Mechanical probes can predict tenderness of cooked beef longissimus using uncooked measurements[1]

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ABSTRACT: Two experiments were conducted to determine the effectiveness of using mechanical probes and objective color measurement on beef LM to predict cooked tenderness. In Exp. 1, sharp needle (SN), sharp blade (SB), blunt needle (BN), blunt blade (BB), and plumb bob (PB) probes were used to measure uncooked LM (n = 29) at 2 d postmortem in both a perpendicular and parallel orientation to the long axis of the strip loin. Additionally, instrumental color measurements were measured on uncooked muscle at 2 d postmortem. Steaks for trained sensory panel (TSP) and Warner-Bratzler shear force (WBSF) measurements were aged 14 d postmortem before cooking. Probe measurements taken perpendicular to the long axis of the LM were not correlated (P = 0.22 to 0.82) to TSP tenderness. Probe measurements (BB, BN, SN, SB, and PB) taken parallel to the long axis were correlated to TSP tenderness (r = –0.57, –0.40, –0.77, –0.52, and –0.53, respectively). A regression equation using the SN probe to predict TSP tenderness had a R^2 value of 0.74. The SB probe combined with L* accounted for 45% of the variation in TSP tenderness, whereas the PB probe combined with L* accounted for 56% of the variation in TSP tenderness. A second experiment (n = 24) was conducted using the SN, SB, and PB probes on uncooked sections at 2 d and on cooked steaks at 14 d postmortem. Probe measurements on cooked steaks were not correlated to TSP tenderness. New regression equations were calculated using the probe measurements on uncooked steaks from both experiments. Prediction equations formulated with L* values and either SN, SB, or PB probes accounted for 49, 50, and 47% of the variability in TSP tenderness scores, respectively. An equation using WBSF of cooked steaks to predict TSP tenderness had an R^2 of 0.58. Of the steaks predicted to be tender (predicted tenderness > 5.0) by the equations using the SN, SB, and PB probes on uncooked steaks and WBSF on cooked steaks, 85, 88, 80, and 84%, respectively, were actually tender (TSP tenderness > 5.0). Mechanical probe measurements of uncooked steaks at 2 d postmortem can potentially classify strip loins into groups based on tenderness, as well as WBSF measurements, which are more costly and time consuming.

Key Words: Beef, Tenderness, Meat Quality, Prediction

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Introduction

Tenderness has long been considered the most important beef palatability attribute. According to the Strategy Workshop conducted as part of the National Beef Quality Audit, two of the top 10 quality challenges to the beef industry were the inadequate tenderness of beef and the low overall uniformity and consistency of cattle, carcasses, and cuts (NCBA, 2000). Boleman et al. (1997) found that consumers were willing to pay a premium price for guaranteed- or proven-tender beef. Researchers have developed numerous methods to predict beef tenderness, including the Warner-Bratzler shear force (**WBSF**; Bratzler, 1932; Warner, 1952), Armour Tenderometer (Hansen, 1972), Meat Animal Research Center Tenderness Classification System (Wheeler et al., 1998), and BeefCam (Wyle et al., 1998). Warner-Bratzler shear force is the most commonly used method to measure tenderness, but is costly, time consuming, and difficult to fit into industry operations because it must be done on cooked steaks.

Timm et al. (2003) modified the Armour Tenderometer into a six-needle probe and found significant correlations to trained sensory panel (**TSP**) tenderness (r = –0.74) and WBSF (r = 0.67). A plumb bob (**PB**) probe (Timm et al., 2003) was also related to TSP tenderness (r = –0.71) and WBSF (r = 0.78). Thus, the objective

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of the current study was to investigate the use of these and additional probes, and the influence of probe orientation to predict TSP tenderness of the LM.

Materials and Methods

Probe Design

The sharp needle (**SN**) and PB probes were previously described by Timm et al. (2003). The SN probe contained six needles, arranged in two rows of three on a 3.8- × 10.7-cm plate, with 2.54 cm between the rows and 1.91 cm between needles within a row. Each needle was 7 cm long, with a 0.32 cm diameter and a 10° point. The PB probe (model 27446, Hempe Manufacturing Co., Inc., New Berlin, WI) was 9.6 cm long and cone shaped, with an angle of 20° and a diameter ranging from 3.5 cm to zero. The PB probe penetrated the steak through a 27° hole in the center of an aluminum plate (10.5 cm × 9.8 cm × 1.2 cm). The blunt needle (**BN**) probe was similar to the SN probe, except that each needle had a rounded point (0.16 cm radius). The sharp blade (**SB**) probe was a stainless steel plate, 13.9 cm long, 4.0 cm wide, and 1.5 mm thick with a 22° edge. The blunt blade (**BB**) probe was also a stainless steel plate, 13.9 cm long, 4.0 cm wide, and 0.15 cm thick, but with a rounded edge (0.75 mm radius).

Experiment 1

Twenty-nine USDA Select beef strip loins (at least 41 cm long) were selected at 36 h postmortem at a commercial processing facility. Loins were collected on five different days (n = 5 or 6 per day) and transported in vacuum-bags to Kansas State University. After chilling overnight at 1°C, strip loins were faced and the exterior fat and posterior section were removed at 48 h postmortem, leaving 33 cm of LM with less than 0.32 cm of exterior fat.

For each loin, six treatment variables (five mechanical probe measurements and WBSF) and one response variable (TSP) were collected at randomly assigned locations along the length of the loin. For the SN, SB, BN, and BB probes, sampling was done on 6.35-cm sections. Steaks (2.54 cm thick) were used for PB probe, TSP, and WBSF. The SN, SB, BN, and BB probes were tested using both a perpendicular and parallel orientation to the long axis of the loin.

Each probe was attached to the Instron Universal Testing Machine (model 4201; Instron Corp., Canton, MA) with a 500-kg compression load cell. Needle and blade probes traveled 30 mm into the sample at a rate of 250 mm/min. Each section was probed four times, once medially and once laterally for the perpendicular and parallel orientations. Peak force and total energy of the medial and lateral locations were averaged separately for both perpendicular and parallel measurements. An additional variable consisting of the product of peak force and total energy (cross product) was created and analyzed for each measurement.

Perpendicular Orientation

Strip loins were not fabricated before taking perpendicular measurements. For each loin, 6.35-cm sections were assigned randomly to each probe. The perpendicular-orientation measurements were taken on the innermost portion of the designated section to imitate as closely as possible measurements made on an intact strip loin. Strip loins were stored at 1°C between probing times to maintain temperature. Temperature was monitored and recorded for each section before being probed. Connective tissue, intercostal muscles, and any bones remaining on the ventral side of the strip loin were removed before measurement. The intact strip loins were placed (ventral side up) under the probe attached to the Instron Universal Testing Machine. Before sampling, the tip of the probe was less than 0.1 cm from the designated section of the strip loin, and the widest point of the probe was perpendicular to the length of the strip loin.

After the perpendicular measurements were made with each probe, the strip loin was fabricated into the sections and steaks according to a strip-specific, random order guide. Steaks assigned to WBSF and TSP were vacuum-packaged and stored at 1°C for 12 d until 14 d postmortem. Steaks and sections assigned to PB and parallel SN, BN, SB and BB probe determinations were identified and stored at 1°C to regulate temperature.

Parallel Orientation

To make certain that the parallel probe measurements would not be confounded by the penetration of perpendicular measurements, the parallel measurements were made on the opposite end of the section than the perpendicular measurements. Each section was placed under the pre-assigned probe attached to the Instron Universal Testing Machine, with the tip of the probe 0.1 mm from the cut surface of the LM. Probes were arranged so that the widest point of the probe was parallel with the width of the LM. Probes were not placed over any visible connective tissue or large deposits of marbling. The pH was also measured on each section using a Sentron Argus X pH meter with a Lance FET pH probe (Sentron, Northbridge, MA). The pH values from the four sections within a strip loin were averaged for analysis.

Color Measurements

Steaks randomly assigned to the PB probe determination were allowed to bloom for at least 80 min before CIE L*, a*, and b* measurements were made using a Mini Scan XE spectrophotometer (3.18 cm diameter aperture and Illuminant A; Hunter Associates Laboratory, Inc., Reston, VA). Three measurements were made on each steak (medial, center, and lateral) and the values were averaged for L*, a*, and b*.

Plumb Bob Determination

Plumb bob determination followed the procedures described by Timm et al. (2003). Steaks were placed on an aluminum plate with a 27° tapered hole in the center. The PB traveled 69 mm at 250 mm/min through the medial, center, and lateral steak locations. Peak force and total energy required to penetrate the steak were recorded, and the product of peak force and total energy (cross product) was used as a separate variable in analysis. Instron measurements were averaged for the three locations within each steak.

Warner-Bratzler Shear Force

Steaks for WBSF were stored at 1°C until 14 d postmortem before WBSF was determined following procedures described by AMSA (1995). Steaks were weighed in their vacuum-packages, removed, and reweighed to calculate purge loss percent. Each steak was cooked to 70°C in a Blodgett dual-airflow convection oven (model DFG-201; G. S. Blodgett Co., Inc., Burlington, VA) preheated to 163°C, and temperature was monitored with a 30-gauge, type T thermocouple inserted into the geometric center of the steak and attached to a Doric temperature recorder (model 205; Vas Engineering, San Francisco, CA). Steaks were weighed to calculate cook loss percents, and then stored overnight at 1°C before six to eight 1.27-cm-diameter cores were removed from each steak parallel to the fiber direction. Each core was sheared once perpendicular to the muscle fibers using the Warner-Bratzler attachment to the Instron with the 50-kg compression load cell and a crosshead speed of 250 mm/min.

Trained Sensory Panel Evaluation

Steaks were aged to 14 d postmortem in vacuum packages and cooked using the same method described previously for WBSF. Outer connective tissue and s.c. fat were trimmed from cooked steaks before being sliced into 1.27-cm × 1.27-cm × steak thickness cubes. Steak cubes were kept warm by placing them in preheated double boilers.

Six to eight trained panelists were seated in an environmentally controlled room, at approximately 21°C and 55% relative humidity, in individual booths under adjustable red and green lighting that was less than 107.64 lumens combined. Panelists were served an orientation sample, which was evaluated and discussed before evaluating the experimental samples. Two cubes from each strip loin were served in random order to each panelist, and a score was determined using an eight-point scale to the nearest 0.5 (AMSA, 1995). Scores were determined for myofibrillar tenderness (1= extremely tough to 8 = extremely tender), juiciness (1 = extremely dry to 8 = extremely juicy), perceived connective tissue amount (1 = abundant to 8 = none), and overall tenderness (1 = extremely tough to 8 = extremely tender), and panelists' scores were averaged for each steak.

Experiment 2

Select-grade beef strip loins (n = 24) were obtained on 2 d (12/d) from a commercial processing facility at 36 h postmortem, and transported to the Kansas State University Meat Laboratory. Sections (6.35 cm) were used for parallel SN and SB probe determination. The same experimental procedures were used for uncooked SN, SB, and PB probes, as well as TSP and WBSF determinations, as previously described for Exp. 1. Steaks (2.54 cm thick) were used for uncooked PB probe determination; cooked SN, SB, and PB probe determinations; WBSF; and TSP.

Cooked Probe Determination

Steaks were cooked to 70°C and chilled overnight at 1°C. Cooked steaks were measured with the PB according to the methods outlined for uncooked PB steaks. Cooked SN and SB probe steaks were placed under the probe with the widest point of the probe parallel with the widest point of the steak. The probe (attached to the Instron with a 500-kg compression load cell) traveled 19 mm through the cut surface of the cooked steak at 250 mm/min. Each steak was measured in two locations (medial and lateral), and peak force and total energy were used in the statistical analysis. The product of peak force and total energy (cross product) also was used as a separate variable in analysis.

Statistical Analyses

Effects of temperature at probing were tested for contribution to the variation in probe measurements in the mixed-model procedure (PROC MIXED) of SAS (SAS Inst., Inc., Cary, NC), blocking on day of collection. Temperature at the time of uncooked measurement had no influence and was removed from further analysis. The correlation procedure (PROC CORR) of SAS was used to calculate correlation coefficients and obtain the simple statistics, including mean, minimum, maximum, and SD.

In Exp. 1, the best prediction equations for predicting TSP tenderness from the mechanical probes and objective color values or WBSF were found using the regression procedure of SAS, and indicator variables were used to remove the variation due to differences between days of collection. Regression equations that accounted for the greatest amount of variation in TSP tenderness were selected. In multiple regressions, SE of coefficient estimates may be inflated when independent variables are highly correlated to each other (Ott and Longnecker, 2001). Correlations were determined between the independent variables using the correlation procedure, and those variables highly related to each other were not used together in regression equations. The partial option of PROC REG of SAS was used to determine the linearity of the separate independent variables. If an independent variable appeared curvilinear, the data were transformed accordingly, and the regression procedure was repeated using the partial option to determine if the transformed data improved the predictive power of the model. The mixed-model procedure of SAS was used with collection day as the blocking factor to determine the final parameter estimates for each independent variable.

The data from Exp. 2 were applied to the regression equations, and the mean squared error of prediction (**MSPR**) was calculated to determine the validity of the models:

$$\text{MSPR} = \{[\Sigma(Y_i - \hat{Y})^2]/n^*\}$$

where n* is the number of observations in the second dataset. If the MSPR was larger ($P < 0.05$) than the mean square error (**MSE**) of the original data, then the model was determined "suspect" and another regression equation was calculated using the pooled data. If the ratio of MSPR:MSE was more than 1.91 (upper tail value of F, n = 24 and 29; $P < 0.05$), the equation was considered "suspect" for the second dataset. Within a probe, the regression equation with the lowest MSPR was determined as the model that best fit the data from Exp 2.

If the regression equations from Exp. 1 were considered "suspect" for the data from Exp. 2, the data from both experiments were combined, and differences due to experiment were removed by blocking on day of collection. Once data were combined, new regression equations were calculated as described previously.

Finally, the regression equations from the pooled data were used to classify the strip loins according to tenderness. The predicted tenderness scores of 5.0, or higher, were classified as tender, whereas tenderness scores below 5.0 were classified as tough. These were compared with actual TSP tenderness scores, which were also used to classify the strips as tough or tender.

Results

Experiment 1

Perpendicular vs. Parallel Orientation. Means, SD, and minimum and maximum values of the SN, BN, SB, BB, and PB probe measurements in the perpendicular and parallel orientations are presented in Table 1. For perpendicular measurements, TSP tenderness was not correlated ($P = 0.22$ to 0.82) with peak force, total energy, or cross product of SN, BN, SB, and BB probes (Table 2). In general, measurements taken in the parallel orientation were more consistently correlated with TSP tenderness than the perpendicular orientation. In the parallel orientation, BB, SB, and SN probes were all correlated ($P < 0.05$) with TSP tenderness (Table 2). Total energy for the BN probe was correlated (r = –0.40) with TSP tenderness, but the peak force and cross product were not ($P = 0.31$ and 0.14).

Sharp Needle Probe. The cross-product variable for the parallel measurements of the SN probe had the strongest correlation with TSP tenderness (r = –0.77). Peak force and total energy were also highly correlated with TSP tenderness (r = –0.71 and –0.71, respectively). The cross product of the SN probe accounted for 64% of the variation in TSP tenderness (Table 3). However, the squared term of the SN probe cross-product variable accounted for 74% of the variation in TSP tenderness, indicating that the SN probe had a curvilinear relationship with TSP tenderness. The addition of objective color variables did not improve the predictive ability of the SN probe equations. Inconsistencies in the relationships of correlation coefficients and R^2 values can be explained by the addition of the indicator variables to the regression equation. These variables removed variation from the model due to difference in taste panels and resulted in R^2 values higher than the squared correlation coefficients.

Blunt Needle Probe. For parallel measurements, only the total energy variable of the BN probe was correlated ($P < 0.05$) with TSP tenderness (r = –0.40). The peak force and cross-product variables were not correlated ($P = 0.31$ and 0.14, respectively) with TSP tenderness, and regression equations using the BN probe measurements were not significant ($P = 0.14$ to 0.40).

Sharp Blade Probe. Peak force, total energy, and cross-product variables of the SB probe in the parallel orientation were correlated with TSP tenderness (r = –0.38, –0.52, and –0.51, respectively). The regression equation for predicting TSP tenderness from the total energy of the SB probe had a R^2 value of 0.37 (Table 3), but the combination of total energy and L* values resulted in an R^2 of 0.43. The regression equation for predicting TSP tenderness from the squared term of the SB probe total energy resulted in an R^2 of 0.39, and L* accounted for an additional 6% of the variation in TSP tenderness.

Blunt Blade Probe. Peak force, total energy, and cross-product variables of the parallel measurements of the BB probe were correlated with TSP tenderness (r = –0.43, –0.57, and –0.53, respectively). Regression equations using the BB probe in the parallel orientation for predicting TSP tenderness were not significant ($P = 0.07$ to 0.10).

Plumb Bob. The PB probe peak force, total energy, and cross-product measurements were moderately correlated with TSP tenderness (r = –0.44, –0.53, and –0.50, respectively). The regression equation for predicting TSP tenderness from PB probe total energy resulted in an R^2 of 0.52, and the addition of L* values improved the R^2 to 0.56 (Table 3).

Warner-Bratzler Shear Force. Peak force, total energy, and cross-product measurements of WBSF were highly correlated with TSP tenderness (r = –0.80,

Table 1. Descriptive statistics for peak force, total energy, and cross product (peak force × total energy) of the blunt blade, blunt needle, sharp blade, sharp needle, and plumb bob probe variables in the perpendicular and parallel orientations, as well as Warner-Bratzler shear force (WBSF) and trained sensory panel (TSP) tenderness (Exp. 1)

Orientation	Probe	Variable	Mean	SD	Min[a]	Max[a]
Perpendicular	Blunt blade	Peak force, kg	13.4	2.3	9.0	17.2
		Total energy, J	139.5	25.0	100.7	183.6
		Cross product	192.0	643.2	1,005.0	3,159.0
	Blunt needle	Peak force, kg	4.4	0.7	3.4	5.7
		Total energy, J	60.7	8.3	47.6	77.8
		Cross product	270.5	72.5	161.0	443.7
	Sharp blade	Peak force, kg	920.0	2.2	6.5	14.5
		Total energy, J	113.3	24.3	69.9	178.4
		Cross product	1,085.0	488.1	467.2	2,589.0
	Sharp needle	Peak force, kg	3.4	0.6	2.2	4.3
		Total energy, J	42.7	9.8	21.0	56.8
		Cross product	151.8	55.0	45.9	241.8
Parallel	Blunt blade	Peak force, kg	8.1	1.8	4.2	11.9
		Total energy, J	83.2	19.9	36.8	123.7
		Cross product	708.6	290.6	152.9	1,340.0
	Blunt needle	Peak force, kg	3.5	0.6	2.1	4.7
		Total energy, J	47.7	7.5	31.3	58.1
		Cross product	170.3	50.3	72.5	268.2
	Sharp blade	Peak force, kg	6.8	1.4	4.5	10.2
		Total energy, J	77.3	18.2	41.0	113.4
		Cross product	543.0	225.6	186.8	1,047.0
	Sharp needle	Peak force, kg	2.7	0.6	1.7	4.0
		Total energy, J	32.6	7.8	19.6	49.1
		Cross product	93.6	43.7	33.2	191.9
	Plumb bob	Peak force, kg	4.7	0.9	3.0	6.7
		Total energy, J	125.7	28.6	65.7	172.2
		Cross product	618.1	236.0	202.4	1,004.0
	WBSF	Peak force, kg	4.3	0.9	3.2	6.5
	TSP tenderness[b]		5.5	0.8	3.3	6.9

[a] Min = minimum value; Max = maximum value.
[b] 1 = extremely tough to 8 = extremely tender.

–0.77, and –0.80, respectively). Peak force accounted for 69% of the variation in TSP tenderness (Table 3).

Experiment 2

Measurements on Cooked Muscle. The simple statistics of mean, minimum, maximum, and SD values for the SN, SB, and PB probe measurements on cooked steaks are presented in Table 4. The SN, SB, and PB peak force, total energy, and cross-product variables of cooked steaks were not correlated ($P = 0.10$ to 0.95) with TSP tenderness, and regression equations to predict TSP tenderness from SN, SB, and PB peak force, total energy, and cross-product variables of cooked steaks were not significant.

Measurements on Uncooked Muscle. Correlation coefficients of probe measurements on uncooked sections with TSP tenderness are presented in Table 5. Peak force, total energy, and cross-product variables of the SN probe were not correlated ($P = 0.06$, 0.08, and 0.08, respectively) with TSP tenderness in Exp. 2, and regression equations for predicting TSP tenderness from SN probe measurements were not significant ($P = 0.48$ to 0.58). The total energy variable of the SB probe was moderately correlated with TSP tenderness (r = –0.43), whereas peak force and cross-product variables of the SB probe were not correlated ($P = 0.13$ and 0.06, respectively) with TSP tenderness. A regression equation was calculated to predict TSP tenderness from SB total energy and L* ($R^2 = 0.52$), and this equation was superior to the WBSF equation from Exp. 2 ($R^2 = 0.41$) in predicting TSP tenderness (Table 6). Plumb bob probe measurements of uncooked steaks were not correlated ($P = 0.43$ to 0.91) with TSP tenderness, and no regression equations ($P < 0.05$) to predict TSP tenderness were calculated using PB probe variables.

Warner-Bratzler Shear Force. Trained sensory panel tenderness was correlated to WBSF (r = –0.63). A regression equation calculated from WBSF predicted only 41% of the variation in TSP tenderness (Table 6).

Validation of Experiment 1

Sharp Needle Probe. The MSPR for the probe regression equations from Exp. 1, using the data from Exp. 2, are presented in Table 3. Regression equations calculated from Exp. 1 data for the SN probe were considered "suspect" for Exp. 2 because the MSPR values

Table 2. Correlation coefficients of peak force, total energy, and cross product (peak force × total energy) for the sharp needle, blunt needle, sharp blade, and blunt blade probes in the perpendicular and parallel orientation, as well as plumb bob and Warner-Bratzler shear force (WBSF), with trained sensory panel tenderness (Exp. 1)

Orientation	Probe	Variable	r
Perpendicular	Sharp needle	Peak force	–0.24
		Total energy	–0.16
		Cross product	–0.17
	Blunt needle	Peak force	0.06
		Total energy	0.18
		Cross product	0.11
	Sharp blade	Peak force	–0.10
		Total energy	–0.20
		Cross product	–0.14
	Blunt blade	Peak force	0.15
		Total energy	0.04
		Cross product	0.09
Parallel	Sharp needle	Peak force	–0.71*
		Total energy	–0.71*
		Cross product	–0.77*
	Blunt needle	Peak force	–0.20
		Total energy	–0.40*
		Cross product	–0.28
	Sharp blade	Peak force	–0.38*
		Total energy	–0.52*
		Cross product	–0.51*
	Blunt blade	Peak force	–0.43*
		Total energy	–0.57*
		Cross product	–0.53*
	Plumb bob	Peak force	–0.44*
		Total energy	–0.53*
		Cross product	–0.50*
	WBSF	Peak force	–0.80*
		Total energy	–0.77*
		Cross product	–0.80*

*$P < 0.05$.

were larger ($P < 0.05$) than the MSE values calculated in Exp. 1. The regression equation using the linear term of the cross-product variable of the SN probe to predict TSP tenderness had a lower MSPR than the equation using the squared term of the cross-product variable, which indicated that the linear model was better than the squared-term model for predicting TSP tenderness in the Exp. 2 dataset.

Sharp Blade Probe. All of the SB probe regression equations created from Exp. 1 were considered valid because the MSPR of the equations, when applied to data from Exp. 2, was not larger ($P > 0.05$) than the MSE of Exp. 1. The equation containing the linear term of the total energy variable and L* values had the lowest MSPR, indicating that this equation was the most predictive for TSP tenderness from the SB probe using data from Exp. 2.

Plumb Bob and Warner-Bratzler Shear Force. Regression equations predicting TSP tenderness from PB measurements were determined to be “suspect” models for the Exp. 2 data. The equation containing the total energy variable and L* values was the best of the PB probe equations for predicting TSP tenderness from Exp. 2 data. Conversely, the regression equation for predicting TSP tenderness from WBSF was “suspect” when applied to the data from Exp. 2.

Combination of Experiments

Most of the prediction equations from Exp. 1 were considered suspect because they did not predict the tenderness differences in Exp. 2 accurately. The SN, SB, and PB probes of uncooked sections and WBSF measurements of cooked steaks from both experiments were combined to develop new regression equations with a larger number of observations. Plots of the predicted tenderness from those equations and actual TSP tenderness are presented in Figure 1. A score of five

Table 3. Exp. 1 regression equations for predicting trained sensory panel tenderness using sharp needle (SN), sharp blade (SB), and plumb bob (PB) probe total energy and cross product variables and L* values, and Warner-Bratzler shear force (WBSF), as well as mean square error of prediction calculated when data from Exp. 2 were applied, and the ratio of mean square error of prediction to mean square error

Equation	R^2	MSE[a]	MSPR[b]	Ratio[c]
$6.84 - (0.014 \times \text{SN cross product})$	0.64	0.28	0.95	3.39
$6.23 - [0.00007 \times (\text{SN cross product})^2]$	0.74	0.20	1.12	5.60
$7.29 - (0.023 \times \text{SB total energy})$	0.37	0.49	0.76	1.55
$4.12 - (0.021 \times \text{SB total energy}) + (0.067 \times L^*)$	0.43	0.47	0.57	1.21
$6.48 - [0.0015 \times (\text{SB total energy})^2]$	0.39	0.48	0.80	1.67
$3.37 - [0.00014 \times (\text{SB total energy})^2] + (0.068 \times L^*)$	0.45	0.45	0.61	1.36
$7.91 - (0.019 \times \text{PB total energy})$	0.52	0.37	1.03	2.78
$4.29 - (0.017 \times \text{PB total energy}) + (0.076 \times L^*)$	0.56	0.36	0.76	2.11
$8.51 - (0.74 \times \text{WBSF})$	0.69	0.25	0.63	2.52

[a] Mean square error of Exp. 1 equations.

[b] Mean square error of prediction = $\{[\Sigma(Y_i - \hat{Y})^2]/n^*\}$, where n^* is the number of observations in the second data set. Lower MSPR indicates a better ‘fit’ of the model for the second set of data.

[c] Ratio of MSPR:MSE. A ratio of less than 1.91 indicated that the equation was valid for the data from Exp. 2.

Table 4. Descriptive statistics for sharp blade, sharp needle, and plumb bob probe peak force, total energy, and cross product (peak force × total energy) of cooked steaks (Exp. 2)

Probe	Variable	Mean	SD	Min[a]	Max[a]
Sharp blade	Peak force, kg	10.8	1.7	7.4	14.4
	Total energy, J	99.3	20.4	61.5	151.1
	Cross product	1,102.0	370.0	452.9	2,009.0
Sharp needle	Peak force, kg	5.3	1.3	2.8	9.0
	Total energy, J	36.4	13.7	10.0	74.2
	Cross product	208.1	135.4	28.3	666.0
Plumb bob	Peak force, kg	13.0	2.7	9.0	18.2
	Total energy, J	286.8	58.7	204.2	414.0
	Cross product	3,850.0	1,471.0	1,840.0	7,524.0

[a] Min = minimum value; Max = maximum value.

(slightly tender) was used as the tenderness threshold separating tender from tough steaks.

Sharp Needle. Regression equations calculated from the combined experiments for predicting TSP tenderness from SN probe and L* measurements are presented in Table 7. The SN probe cross-product equation had an R^2 of only 0.38 but improved to 0.49 when L* was added. Of the 41 loins predicted to be tender (predicted tenderness ≥ 5.0) by the sharp needle and L* equation, 35 (85.4%) were actually tender (TSP tenderness ≥ 5.0), and 9 of the 12 (75%) loins predicted to be tough (predicted tenderness < 5.0) were actually tough (TSP tenderness < 5.0; Figure 1a).

Sharp Blade. Even though the Exp. 1 equations were considered valid for the SB probe, the two experiments were combined to improve the predictive ability of the probe. The regression equation for predicting TSP tenderness from the total energy variable of the SB probe alone had an R^2 of only 0.37, which increased to 0.50 with the addition of L* values to the model. The SB probe and L* equation was correct in its classification of 35 of 40 (87.5%) loins as tender and 10 of 13 (76.9%) as tough (Figure 1b).

Plumb Bob. The squared term of the PB probe total energy variable and L* accounted for 47% of the variability in TSP tenderness when the data from the two experiments were combined. Of the 45 loins the PB and L* equation predicted to be tender, 36 (80%) were actually tender, and 6 of the 8 (75%) loins predicted to be tough were actually tough (Figure 1c).

Warner-Bratzler Shear Force. A regression equation from the combined experiments to predict TSP tenderness from WBSF resulted in an R^2 of 0.58. The WBSF equation predicted 38 loins to be tender and 32 (84.2%) were actually tender, and the WBSF equation predicted 15 loins to be tough, but only 9 (60%) were actually tough (Figure 1d).

Table 5. Correlation coefficients of sharp blade, sharp needle, and plumb bob probe variables and Warner-Bratzler shear force (WBSF) measured in uncooked LM with trained sensory panel tenderness in Exp. 2

Probe	Variable	r
Sharp needle	Peak force	–0.38
	Total energy	–0.37
	Cross product	–0.36
Sharp blade	Peak force	–0.32
	Total energy	–0.43*
	Cross product	–0.40
Plumb bob	Peak force	–0.02
	Total energy	–0.17
	Cross product	–0.15
WBSF		–0.63*

*$P < 0.05$.

Discussion

Orientation. In the current study, measurements made in a perpendicular orientation were not related to trained sensory panel tenderness. George et al. (1997) studied the Tendertec beef-grading instrument, which also measured tenderness perpendicular to the length of the LM, and found no relationship between Tendertec output variables and TSP tenderness scores or WBSF. A later study by Belk et al. (2001) found low correlations of Tendertec with TSP and WBSF. To assess LM tenderness in an orientation perpendicular to the length of the muscle, the epimysium must be removed or the probe must penetrate through the epimysial connective tissue before it begins taking measurements. It is difficult to remove the outer connective tissue in its entirety, and small pieces of connective tissue remaining on the strip loin may affect probe measurements. Removal of the epimysium and the oval shape of the muscle create an uneven surface on which to initiate penetration. In the case of the needle probes, the uneven shape of the muscle sometimes re-

Table 6. Regression equations (Exp. 2) predicting trained sensory panel tenderness from sharp blade (SB) probe and L* values and Warner-Bratzler shear force (WBSF)

Equation	R^2	MSE[a]
1.37 – (0.019 × SB total energy) + (0.12 × L*)	0.52	0.44
8.76 + (0.86 × WBSF)	0.41	0.52

[a] Mean square error.

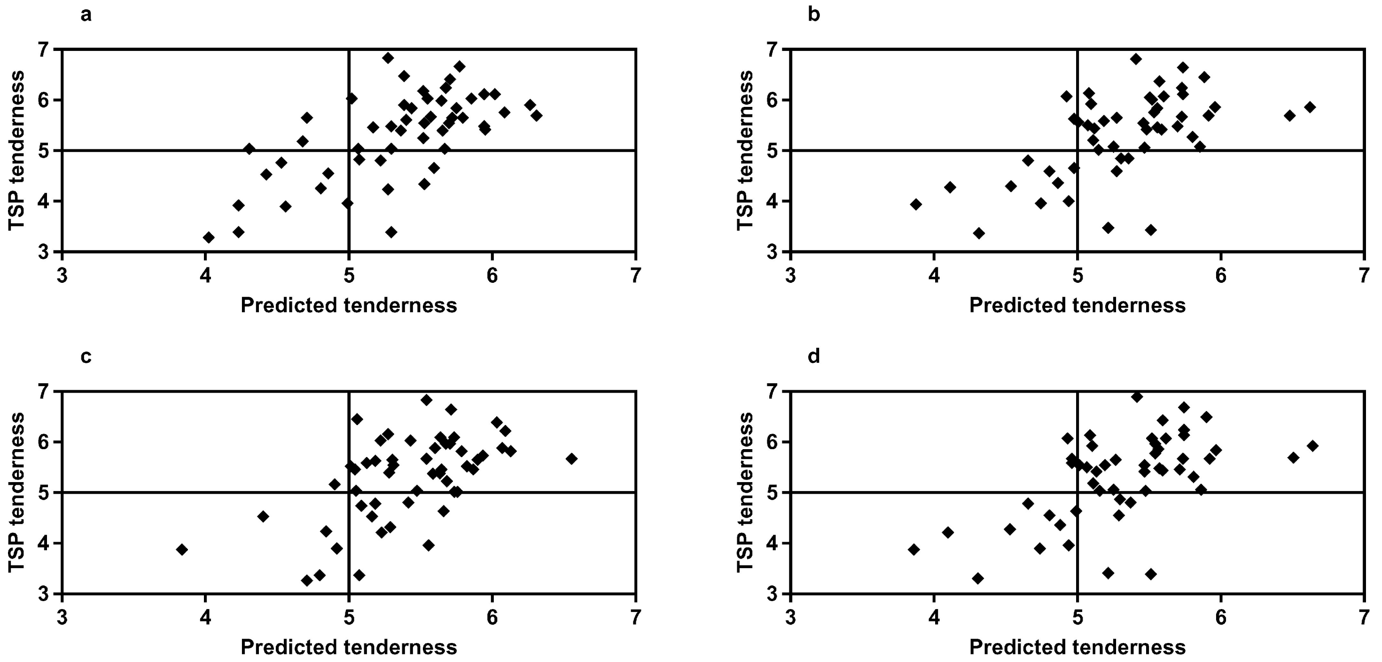

Figure 1. Comparison of trained sensory panel (TSP) tenderness (1 = extremely tough to 8 = extremely tender) with the tenderness predicted by a) sharp needle and L*; b) sharp blade and L*; c) plumb bob and L*; and d) Warner-Bratzler shear force equations.

sulted in not having all needles in contact with the muscle at the time the Instron began taking measurements. The entire width of the blade probes was sometimes not completely flush with the uneven muscle; therefore, the Instron began recording energy measurements when the probe was not entirely in the muscle.

In general, measurements taken in the parallel orientation were more consistent in predicting TSP tenderness than the perpendicular orientation. Many researchers have measured tenderness parallel to the long axis of the LM with mixed results (Hansen, 1972; Jeremiah and Phillips, 2000; Timm et al., 2003). The surface of the LM is exposed during the grading process, and no obstruction is present to hinder parallel measurements. However, the muscle fibers in the LM are neither parallel nor perpendicular to the length of the loin; consequently, tenderness is evaluated at varying angles to the fiber direction when the parallel orientation is used.

Table 7. Regression equations predicting trained sensory panel tenderness from the sharp needle (SN), sharp blade (SB), and plumb bob (PB) probes, L* values, and Warner-Bratzler shear force (WBSF) calculated from the combined data

Equation	R^2	MSE[a]
6.25 – (0.0098 × SN cross product)	0.38	0.53
1.92 – (0.0087 × SN cross product) + (0.096 × L*)	0.49	0.45
6.99 – (0.0216 × SB total energy)	0.37	0.54
2.14 – (0.0196 × SB total energy) + (0.106 × L*)	0.50	0.44
0.82 – [0.00004 × (PB total energy)^2] + (0.119 × L*)	0.47	0.49
8.51 – (0.74 × WBSF)	0.58	0.36

[a] Mean square error.

Sharp Needle Probe. Parallel measurements with the SN were moderately correlated to TSP tenderness, and were equal to WBSF in classifying loins into tenderness groups. Timm et al. (2003) found a curvilinear relationship between the SN probe and TSP tenderness, and they speculated that the SN probe pierced the muscle fibers and measured the force needed to separate the myofibrils and/or muscle fibers. The SN probe was developed from the Armour Tenderometer. Hansen (1972) found correlations between the Armour Tenderometer and TSP tenderness of –0.69 and –0.77 for USDA Good and Choice carcasses, respectively. Huffman (1974) stated that Tenderometer measurements were superior to WBSF, USDA grade, and marbling score at predicting TSP tenderness. Nonetheless, some researchers have found the Armour Tenderometer was not correlated to TSP tenderness (Luckett et al., 1972; Campion et al., 1975) or WBSF (Dikeman et al., 1972; Hansen, 1972; Hendrickson et al., 1972). The Armour Tenderometer probe measured tenderness by penetrating the LM with one measurement using 10 needles, whereas the SN probe used in the current study penetrated the muscle with six needles in two locations. Timm et al. (2003) stated that the medial and lateral portions of the LM differ in tenderness. By averaging the medial and lateral measurements, the SN probe has the ability to account more precisely for more variation in the muscle tenderness, and will account for differences between the two locations within the muscle. The larger number of needles on the Armour Tenderometer may have also contributed to the dimpling effect observed in the muscle and the relationship of that probe to subjective firmness scores (Parrish et al., 1973; Campion et al., 1975).

Blunt Needle Probe. The blunt needle probe was not well correlated to TSP tenderness in the current study. Hansen (1972) found that measurements made by a sharp needle probe had a stronger relationship with WBSF than did those made by a blunt needle. In contrast, Hinnergart and Tuomy (1970) indicated that a semi-blunt needle had higher correlation coefficients with the penetrometer than blunt or fine-pointed needles.

Sharp Blade Probe. Sharp blade probe measurements were moderately correlated to TSP tenderness, and were successful at segregating strip loins into groups based on tenderness. The SB probe was patterned after the Warner-Bratzler shear and slice-shear-force blades. The WBSF method measures cores perpendicular to the muscle fiber direction; yet, due to the varying fiber direction of the LM, the SB probe did not measure the muscle with a consistent orientation to the fiber direction of the muscle. Markings left in the steak from the SB probe were not noticeable after the steak was cooked, and would not affect the value of a strip loin.

Blunt Blade Probe. Although the correlation coefficients of the BB with TSP tenderness were equal to the SB probe, it was not as highly related to WBSF ($r = 0.41$ vs. 0.60). The deformation curves of the BB probe were not as smooth as those from the SB probe, and the BB probe did not always shear the muscle when used in the parallel orientation. The probe often pressed into the muscle, dimpling the cut surface. The BB measured the same effects of tenderness as the SB probe; therefore, it was not used in Exp. 2.

Plumb Bob Probe. The PB accounts for moderate variation in tenderness within the muscle. The action of the PB probe was related to both compression and tensile strength of the connective tissue (Timm et al., 2003). The PB probe method leaves a steak unusable for sale as a whole muscle product, but PB steaks can still be used as cubed steaks or ground beef, retaining some value.

Probe Applications. Probes used in a perpendicular orientation to the length of the strip loin were unsuccessful in predicting TSP tenderness. In addition, the use of probes on cooked steaks after aging did not accurately relate to TSP tenderness. However, using the SN, SB, and PB probes in a parallel orientation on uncooked LM sections at 2 d postmortem can predict TSP tenderness at 14 d postmortem.

The SN and SB probes, combined with instrumental color measurements (L^*), on uncooked muscle at 2 d postmortem show the most promise as early predictors of tenderness. These methods were equal to WBSF in their ability to segregate strip loins into groups based on TSP tenderness scores. The SN and SB were advantageous to the WBSF method because the strip loins were measured at 2 d postmortem on uncooked product that could still be marketed. The PB probe also predicts tenderness effectively on uncooked muscle, but the damage to the product during measurement is detrimental to further development of this probe.

Implications

The sharp needle, sharp blade, and plumb bob probe measurements taken in an orientation parallel to the length of the longissimus muscle at 2 d postmortem on U.S. Select steaks predicted cooked sensory panel tenderness scores after 14 d of aging. Quality grades other than Select will need to be used in future experiments to determine whether marbling affects probe measurements. Eventually, marketing systems could be created and evaluated using probe and color measurements to classify carcasses based on predicted tenderness.

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