reach 4°± 2°C prior to cooking. Cooking was conducted using convection ovens/broilers (Farberware Turbo ovens, Model T4850, Bronx, N.Y.) preheated to 163°C. Temperatures at the center of the samples were monitored using a J-type iron-constantan thermocouple. All meat samples were cooked to the final temperature of 71°± 2°C. Cooked samples remained at room temperature for about two hours, then sealed in plastic bags and placed in cold storage at 1°C.

Specimen Preparation

Specimens were excised from raw and cooked muscle samples to determine their tensile properties and WB shear values. The raw samples were removed from the freezer and placed in a walk-in cooler at 1°C for 12 h before mechanical testing. At the time when specimens were about to be excised, the muscle samples remained frozen (at about –6° to –2°C) because it was difficult to excise specimens to the specified size from thawed, soft muscle samples. Two slices of meat with a thickness of 5 mm were obtained from each muscle sample parallel to the muscle fibers, using a meat slicer. These meat slices were then trimmed to the final dimensions of 5 mm thick, 15 mm wide, and no less than 9 mm long.

For WB shear tests, two core specimens of 15.8-mm diameter were obtained parallel to the muscle fibers from the same muscle sample from which tensile specimens had been excised. The core diameter was greater than the one (12.7 mm) recommended by AMSA (1995) but was well within the range between 13 mm and 25 mm reported in the literature (Zhang and Mittal, 1993). The same procedure was applied to obtain specimens from cooked samples for tensile and WB shear tests, with the exception that these samples remained at 1°C at the time specimens were excised. All specimens were kept in plastic plates and allowed to reach room temperature before mechanical tests were conducted.

Mechanical Tests

Mechanical tests were conducted using an Instron universal testing machine (Model 4464) equipped with a 500-N load cell and a computer data acquisition system. Gripping of meat specimens for tensile tests was achieved by mounting self-gripping fastening strips made of nylon to the metal gripping plates. These nylon-fastening strips provided sufficient friction to hold meat specimens tightly during the tensile test, and they did not cause damage to specimen tissues. The gauge length for the tensile tests was set at 41 mm and the loading speed at 30 mm/min.

The crosshead was stopped after the specimens were ruptured completely. The force-deformation curve for each specimen was recorded for later analyses. Data for those tests in which specimens failed at the gripping points were discarded.

WB shear tests of meat tenderness were conducted at a loading speed of 200 mm/min (ASMA, 1995) using a WB shear test cell mounted on the Instron machine.

Data Analyses

The tensile curves of muscle specimens were markedly nonlinear (see the Results and Discussion section) and exhibited some unique characteristics that cannot be described by existing rheological models developed for other foods and biological materials. The property parameters extracted from the force-deformation curves include maximum force and the corresponding deformation or elongation, force and deformation at break, and strain energy at break. A specimen was considered broken when the force dropped 30% or more without increase in deformation. However, there were specimens that did not show a sudden drop in force before they were completely ruptured or broken. These specimens were considered to be broken when the force was less than 0.2 N. Because of the difficulty in determining the exact breaking point in some raw specimens, the data on breaking force and stretch for raw specimens were not as consistent as one would otherwise like to have. Therefore, in the following discussion emphasis will be on the maximum tensile force and stretch at maximum force and strain energy at break.

For WB shear data, only the maximum force was extracted from each force-deformation curve since this is the value currently used to measure meat tenderness.

Statistical analyses were performed using SAS software (SAS, 1996). The data were first averaged over two measurements from each muscle sample. Analyses of variance were first performed on the pooled data for all four muscles, where the experiments were considered a randomized complete block design in which muscle type (4), cooking status (2, i.e., raw or cooked), and aging (3) were treatments and animals (10) were blocks. Further analyses of variance were performed for each muscle to determine how cooking affected the measured properties. Finally, correlation analyses were performed between tensile properties and WB shear value.

Results and Discussion

Tensile Behavior

Raw Muscles. Figure 1 shows five typical tensile force-deformation curves from single raw specimens of four muscles. Raw muscle specimens exhibited some unique characteristics in their tensile force-deformation behavior that most biological materials and foods, such as horticultural products, grains, woods, do not possess (Mohsenin, 1986). Broadly speaking, raw muscle specimens exhibited all or some of the three general behaviors: linearity at small deformations, stress yielding at intermediate deformations, and work hardening (or stiffening) at large deformations. When deformation was small, there often existed a linear relationship between force and deformation. As deformation further increased, stress yielding started in muscle tissue. This was characterized by the decrease in the slope of the force-deformation curve, as shown more prominently in curves A and B of figure 1 and less obviously in curves C, D, and E. Finally, as deformation continued to increase, muscle tissue started to harden; the slope of the force-deformation curves increased with deformation (curves D and E).

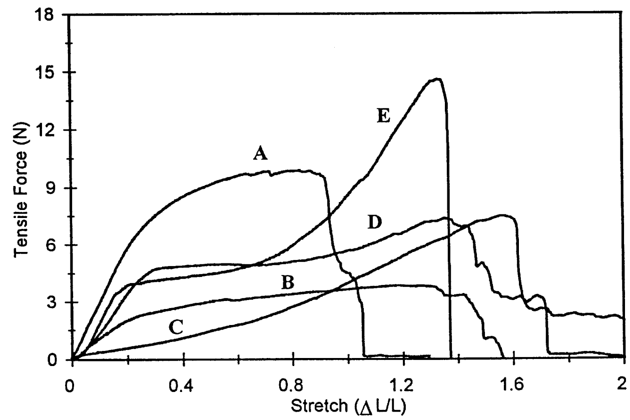

Figure 1–Typical force-deformation curves from single raw specimens of four bovine muscles subjected to tensile load at a loading speed of 30 mm/min.

The tensile curves presented in figure 1 were observed in all four muscles. However, specimens from a particular muscle tended to have a higher probability of exhibiting one or two particular types of tensile behavior. Curves A and B in figure 1 clearly exhibited the first two characteristics, which were more typical of LD and SM muscles. Curve C showed linearity and work hardening but did not have the stress-yielding characteristic. The C-type curves were observed only in a small number of specimens and mainly in BF muscle specimens. Curves D and E had all three characteristics and were more common for BF and ST muscles. The tensile force-deformation curves of muscle tissue, especially curves D and E of figure 1, are very similar to those of rubber, although rubber normally can sustain higher strains before being ruptured. The discussion of the force-deformation curves in view of muscle structures is given in Lu et al. (1997). The force-deformation curves similar to those presented in figure 1 from this study have been reported previously, although not all in one single study (Davey and Gilbert, 1977; Mutungi et al., 1995; Rao and Gault, 1990; Sacks et al., 1988).

Cooked Beef. The typical force-deformation curves for single cooked specimens in tension are shown in figure 2. Cooked beef exhibited the tensile behavior similar to the type A or B curve in figure 1 for raw muscles and rarely had a curve like those of type C, D or E. In other words, the work-hardening phenomenon, one important characteristic for some raw muscle specimens, had disappeared after cooking. This may be an indication that collagen in the connective tissue network had been greatly weakened during cooking. Cooked specimens generally had a higher slope (or Young's modulus) in the initial part of the force-deformation curves. Stress yielding for cooked specimens appeared to occur at approximately the same deformation level as that for raw specimens. In the stress-yielding region, the stress continued to increase with deformation at a rate normally higher than that for raw muscle specimens.

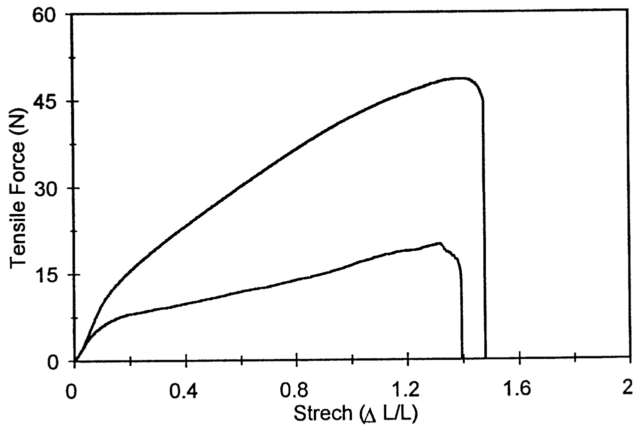

Figure 2–Typical force-deformation curves from single cooked specimens of four bovine muscles subjected to tensile load at a loading rate of 30 mm/min.

For a majority of cooked specimens, a dramatic drop in force was observed when they were ruptured or broken. These results indicated that cooking had produced different effects on muscle fibers and connective tissues. The elasticity (as measured by the slope of the initial portion of the curve) and tensile strength of muscle fibers increased after cooking while that of the connective tissues appeared to decrease. Further discussion on the cooking effect on the beef tensile properties is given in a later subsection.

Warner-Bratzler Shear Curves

Figure 3 shows typical force-displacement curves from the WB shearing of single raw and cooked specimens for the same LD and ST samples. Similar curves were also obtained for the other two muscles. Differences between raw and cooked specimens are evident in their respective force-displacement curves. When a raw muscle specimen was subjected to WB shearing, the force-displacement curve had an upward trend; its slope increased with increasing displacement of the blade. Most raw muscle specimens had a relatively smooth force-displacement curve before the maximum force was reached. The force increased dramatically just before reaching the maximum, and it had a sudden drop thereafter. This dramatic increase or decrease appeared to be related to the connective tissue. Moller (1981) analyzed the WB shear curves of ST muscle specimens heated in water bath at various temperatures. He reported that the force corresponding to the point where a dramatic change occurred reflected the contribution from muscle fibers and that the force at peak (or the final yield point) was due primarily to the connective tissue. Hence, the connective tissue in raw muscle had a considerable contribution to the maximum force during WB shearing. Specimens from LD muscle normally had a lesser increase or decrease in force around the peak, while the ST muscle specimens often showed a sharper peak. The different force-deformation responses around the peak for the two muscles could be due to the difference in the amount of connective tissues in the two muscles. According to Schön (1977), the amount of connective tissue is low in LD muscle and high in ST muscle.

Cooked beef specimens had a smoother force-displacement curve until the maximum was reached (fig. 3). During the initial shearing, the force-displacement

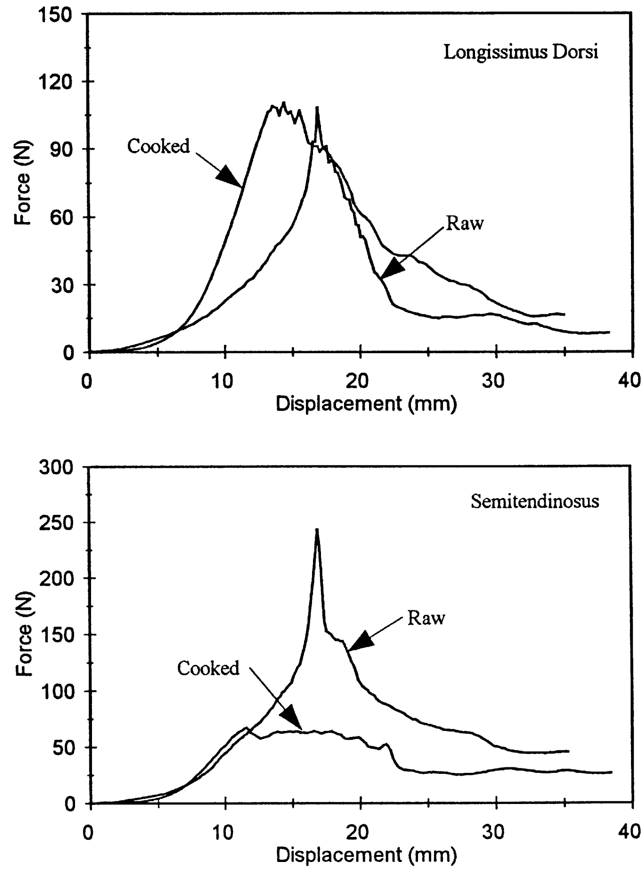

Figure 3–Typical force-displacement curves for single raw and cooked specimens from the same *longissimus dorsi* and semitendinosus muscles under Warner-Bratzler shearing at a loading rate of 200 mm/min.

curve was nonlinear. As the blade continued to shear the specimen, the slope of the force-displacement curve changed little and sometimes even showed a slight decrease before the maximum force was reached. The displacement from the start of shearing to the point where the maximum force was reached was smaller for cooked beef than for raw beef. Unlike raw specimens, cooked beef generally did not show a dramatic change around the peak. This again indicates that collagen in the connective tissue network had been solubilized during cooking and therefore had a lesser contribution to the WB shear value. Moller (1981) reported that the contribution of muscle fibers to WB tenderness measurement increased as the end-point temperature of beef increased from 60°C to 80°C, while that of connective tissue decreased. He further stated that changes in muscle fibers due to cooking had a toughening effect on meat, whereas changes in connective tissue had a tenderizing effect. The observations from this study appeared to agree with these findings.

Tensile Properties of Raw and Cooked Beef

The results from ANOVA on the effect of muscle type, cooking status, and aging on the measured mechanical properties are presented in table 1. As expected, the measured tensile properties were significantly influenced by muscle type ($P < 0.01$). Cooking also significantly affected all measured property values ($P < 0.01$). The effects of aging on tensile properties varied from insignificantly for

Table 1. Analysis of variance on the measured properties† of beef from four types of muscle

Source	D.F.	Mean Squares F_x	λ_x	F_B	λ_B	W_B	WB
Muscle (M)	3	1302.9**	26648.0**	413.3**	22197.2**	1.3**	10535.4**
Cooking (C)	1	2406.0**	290347.8**	431.9**	289309.1**	0.5**	39852.4**
Aging (A)	2	253.7**	460.2	36.1	444.1	0.4**	242.6
Animal (B)	9	60.4*	1382.4	24.4	1944.2**	0.1*	6725.8**
M × C	3	162.0**	21144.3**	171.7**	13445.5**	0.3**	18679.5**
M × A	4	8.1	2259.4*	12.0	2379.1*	0.2	601.2
C × A	2	146.5**	7517.6**	35.6	6841.3**	0.2*	420.4

* P < 0.05.
** P < 0.01.
† F_X — maximum force; λ_X — stretch at maximum force; F_B — force at break; λ_B — stretch at break; W_B — strain energy at break; WB — Warner-Bratzler shear value.

break force and the strain at maximum force and at break to significantly for maximum force (P < 0.01) and strain energy (P < 0.01). It should be mentioned that the inclusion of the aging factor in the experiments was primarily to obtain various degrees of tenderness among meat samples and not to examine its effect on the measured properties of meat. Apparently, there were some significant effects on the measured tensile properties due to the muscle-cooking and cooking-aging interactions.

Table 2 summarizes the mean values of maximum tensile force and stretch at maximum force, force at break and the corresponding stretch, and strain energy at break for raw and cooked beef for the four types of muscle. Cooking resulted in various degrees of increase in maximum force for all four types of muscles, ranging from 65% for BF muscle to 144% for SM muscle. On the other hand, stretch at maximum force decreased significantly after cooking, ranging from 32% for ST muscle to 72% for SM muscle. Similar trends were also observed for the force and stretch at break. It is interesting to note that the strain energy at break did not increase significantly (P > 0.05) after cooking for BF, LD, and SM muscles (table 2). Only ST muscle showed a significant increase (P < 0.05) in strain energy after cooking, mainly because it did not show as great a decrease in stretch after cooking as other muscles. Overall, cooked beef was much stiffer and less stretchable than raw beef, requiring greater forces to break. The degree to which measured property parameters changed due to cooking was influenced by muscle type.

Table 3 summarizes the results of correlation analyses between raw and cooked beef from the pooled data of all

Table 2. Mean values of selected tensile properties* and Warner-Bratzler shear measurements of raw and cooked beef of four types of muscle†

Muscle‡	Cooking Status§	Number of Samples‖	F_X (N)	λ_X (%)	F_B (N)	λ_B (%)	W_B (J)	WB (N)
BF	R	23	7.5b	180.8a	4.5a	193.0a	0.28a	133.2a
	C	24	12.4a	47.4b	6.0a	72.3b	0.31a	87.2b
			(3.3)	(19.5)	(3.0)	(18.0)	(0.18)	(27.3)
LD	R	18	3.5b	77.7a	1.5b	106.9a	0.09a	76.0a
	C	20	7.8a	36.0b	2.5a	51.5b	0.11a	86.0a
			(1.4)	(15.4)	(0.6)	(13.8)	(0.04)	(18.7)
SM	R	26	5.4b	129.6a	2.5b	148.3a	0.19a	107.7a
	C	26	13.2a	35.9b	4.0a	54.7b	0.25a	90.3a
			(2.6)	(15.9)	(1.0)	(14.2)	(0.09)	(21.0)
ST	R	18	12.8b	125.6a	4.6b	139.4a	0.35b	166.4a
	C	18	26.4a	85.2b	14.5a	97.5b	0.72a	73.6b
			(4.4)	(17.2)	(4.9)	(18.2)	(0.20)	(24.9)

* F_X — maximum force; λ_X — stretch at maximum force; F_B — force at break; λ_B — stretch at break; W_B — strain energy at break; WB — Warner-Bratzler shear value.
† Pairs of mean values with the different letters for raw and cooked beef of each muscle type are significantly different based on the least significant difference test (LSD) at the 0.05 level. The values in the parentheses are the l.d.s.
‡ BF — biceps femoris; LD — longissimus dorsi; SM — semimembranosus; ST — semitendinosus.
§ R — raw; C — cooked.
‖ There were two replicated measurements from each muscle sample.

four muscles. Most of the measured tensile properties were significantly correlated with each other, with the exception of the stretch at maximum force and at break for raw muscles that did not correlate with any tensile properties of cooked beef. There were particularly high correlations between maximum force and strain energy for raw and cooked beef (r = 0.84 and 0.93, respectively). Overall, the correlations between tensile properties of cooked beef were higher than those for raw muscles. This could be due to the fact that cooked beef was generally more consistent and controllable in mechanical measurements than raw muscle samples.

Figure 4 shows the relationship of the maximum tensile force between raw and cooked beef for the pooled data of the four muscles, with a correlation coefficient of 0.65 (P < 0.05). However, the significant correlation between raw and cooked beef for the pooled data of four muscles has actually masked large differences for individual muscles. There were significant correlations of the maximum tensile force for BF (r = 0.53, P < 0.01) and LD (r = 0.72, P < 0.01) muscles. No significant correlations were found for SM (r = –0.13) and ST (r = 0.36) muscles.

Table 3. Correlation coefficients between tensile properties and Warner-Bratzler shear value of raw and cooked beef for the pooled data of four muscles†

	F_{XR}	λ_{XR}	F_{BR}	λ_{BR}	W_{BR}	F_{XC}	λ_{XC}	F_{BC}	λ_{BC}	W_{BC}	WB_R	WB_C
F_{XR}	1.00	0.14	0.66**	0.09	0.84**	0.65**	0.60**	0.70**	0.55**	0.62**	0.55**	–0.07
λ_{XR}		1.00	0.43**	0.97**	0.40**	0.01	0.01	0.02	0.11	0.02	0.29*	0.05
F_{BR}			1.00	0.33**	0.59**	0.33**	0.33**	0.33**	0.36**	0.36**	0.36**	0.03
λ_{BR}				1.00	0.40**	–0.04	–0.03	–0.02	0.07	–0.02	0.27*	0.06
W_{BR}					1.00	0.61**	0.54**	0.65**	0.54**	0.61**	0.48**	0.02
F_{XC}						1.00	0.84**	0.86**	0.78**	0.93**	0.30**	0.12
λ_{XC}							1.00	0.82**	0.94**	0.88**	0.32**	0.10
F_{BC}								1.00	0.71**	0.86**	0.33**	–0.01
λ_{BC}									1.00	0.87**	0.25*	0.12
W_{BC}										1.00	0.22*	0.09
WB_R											1.00	0.04
WB_C												1.00

* P < 0.05.
** P < 0.01.
† The number of samples used to calculate the correlation coefficients varied between 79 and 88. F_X - maximum tensile force; λ_X - stretch at maximum force; F_B - force at break; λ_B - stretch at break; W_B - strain energy at break; WB - Warner-Bratzler shear value. The subscripts $_R$ and $_C$ represent raw and cooked beef, respectively.

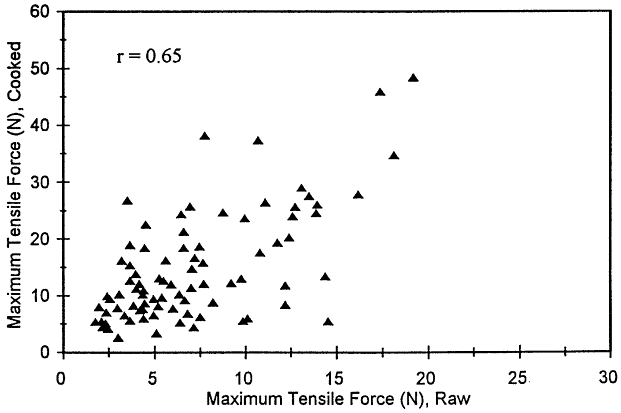

Figure 4–Comparison of the maximum tensile forces for cooked specimens with those for raw muscle specimens from all four muscles. Each data point represents the average of two measurements.

There was a relatively high, significant correlation (r = 0.61, P < 0.01) for the strain energy between raw and cooked beef from the pooled data (table 2). When the data were analyzed by muscle type, only BF and LD muscles showed a significant correlation (r = 0.66 and r = 0.77, respectively).

WB Shear Measurements of Raw and Cooked Beef

Muscle type and cooking as well as animal had a significant (P < 0.01) effect on WB shear values (table 1). However, in this particular study, aging did not have a significant effect on WB values. The statistical results suggest that aging apparently had more influences on tensile properties, particularly maximum tensile force and strain energy, than on WB shear measurements. Table 2 shows that raw LD specimens had the lowest WB shear value (76.0 N) and ST specimens had the highest WB shear value (166.4 N). The average WB shear value for raw BF and ST specimens was significantly (P < 0.05) higher than that for cooked specimens. Cooking resulted in a decrease in WB shear value for BF (35%) and ST (56%) muscles. However, cooking did not result in a significant increase in WB shear value for LD muscle nor a significant decrease for SM muscle. Again, these results indicate the significant effects of cooking and muscle type on WB shear measurements. Data analyses further showed that there was no significant correlation in WB shear value between raw and cooked beef when the data for the four muscles were pooled (table 3) or analyzed separately for each individual muscle.

It is interesting to note that cooking had opposite effects on the maximum tensile force and WB shear value for the four muscles. These results do not seem to support the hypothetical reasoning by Voisey (1976) that meat specimens primarily fail in tensile strength during the WB shear measurement. If WB shear measurements were related to tensile strength of meat specimens, then one would expect that WB shear value for cooked beef would be higher than that for raw beef, which is not true from the results presented in table 2. One possible explanation would be that during WB shearing of raw specimens, connective tissues had a higher contribution to the maximum force. After cooking, connective tissues had been greatly weakened so their contribution to WB shear value was diminished considerably. While in tensile tests, connective tissues perhaps had a far lesser contribution to the maximum force of muscle specimens whether they were tested in raw or cooked.

Relationship between WB Shear Measurements and Tensile Properties

Table 3 shows that WB shear value of raw beef was significantly correlated, at different degrees, with the measured tensile properties of either raw or cooked beef for the pooled data. The most significant correlation (r = 0.55) was obtained between WB shear value of raw beef and the maximum tensile force of raw beef. WB shear value of cooked beef was neither correlated with the tensile properties of cooked beef nor with those of raw beef for the pooled data.

The effect of muscle type on the tensile properties and WB shear measurements of cooked beef is clearly demonstrated in figures 5 and 6. When the data from all four muscles were pooled, there was no significant correlation (P = 0.27) between WB shear value and the maximum tensile force for cooked beef (fig. 5). However, when the data were analyzed by muscle type, significant differences due to muscle type appeared. Figure 6 shows that the correlation between WB shear value and the maximum tensile force was significant for LD muscle (r = 0.65, P < 0.01) and was somewhat significant (r = 0.48, P < 0.05) for SM muscle. These results appeared to be in agreement with those reported by Bouton and Harris (1972) for the same two muscles.

Among the four types of muscle, ST muscle deserves some special attention. On average, this muscle could sustain a much higher (two to three times) tensile force than the other three muscles in both raw and cooked status (table 2). Cooked ST muscle specimens could sustain a much higher stretch (about two-fold) at maximum force and at break than the other muscles. Its WB shear value for raw specimens was also considerably higher than that for the other muscles. However, after cooking ST muscle showed the lowest WB shear value among the four muscles (table 2). It is interesting to note the significant differences in the relationship between WB shear value and the maximum tensile force for LD and ST muscles (fig. 6). When the maximum tensile force for the LD muscle specimens varied from 4 N to 12 N (three-fold), the

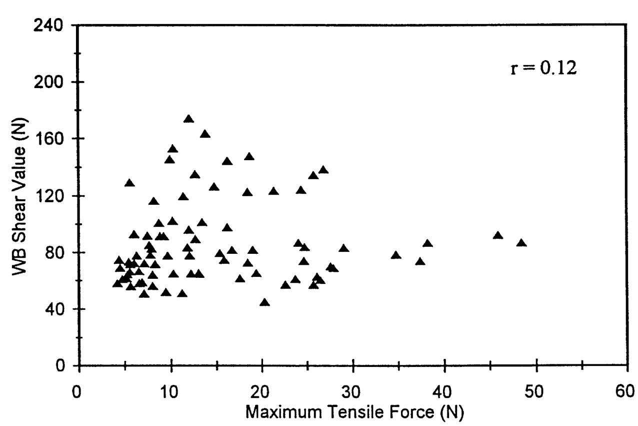

Figure 5–Warner-Bratzler shear values vs the maximum tensile forces for cooked beef specimens from all four muscles. Each data point represents the average of two measurements.

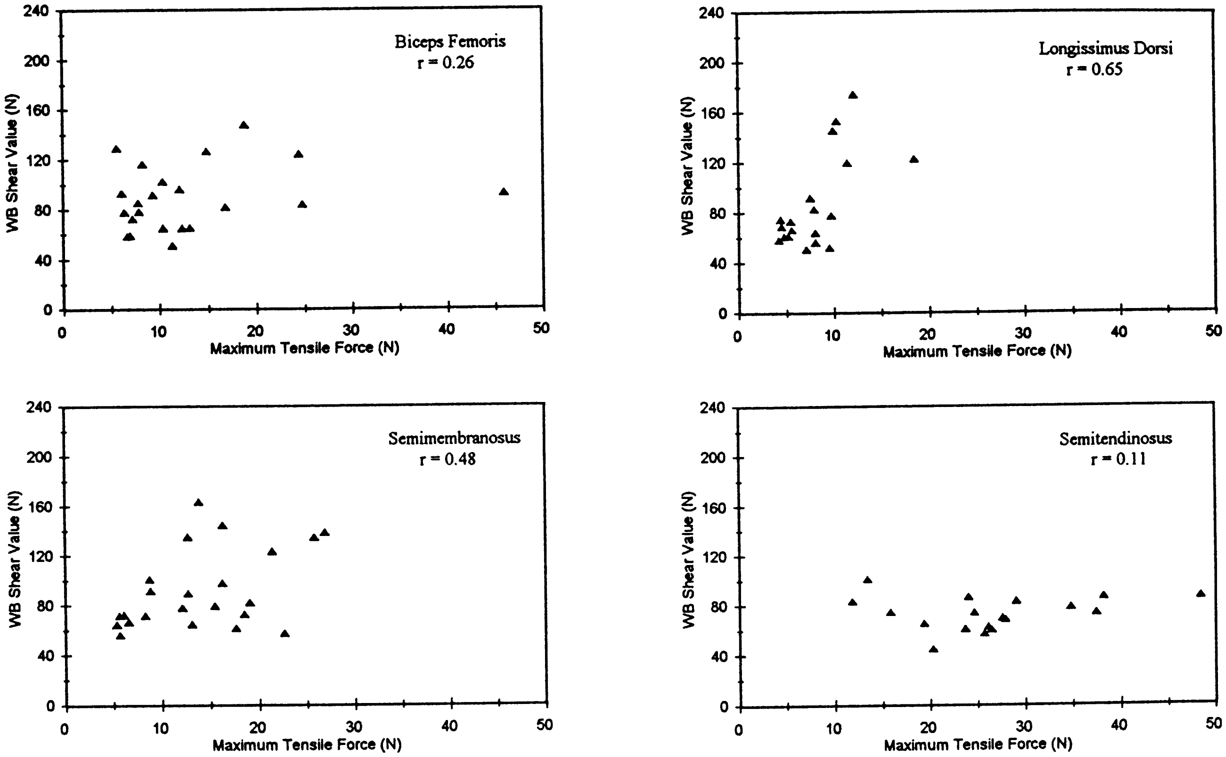

Figure 6–Correlation of Warner-Bratzler (WB) shear value with the maximum tensile force for cooked beef specimens from each individual muscle. Each data point represents the average of two measurements.

corresponding WB shear value also varied from 60 N to 180 N (three-fold). Contrarily, when the maximum tensile force for ST muscle specimens changed from about 12 N to 50 N (four-fold), the WB shear value did not show a significant change (P = 0.66). These observations imply that cooked ST muscle specimens may have failed in a different mechanism than the other three muscles. Further investigation of this issue is certainly needed to better understand the WB shearing process.

Similarly, there was no correlation (P = 0.52) between WB shear value of cooked beef and the maximum tensile force of raw beef for the pooled data (table 3). However, when the data were analyzed for each individual muscle, similar patterns of correlation were found. Figure 7 shows that there was a significant correlation (r = 0.64, P < 0.01) between WB shear value of cooked beef and the maximum tensile force of raw beef from LD muscle. For the other three muscles, no significant correlation was found.

The above discussion indicates that among the four muscles tested, LD muscle had shown consistently higher, significant correlations between the maximum tensile force of raw and cooked beef, and WB shear value. The correlations for the other three muscles were either lower or insignificant. Such results seem to be justifiable in view of the muscle structures and their changes caused by cooking. Among the four muscles, LD muscle had the lowest amount of connective tissues (Schön, 1977). Hence, the relative contribution of the connective tissues in LD muscle to both tension and WB shearing was expected to be low whether tests were performed on raw meat or cooked. This can be seen clearly from the tensile and WB shear curves presented in figures 1 to 3. In other words, it was mainly the strength of muscle fibers in LD muscle that was measured in both tensile and WB shear tests. On the other hand, BF, SM, and ST muscles all had a higher amount of connective tissues than LD muscle and the differences among BF, SM, and ST muscles were less prominent (Schön, 1977). Cooking produced confounded effects on the connective tissues and muscle fibers (Moller, 1981) and, thus, profoundly changed the relative contribution of each structure to the overall tensile and WB shear behavior of these muscles. Therefore, lower or insignificant correlations among the measured properties were expected for these three muscles.

This study indicates that tensile tests can be used to study the mechanical properties of beef in relation to cooking and aging and can be a useful method for measuring tenderness from raw or cooked beef. Overall, tensile measurements from LD muscle appear to be related better to WB shear values than other muscles. The success of tensile tests for measuring tenderness is strongly influenced by muscle type.

Summary and Conclusions

In this study, the tensile properties and Warner-Bratzler (WB) shear properties of four bovine muscles were studied before and after cooking. The characteristics of the tensile behavior of raw and cooked meat were analyzed and were related to WB shear measurements of both raw and cooked beef. The following conclusions were drawn from this study:

1. Raw muscle specimens exhibited nonlinear tensile behavior, characterized by linearity (or elasticity) at small deformation, stress yielding at intermediate

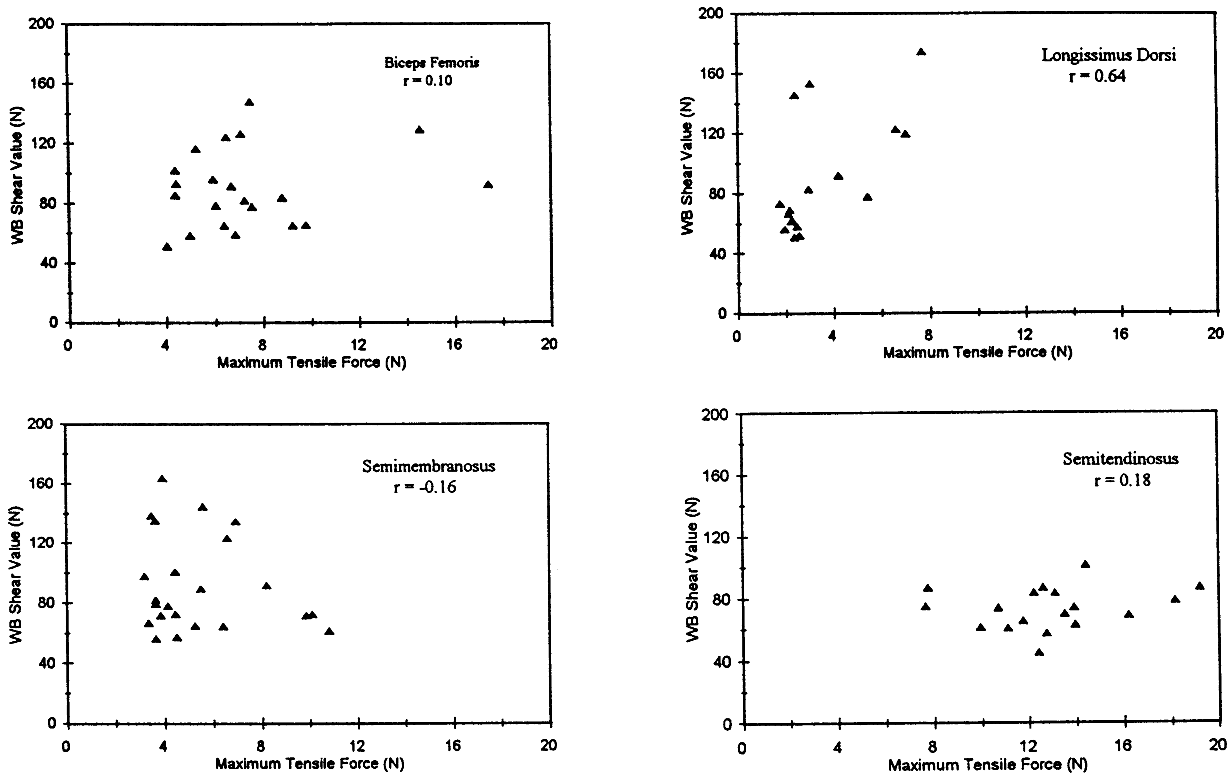

Figure 7–Correlation of Warner-Bratzler (WB) shear value of cooked specimens with the maximum tensile force for raw specimens from each individual muscle. Each data point represents the average of two measurements.

deformation, and work hardening at large deformation. The work-hardening behavior generally disappeared after cooking.

2. On average, cooked beef could sustain a significantly higher tensile force and would break at a lower stretch than raw beef. The strain energy increased significantly for ST muscle after cooking and not for the other three muscles. Contrarily, WB shear value decreased about 50% after cooking in BF and ST muscles and did not show a significant change in LD and SM muscles.
3. Muscle type had a considerable effect on the relationship between tensile properties and WB shear measurements. There was a significant correlation between WB shear value and the maximum tensile force for cooked LD and SM specimens (r = 0.65 and r = 0.48, respectively). No correlations were found for BF and ST muscles. The correlation between WB shear value of cooked beef and the maximum tensile force of raw beef was significant for LD muscle (r = 0.64) and was not significant for the other three muscles.
4. There was no significant correlation in WB shear value between raw and cooked beef either when the data for the four muscles were pooled or analyzed separately. This was because the connective tissues in raw and cooked beef had different contributions to WB shear value.

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