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Correlations among selected pork quality traits

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Abstract
Establishing relationships among specific quality traits is important if significant progress toward developing improved pork quality is to be realized. As part of a study to examine the individual effects of genes on meat quality traits in pigs, a three-generation resource family was developed. Two Berkshire sires and nine Yorkshire dams were used to produce nine F1 litters. Sixty-five matings were made from the F1 litters to produce four sets of F2 offspring, for a total of 525 F2 animals used in the study. These F2 animals were slaughtered at a commercial facility upon reaching approximately 110 kg. Carcass composition traits, pH measurements, and subjective quality scores were made at 24 h postmortem. Loin samples (n = 525) were collected at 48 h postmortem, and meat quality traits were evaluated. These traits included pH (48 h), Hunter L-values, drip loss, glycolytic potential, ratio of type IIa/IIb myosin heavy chains (IIa/IIb), total lipid, instrumental measures of tenderness using the Star Probe attachment of the Instron, cook loss measurements, and sensory evaluations. Significant phenotypic correlations were found between many carcass, instrumental, and biochemical measurements, and sensory quality traits. Star Probe measurements were significantly correlated with drip loss (0.29), glycolytic potential (0.30), pH (-0.29), total lipid (-0.14), and Hunter L-values (0.28). Drip loss was significantly correlated with glycolytic potential (0.36), pH (-0.28), IIa/IIb (-0.10), and Hunter L-values (0.33). Hunter L-values were also significantly correlated with total lipid (0.33) and IIa/ IIb (-0.11). Sensory tenderness, flavor, and off-flavor scores were significantly correlated with drip loss, pH, and glycolytic potential measurements. Marbling score, total lipid, and drip loss were not significantly correlated with sensory juiciness scores, but cooking loss was. Marbling and total lipid were significantly correlated with firmness scores (0.37 and 0.31, respectively). Taken together, the data in this study suggest that changes in some meat quality traits can affect many other meat quality attributes. The correlations yield information that could aid in directing future studies aimed at understanding the underlying biological mechanisms behind the development of many quality traits.

Keywords
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Comments
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Correlations among selected pork quality traits[1]

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ABSTRACT: Establishing relationships among specific quality traits is important if significant progress toward developing improved pork quality is to be realized. As part of a study to examine the individual effects of genes on meat quality traits in pigs, a three-generation resource family was developed. Two Berkshire sires and nine Yorkshire dams were used to produce nine F1 litters. Sixty-five matings were made from the F1 litters to produce four sets of F2 offspring, for a total of 525 F2 animals used in the study. These F2 animals were slaughtered at a commercial facility upon reaching approximately 110 kg. Carcass composition traits, pH measurements, and subjective quality scores were made at 24 h postmortem. Loin samples (n = 525) were collected at 48 h postmortem, and meat quality traits were evaluated. These traits included pH (48 h), Hunter L-values, drip loss, glycolytic potential, ratio of type IIa/IIb myosin heavy chains (IIa/IIb), total lipid, instrumental measures of tenderness using the Star Probe attachment of the Instron, cook loss measurements, and sensory evaluations. Significant phenotypic correlations were found between many carcass, instrumental, and biochemical measurements, and sensory quality traits. Star Probe measurements were significantly correlated with drip loss (0.29), glycolytic potential (0.30), pH (–0.29), total lipid (–0.14), and Hunter L-values (0.28). Drip loss was significantly correlated with glycolytic potential (0.36), pH (–0.28), IIa/IIb (–0.10), and Hunter L-values (0.33). Hunter L-values were also significantly correlated with total lipid (0.33) and IIa/IIb (–0.11). Sensory tenderness, flavor, and off-flavor scores were significantly correlated with drip loss, pH, and glycolytic potential measurements. Marbling score, total lipid, and drip loss were not significantly correlated with sensory juiciness scores, but cooking loss was. Marbling and total lipid were significantly correlated with firmness scores (0.37 and 0.31, respectively). Taken together, the data in this study suggest that changes in some meat quality traits can affect many other meat quality attributes. The correlations yield information that could aid in directing future studies aimed at understanding the underlying biological mechanisms behind the development of many quality traits.

Key Words: Color, Meat Quality, pH, Pork, Tenderness, Water Holding Capacity

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Introduction

The evaluation of pork quality traits is of particular importance if these traits are to be improved. For many years, one of the major objectives of the swine industry was to increase the lean:fat ratio of pork carcasses (Cameron, 1990; Cliplef and McKay, 1993). As a result, dramatic improvements in the body composition of pigs have been made through genetic selection (Sellier and Rothschild, 1991). More recently, an increasing amount of emphasis has been placed on improving pork quality traits (Hovenier et al., 1993). Improvements in these characteristics have proven to be somewhat more elusive. Pork quality traits are often truly composite traits, being influenced by several antemortem and postmortem factors (Honikel, 1987; Warriss, 1987; Sellier and Monin, 1994), thereby making the prediction of ultimate pork quality more difficult. In turn, this fact makes genetic selection for improved pork quality more difficult (deVries and van der Wal, 1993). Many physical and biochemical factors have been evaluated in an attempt to assess meat quality. Some of these include Hunter L-values (measures of the relative lightness or darkness of the product), marbling and lipid content, ultimate pH of the meat, glycolytic potential (estimate of the muscle glycogen concen-

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tration at slaughter) and muscle fiber type (Honikel, 1993; Sellier and Monin, 1994). However, a limited number of studies have made a comprehensive effort to look at a wide variety of biochemical, sensory, and physical traits in one population. Before variation in pork quality can be controlled, relationships among biochemical measurements and sensory and processing characteristics must be known. The objective of this study was to determine phenotypic associations between specific biochemical and physical-sensory characteristics to obtain a better understanding of how changes in specific traits may influence pork quality overall.

Materials and Methods

Animals

Data from a three-generation resource family that was established to map genes affecting meat quality were used. To establish this group of pigs, two purebred Berkshire boars and nine purebred Yorkshire females were used to produce nine F1 litters. These breeds were chosen for their divergence in meat quality characteristics, with Berkshires, in general, having very positive meat quality traits (Johnson and Goodwin, 1995). The boars representing typical Berkshire boars (based on progeny information) were chosen from commercial boar studs and were mated artificially to halothane-negative Yorkshire sows from the Iowa State University Swine Breeding Farm. From the resulting F1 litters, eight boars and 26 gilts were selected to produce the 525 F2 animals used in this study. A total of 65 matings were made to produce four sets of F2 offspring. The pigs were weighed weekly and sent to a commercial facility to be slaughtered when they reached approximately 110 kg. Details of the rearing and management procedures are described in Malek et al. (2001).

After slaughter and chilling, carcass traits were evaluated by according to the National Pork Producers Council guidelines (NPPC, 1991). The same trained university personnel evaluated all of the product in this study. These data included carcass composition traits, 24-hour pH measured at the 10th rib with a Mettler Toledo (Columbus, OH) glass penetration pH electrode, and the subjective quality traits of marbling, firmness, and color in the loin (on 1-to-5 scale) at the 10th rib. Loins were removed from the carcasses and transported back to the Iowa State University Meat Lab under refrigeration. At 48 h postmortem, pH was again measured at the 10th rib with a Mettler Toledo glass penetration pH electrode, Hunter L-values were collected at the 10th rib using a HunterLab Miniscan (Hunter Associates Laboratory, Inc., Reston, VA) calibrated according to the manufacturer's instructions. Loin samples were collected from the 10th-rib region for the laboratory evaluations described below.

Laboratory Evaluations

Drip loss was measured on a size-standardized sample from the longissimus muscle (3 cm in diameter × 2.5 cm thick) (Honikel et al., 1986; Kauffman et al., 1986) that was collected at 48 h postmortem. The sample was weighed, suspended in a plastic bag, and held at 4°C for 72 h. The sample was reweighed at the end of the holding time. Drip loss was calculated as the percentage of product weight that was lost over 72 h of storage.

At 48 h postmortem, a subsample of the loin was frozen and sent to the University of Illinois where glycogen, free glucose, glucose-6-P, and lactate were measured. Glycolytic potential was calculated as follows: Glycolytic potential = 2 × (glycogen + glucose + glucose-6-phosphate) + lactate (Monin and Sellier, 1985; Maribo et al., 1999). The values for glycolytic potential were expressed as micromoles of lactate equivalents per gram of muscle wet weight. The values for total glycogen (μmol/g) and lactate (μmol/g) as well as glycolytic potential were used in the study.

Total lipid in the longissimus muscle was measured following the method of Bligh and Dyer (1959) and expressed as a percentage of the tissue. Total lipids were dissolved in isopropanol and assayed for concentration of total cholesterol using an enzymatic procedure (Sigma Cholesterol Kit No. 352, Sigma Chemical Co., St. Louis, MO). Cholesterol was reported as milligrams per 100 g of tissue.

Differences in muscle fiber type were evaluated in 48-h postmortem samples from the longissimus muscle by separation of myosin isoforms on high-porosity SDS-PAGE gels (Figure 1). The procedure used was as described by Talmadge and Roy (1993) with modifications to further improve myosin isoform separation. Muscle samples were extracted in 9 vol of ice-cold homogenization buffer (250 m*M* sucrose, 100 m*M* KCl, 5 m*M* EDTA, and 20 m*M* Tris, pH 6.8) using a Dounce

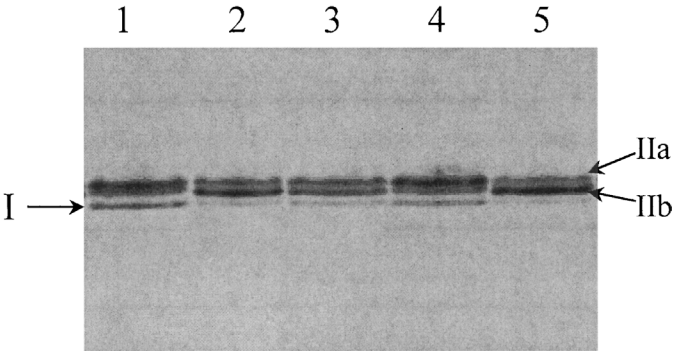

Figure 1. Representative SDS-PAGE gel used for evaluating myosin heavy-chain isoforms. Lanes 1–5 represent individual LD samples from five different pigs. The label IIa refers to where the IIa isoforms migrated, IIb refers to where the IIb isoforms migrated, and I refers to where the Type I isoforms migrated.

homogenizer (Kontes Glass, Vineland, NJ) and centrifuged at 1500 × *g* for 15 min at 4°C. The pellets were homogenized with a Dounce homogenizer in 25 vol (wt/vol) of whole muscle extraction buffer (2% sodium dodecyl sulfate [SDS] [wt/vol], 10 m*M* sodium phosphate, pH 7.0). Samples were then centrifuged at 1,500 × *g* for 15 min at 20°C (Huff-Lonergan et al., 1996). Protein concentration of the supernatant was determined using the BioRad DC assay (modification of Lowry et al., 1951). Samples were heated in sample buffer (Laemmli, 1970) at 50°C for 20 min at a final protein concentration of 0.125 mg/mL, and a total of 2 μg of protein was loaded on each lane of 18 cm × 16 cm × 1.5 mm SDS-PAGE gels. The stacking gels were composed of 30% glycerol, 4% acrylamide-N,N′-methylene-bis-acrylamide (acrylamide-bis) (50:1), 70 m*M* Tris (pH 6.7), 4 m*M* EDTA, and 0.4% SDS. The separating gels were composed of 30% glycerol, 6% acrylamide-bis (50:1), 200 m*M* Tris (pH 8.8), 100 m*M* glycine, and 0.4% SDS. Polymerization of stacking and separating gels was initiated with 0.05% N,N,N′,N′-tetramethylethylenediamine and 0.1% ammonium persulfate. The upper running buffer consisted of 100 m*M* Tris (base), 150 m*M* glycine, 0.1%β-mercaptoethanol, and 0.1% SDS. The lower running buffer consisted of 50 m*M* Tris (base), 75 m*M* glycine, and 1% SDS. Gels and running buffers were cooled to 4°C before use. Gels were electrophoresed at 250 V for 24 h at 4°C. Bands were visualized by staining with Coomassie blue. Gel images were captured using a Kodak DC120 digital camera, and the images were analyzed using the Kodak 1D Image Analysis software (Eastman Kodak Co., Rochester, NY.) Results were expressed as the ratio of the density of the IIa band of myosin to the density of the IIb band within a sample. This ratio was chosen because it was of interest to note how those two isoforms differed in relationship to each other. Porcine diaphragm muscle (extracted as outlined above) was used as a standard on each gel to aid in identifying the isoforms of myosin. Diaphragm muscle contains primarily type IIa, IIx, and type I associated myosin isoforms (Talmadge and Roy, 1993).

For evaluation of the cooked product, 2.54-cm thick vacuum-packaged boneless chops from the 10th-rib region of the longissimus of each animal were stored for 10 d at 4°C. Care was taken to ensure uniform sampling of the chops. Following the storage period, chops were broiled to 71°C under an electric oven broiler (Amana Model ARE 60) that had been previously preheated to 210°C. The temperature of each chop was monitored using 0.51 mm diameter thermocouples (Chromega/Alomega) attached to an Omega digital thermometer (Model DSS-650, Omega Engineering, Inc., Stamford, CN). Instrumental measurement of tenderness was evaluated using a circular, five-pointed star-probe (9 mm in diameter with 6 mm between each point) attached to an Instron Universal Testing Machine (Model 1122, Canton, MA). A 100-kg load cell was used with a crosshead speed of 200 mm/min. The star-probe attachment was used to determine the amount of force needed to puncture and compress the chop to 80% of the sample height. Each chop was punctured three times and an average was recorded. Sensory evaluation was done using a highly trained professional sensory panel. This is a standing panel with each panelist receiving training over a 6-mo period. During training, panelists were presented with numerous samples that represented extremes in all attributes of interest. Before a new panelist was approved, they had an additional 6-mo probation period that involved data collection along with the established trained panel. Their data are compared with the highly trained panel before they are allowed to join the panel. This standing panel evaluates over 2,000 samples per year. Three of these highly trained panelists were used to evaluate all samples in this study. Cubes of 1.3 cm in size were removed from the center of the broiled loin chops immediately after removal from the oven. The cubes from each loin were placed in preheated, individually coded glass Petri dishes and served to each panelist. Serving temperature of the samples was 65 ± 2°C. Samples were evaluated for degree of juiciness, tenderness, chewiness, pork flavor, and off-flavor using a 10-point category scale. The scale was anchored on the left end with a term representing a low degree of juiciness, tenderness, chewiness, flavor, and off-flavor intensity. On the right end of the scale was a term representing a high degree of each characteristic. Each panelist was seated at an individual booth with red lighting overhead. Room-temperature deionized, distilled water and unsalted crackers were used to cleanse the palate between samples.

Statistical Analysis

The purpose of this study was to look at the phenotypic relationships between many measures of meat quality. In order to obtain and compare values observed in this study with those from previous studies, means and standard deviations were calculated for all traits. Associations between traits (phenotypic) were determined by calculating phenotypic correlations using the computer package developed by SAS (SAS Inst. Inc., Cary, NC). Genetic correlations were not calculated due to the small numbers of sires used in this study.

Results and Discussion

The means for the major traits evaluated in this population are presented in Table 1. In general, the meat quality characteristics for this F2 population compared favorably with the results obtained in the National Pork Producers Council's National Genetic Evaluation Program (Johnson and Goodwin, 1995) for the two purebred foundation breeds (Berkshire and Yorkshire) used to generate the F2 population in this study. Standard deviations of the traits were also simi-

Table 1. Means and standard deviations of the traits measured in pork

Trait	n	Mean	Standard deviation
Carcass characteristics			
Carcass weight, kg	525	87.08	5.73
10th-rib back fat, cm	525	3.19	0.779
Last-rib back fat, cm	525	3.16	0.609
Loineye area, cm^2	525	35.59	5.684
Meat quality characteristics			
Subjective color (loin) (1–5 scale)	525	3.25	0.482
Subjective marbling (loin) (1–5 scale)	525	3.80	0.732
Subjective firmness (loin) (1–5 scale)	525	3.42	0.627
24-h semimembranosus pH	525	5.90	0.218
24-h loin pH	525	5.78	0.174
48-h loin pH	525	5.83	0.190
Loin Hunter L (24 h)	524	44.07	6.12
Loin Hunter L (48 h)	525	46.87	3.39
Semimembranosus Hunter L (24 h)	525	41.65	3.46
Drip loss (loin), %	525	5.84	1.99
Cook loss (loin), %	514	18.23	4.40
Biochemical measures			
Glycogen, μmol/g	519	8.68	3.34
Lactate, μmol/g	519	86.67	13.30
Glycolytic potential, μmol/g	518	104.00	16.31
Ratio IIa/IIb fiber type	513	1.04	0.77
Total lipid, %	525	3.23	1.318
Total cholesterol, mg/100 g	525	57.72	8.29
Textural and sensory characteristics			
Star Probe penetration force, kg	488	4.36	0.863
Sensory tenderness score (1–10 scale)	513	7.84	1.17
Sensory juiciness score (1–10 scale)	513	6.02	1.49
Sensory flavor score (1–10 scale)	513	2.85	1.76
Sensory off-flavor score (1–10 scale)	513	1.59	2.03

lar to those expected. Few studies have been published on the Berkshire breed. These results with (on average) 50% Berkshire genetics should be of value given the recent interest in the Berkshire breed in the United States.

Correlations Among Important Pork Quality Traits

There were significant correlations among many of the quality traits that are important for both fresh pork sensory attributes and processing factors (Table 2). Subjective color, marbling, and firmness scores were all significantly correlated with most sensory traits except juiciness. Subjective color was also significantly correlated with firmness, drip loss, and instrumental evaluation of tenderness (Star Probe). These data indicate that in this study, darker product had a greater propensity to be firmer, have less drip loss, and be more tender. Although the correlation between subjective color and flavor was significant, the magnitude of the correlation is small enough to indicate that, in this population, other factors may have a greater influence on flavor. Marbling was significantly correlated with firmness, drip loss, percentage cook loss, and measures of tenderness (Table 2). Of these traits, the strongest correlation was between marbling and firmness. The positive correlation observed indicated that product with a higher degree of marbling also tended to be evaluated as firmer. The same relationship was found when comparing percent intramuscular lipid and product firmness (Table 3). It is possible that in chilled product higher amounts of lipid may aid in improving the firmness of the product. The modest relationship between marbling and(or) lipid and instrumental measurements of tenderness is in agreement with several studies showing that higher levels of marbling are related to lower shear force (De Vol, et al., 1988; Hodgson et al., 1991; Candek-Potokar et al., 1998). However, numerous other authors have shown little or no consistent relationship of measures of marbling or lipid with measures of tenderness (Tornberg et al., 1993; Jones et al., 1994; Blanchard et al., 2000). Other parameters such as proteolysis and myofibrillar fragmentation may also play a role in determining tenderness (Wheeler et al., 2000).

Interestingly, in this study, neither marbling (Table 2) nor percentage intramuscular lipid (Table 3) was significantly correlated with juiciness score. Other investigators have also found this relationship (Cameron, 1990; Blanchard et al., 2000). However, both marbling and percentage intramuscular lipid were positively correlated with flavor scores and negatively correlated with off-flavor scores, indicating that the panelists in this study associated more normal pork

Table 2. Correlations between subjective evaluations, drip loss and cooking loss, instrumental measurement of tenderness, and sensory characteristics of porcine longissimus muscle

Item	Color	Marbling	Firmness	Drip loss	% Cook loss	Star Probe	Tenderness score	Juiciness score	Flavor score
Marbling	0.03 (0.4972)								
Firmness	**0.27** (0.0001)	**0.37** (0.0001)							
Drip loss	**–0.33** (0.0001)	**–0.12** (0.0049)	**–0.25** (0.0001)						
% Cook loss	**–0.21** (0.0001)	**–0.11** (0.0131)	**–0.12** (0.0075)	**0.016** (0.0004)					
Star Probe	**–0.27** (0.0001)	**–0.27** (0.0001)	**–0.21** (0.0001)	**0.29** (0.0001)	**0.34** (0.0001)				
Tenderness score	**0.19** (0.0001)	**0.21** (0.0001)	**0.21** (0.0001)	**–0.30** (0.0001)	**–0.28** (0.0001)	**–0.54** (0.0001)			
Juiciness score	0.07 (0.14)	0.02 (0.59)	0.07 (0.09)	–0.05 (0.23)	**–0.43** (0.0001)	**–0.16** (0.0005)	**0.46** (0.0001)		
Flavor score	**0.09** (0.05)	**0.20** (0.0001)	**0.16** (0.0002)	**–0.24** (0.0001)	**0.12** (0.0054)	**–0.21** (0.0001)	**0.37** (**0.0001**)	**0.12** (0.01)	
Off-Flavor score	**–0.17** (0.0001)	**–0.15** (0.0005)	**–0.18** (0.0001)	**0.35** (0.0001)	–0.03 (0.5352)	**0.13** (0.004)	–0.30 (0.0001)	–0.08 (0.06)	**0.62** (0.0001)

Upper row = phenotypic correlations, bold values indicate significant correlations.
P-values for difference from zero in parentheses.

flavor with products that had higher marbling and(or) percentage intramuscular lipid. It is important to note, however, that the magnitude of these correlations was not high; therefore, other factors also influence the perception of pork flavor.

Drip loss has long been primarily evaluated as a key variable in processing situations when product yield is important. It is apparent in this study that drip loss may be related to sensory parameters of fresh product as well; drip loss was significantly correlated with measures of subjective color, tenderness (Star Probe and tenderness score), and flavor of the product. These data indicate that product with a high degree of drip loss would also tend to be lighter in color, be less tender, have less pork flavor, and have more off-flavor.

When considering the relationships between the sensory traits of tenderness, juiciness, flavor, and off-flavor, many significant correlations were observed (Table 2). Tenderness was most highly correlated with juiciness, flavor, and off-flavor, in a manner that indicated that panelists in this study tended to rate more-tender products as also being more juicy, having more pork flavor, and having less off-flavor. In this study, product that lost more weight during cooking had a tendency to be rated as being less juicy. This is as expected, because a large proportion of the weight lost during cooking results from moisture loss. It is interesting to note that drip loss of the product (moisture lost prior to cooking) was not significantly correlated with juiciness. The correlation between cook loss and drip loss, although significant, was low (0.16, Table 2). This is not surprising, as moisture lost prior to cooking obviously could not be lost during cooking.

This study also provided a venue to compare the instrumental measure of tenderness (Star Probe) with sensory evaluations of tenderness. The Star Probe device measures the amount of force needed to both puncture and compress a meat sample, a procedure similar to what takes place in the first chews by human molars. The relationships between sensory tenderness measurements and Star Probe measurements were significant and were moderate in magnitude (Table 2), indicating relatively good agreement between the measures. The negative correlation indicates that product that required less force to puncture and compress it would also tend to be rated as being more tender.

Correlations Among Pork Quality Traits and Biochemical-Instrumental Predictors of Quality

It is not practical, in most cases, to measure sensory, textural, and processing traits directly. Additionally, many of these traits are subjective in nature. Therefore, it is important to know the relationship between these traits and many of the commonly used objective instrument-based measures of pork quality in order to more accurately evaluate pork quality in a commercial setting. In addition, insight into the relationships between biochemical parameters and pork quality traits is useful in the search for genetic markers of pork quality. The correlations that are reported in Table 3 provide more insight into some of these relationships.

Table 3. Correlations between pork carcass measurements and biochemical measurements of porcine longissimus muscle and sensory characteristics

Item	Carcass weight	10th-rib backfat	Loineye area	pH 24 h	pH 48 h	Loin Hunter L (48 h)	IIa/IIb	Glycogen	Lactate	Glycolytic potential	% Lipid	Cholesterol
Color	0.06	**–0.10**	0.07	**0.30**	**0.28**	**–0.69**	**0.13**	**–0.18**	**–0.27**	**–0.30**	**–0.15**	**–0.07**
	(0.18)	(0.02)	(0.13)	(0.003)	(0.0001)	(0.0001)	(0.003)	(0.0001)	(0.0001)	(0.0001)	(0.0001)	(0.03)
Marbling	**0.09**	**0.38**	**–0.25**	**0.13**	**0.15**	0.04	0.06	**–0.08**	**–0.10**	**–0.12**	**0.57**	**0.09**
	(0.04)	(0.0001)	(0.0001)	(0.003)	(0.0006)	(0.35)	(0.18)	(0.06)	(0.02)	(0.01)	(0.0001)	(0.04)
Firmness	0.08	**0.24**	**–0.11**	**0.20**	**0.21**	**–0.20**	**0.11**	–0.08	**–0.23**	**–0.22**	**0.31**	0.02
	(0.06)	(0.0001)	(0.01)	(0.0001)	(0.0001)	(0.0001)	(0.01)	(0.07)	(0.0001)	(0.0001)	(0.0001)	(0.72)
% Drip loss	0.01	0.01	0.02	**–0.33**	**–0.28**	**0.33**	**–0.10**	**0.21**	**0.34**	**0.36**	–0.01	0.001
	(0.83)	(0.88)	(0.64)	(0.0001)	(0.0001)	(0.0001)	(0.03)	(0.0001)	(0.0001)	(0.0001)	(0.83)	(0.97)
% Cook loss	–0.03	**0.11**	–0.06	**–0.20**	**–0.20**	**0.31**	0.02	**0.21**	**0.19**	**0.24**	**0.12**	0.07
	(0.4853)	(0.0154)	(0.1853)	(0.0001)	(0.0001)	(0.0001)	(0.5776)	(0.0001)	(0.0001)	(0.0001)	(0.006)	(0.0989)
Star Probe	–0.01	**–0.19**	**0.22**	**–0.31**	**–0.29**	**0.28**	–0.08	**0.25**	**0.24**	**0.30**	**–0.14**	0.08
	(0.74)	(0.0001)	(0.0001)	(0.0001)	(0.0001)	(0.0001)	(0.08)	(0.0001)	(0.0001)	(0.0001)	(0.002)	(0.10)
Tenderness score	0.03	**0.19**	**–0.18**	**0.27**	**0.28**	**–0.15**	0.02	**–0.20**	**–0.28**	**–0.31**	**0.19**	**–0.12**
	(0.57)	(0.0001)	(0.0001)	(0.0001)	(0.0001)	(0.0004)	(0.59)	(0.0001)	(0.0001)	(0.0001)	(0.0001)	(0.01)
Juiciness score	**0.09**	0.01	0.07	**0.17**	**0.15**	–0.02	–0.06	–0.07	**–0.22**	**–0.21**	0.05	**–0.09**
	(0.04)	(0.83)	(0.09)	(0.0001)	(0.001)	(0.64)	(0.18)	(0.11)	(0.0001)	(0.0001)	(0.27)	(0.04)
Flavor score	0.05	**0.24**	**–0.16**	**0.25**	**0.32**	–0.04	–0.01	**–0.13**	**–0.23**	**–0.24**	**0.23**	–0.04
	(0.27)	(**0.001**)	(0.0001)	(0.0001)	(0.0001)	(0.38)	(0.86)	(0.003)	(0.0001)	(0.0001)	(0.0001)	(0.41)
Off-Flavor score	**0.14**	**–0.21**	**0.10**	**–0.23**	**–0.32**	**0.12**	0.01	0.07	**0.20**	**0.19**	**–0.19**	–0.02
	(0.002)	(0.0001)	(0.03)	(0.0001)	(0.0001)	(0.01)	(0.86)	(0.14)	(0.0001)	(0.0001)	(0.0001)	(0.60)

Upper row = phenotypic correlations, bold values indicate significant correlations. *P*-values for difference from zero in parentheses.

Carcass weight was significantly correlated only with marbling, juiciness score, and off-flavor score. Tenth-rib backfat was significantly correlated with marbling, firmness, tenderness (Star Probe and sensory tenderness), flavor, and off-flavor. The correlation between 10th-rib backfat and color was also significant but the magnitude of this correlation was relatively low. Loin eye area was significantly correlated with marbling, tenderness (Star Probe and sensory tenderness), flavor, and off-flavor scores. These correlations suggest that there could be a tendency for leaner, heavier-muscled carcasses in this study to have chops with less marbling and that are less firm, less tender, and have less characteristic pork flavor than chops from carcasses with greater amounts of 10th-rib backfat and(or) smaller loin eyes.

pH and Glycolytic Potential. Postrigor pH measurements are commonly used to predict several meat quality traits. To gain a better understanding of the mechanism behind the variation in ultimate postmortem pH, it is important to examine relationships between pork quality measures and some of the biochemical parameters related to muscle pH. Therefore, factors relating to postmortem glycolysis were also evaluated.

Loin pH measurements were taken both at 24 and at 48 h postmortem. The correlation between these two measurements was significant, and, as expected, the magnitude of the correlation was relatively high (0.71, Table 4). Correlations of pH measured at 24 or 48 h postmortem with other quality measurements were very similar (Table 3). Significant correlations were found between both 24- and 48-h pH measurements and many of the quality traits measured. The traits that were most highly correlated with pH (at 24 and 48 h) measures were color, drip loss, tenderness (Star Probe and sensory tenderness), flavor and off-flavor scores, and cook loss. These results indicate that a lower ultimate pH of the product was associated with lighter-colored product, product with higher drip loss, less tender product, and with less pork flavor and more off-flavor in the product.

Glycolytic potential is an estimate of the amount of glycogen that is present in the muscle at slaughter. Greater amounts of glycogen in the tissue at slaughter can provide the potential for a sustained glycolysis in the muscle after slaughter, which could result in lower ultimate pH (Monin and Sellier, 1985). Indeed, very high glycolytic potential values are associated with significantly lower ultimate pH values observed in meat from pigs with the RN gene (Monin and Sellier, 1985). In this study, glycolytic potential had a significant and positive correlation with Hunter L-values and drip loss and was negatively correlated with pH ($P < 0.0001$, Table 4). Lower glycolytic potential was associated with product that was more tender and juicier. Lower glycolytic potential was also associated with pork that was evaluated as having more pork flavor and less off-flavor. Similar relationships were also seen for lactate (Table 3). Glycogen was also significantly correlated with measures of pH (Table 4), tenderness, and pork flavor evaluations (Table 3), but, unlike glycolytic potential and lactate concentration, residual glycogen was not significantly correlated with juiciness or off-flavor scores.

Color. Subjective color of the product was significantly correlated with Hunter L values, an instrumental measure of the lightness/darkness of the product. The magnitude of this correlation was relatively high (–0.69, Table 3), indicating that Hunter L-values are predictive of subjective color scores. One reason that the magnitude of the correlation was not higher could be that subjective scores of color often take into account not only the lightness/darkness of the product, but also the amount of redness observed in the product. Nevertheless, both subjective color and Hunter L-values were significantly correlated with most of the same traits. The postrigor pH measures of the product (at both 24 and 48 h) were among the traits measured that had the highest correlations to both subjective color score (Table 3) and Hunter L-values (Table 4). Additionally, traits that are closely related to ultimate pH (glycolytic potential and lactate concentration) were also among the traits that were significantly correlated with color measures (Tables 3 and 4).

In this study, products that were evaluated as having a higher color score or a lower Hunter L-value (darker) tended to be associated with a higher postrigor pH. This relationship is not uncommon (DeVol et al., 1988; Hovenier et al., 1992). Pork with high ultimate pH often is darker in color. Conversely, pork with a low ultimate pH can be lighter in color (Monin and Sellier, 1985). One reason for this is that low pH values may result in the denaturation of myoglobin and other muscle proteins. The denaturation of proteins reduces their solubility and causes them to precipitate and to reflect rather than absorb light, resulting in lighter-colored product (Honikel, 1987).

Firmness. The biochemical-instrumental measures that were most closely correlated with firmness were lipid concentration, color measures (subjective color, Table 2, Hunter L, Table 3), postrigor pH measures, lactate concentration, and glycolytic potential (Table 3). However, postrigor glycogen concentration was not significantly correlated with firmness (Table 3). Postrigor pH is often associated with firmness of the product, with product having a low ultimate pH or more rapid pH decline often categorized as being less firm (Bowker et al., 1999; Lonergan et al., 2001). In general, it appears that these same relationships held in the population used in this study.

Percentage Drip Loss and Percentage Cook Loss. Biochemical and instrumental traits that were most closely associated with drip loss and percentage cook loss included Hunter L-values, postrigor pH, and factors related to the development of ultimate pH (glycolytic potential, residual glycogen and lactate concentration) (Table 3). These relationships indicated that product with a low ultimate pH (and high lactate con-

Table 4. Correlations between pork carcass measurements and biochemical measurements of porcine longissimus muscle

Item	Carcass weight	10th Rib backfat	Loineye area	pH, 24 h	pH, 48 h	Loin Hunter L, 48 h	IIa/IIb ratio	Glycogen	Lactate	Glycolytic potential	% Lipid
10th Rib backfat	**0.27** (0.0001)										
Loineye area	**0.17** (0.0001)	**–0.57** (0.0001)									
pH, 24 h	–0.03 (0.46)	0.02 (0.68)	–0.01 (0.80)								
pH, 48 h	–0.03 (0.51)	0.02 (0.60)	–0.04 (0.41)	**0.71** (0.0001)							
Hunter L, 48 h	–0.03 (0.46)	**0.19** (0.0001)	**–0.13** (0.002)	**–0.32** (0.0001)	**–0.27** (0.0001)						
IIa/IIb ratio	–0.001 (0.94)	**0.14** (0.002)	**–0.13** (0.004)	0.02 (0.64)	–0.01 (0.77)	**–0.11** (0.02)					
Glycogen	**0.10** (0.02)	0.08 (0.08)	**0.10** (0.02)	**–0.21** (0.0001)	**–0.15** (0.0007)	**0.22** (0.0001)	–0.02 (0.70)				
Lactate	**0.10** (0.02)	0.08 (0.07)	–0.06 (0.19)	**–0.37** (0.0001)	**–0.38** (0.0001)	**0.26** (0.0001)	–0.02 (0.72)	**0.25** (0.0001)			
Glycolytic potential	**0.12** (0.006)	**0.10** (0.03)	–0.01 (0.86)	**–0.38** (0.0001)	**–0.39** (0.0001)	**0.30** (0.0001)	–0.02 (0.67)	**0.61** (0.0001)	**0.92** (0.0001)		
% Lipid	0.03 (0.54)	**0.45** (0.0001)	**–0.27** (0.0001)	0.02 (0.57)	0.08 (0.07)	**0.33** (0.0001)	0.04 (0.36)	0.06 (0.19)	–0.04 (0.32)	–0.01 (0.79)	
Cholesterol	0.06 (0.19)	**0.11** (0.01)	–0.07 (0.13)	0.01 (0.88)	0.02 (0.61)	0.04 (0.35)	0.001 (0.99)	**0.09** (0.04)	0.04 (0.37)	0.07 (0.11)	**0.11** (0.01)

Upper row = phenotypic correlations, bold values indicate significant correlations. *P*-values for difference from zero in parentheses.

centration) and a high glycolytic potential might be expected to have higher drip loss. Similar phenotypic relationships have been reported in other populations (Hovenier et al., 1992; de Vries et al., 1994; Lonergan et al., 2001).

Palatability Traits. Evaluations of tenderness (Star Probe measurements and sensory panel tenderness scores), juiciness, flavor, and off-flavor were most highly correlated with ultimate pH measures and to biochemical factors that are expected to impact the extent of pH decline (residual glycogen, lactate and glycolytic potential) (Table 3). Relationships between tenderness and pH were also noted by DeVol et al. (1988) and Cameron (1990). These data indicate that higher ultimate pH tends to be associated with more-desirable eating qualities (more tender and juicy, greater pork flavor, and less off-flavor).

Muscle Fiber Characteristics. Muscle fibers can be classified by metabolic characteristics as type I (slow twitch, oxidative), type IIa (fast twitch, oxidative-glycolytic), or type IIb (fast twitch, glycolytic). Type IIb fibers tend to have less myoglobin and be larger in diameter than other fiber types. Some studies have indicated that selection for rapid growth rate or less backfat could alter muscle fiber composition toward a higher percentage of type IIb fibers (Rahelic and Puac, 1981; Brocks et al., 2000). Ratios of these fiber types may influence metabolic properties of the muscle. In turn, this could result in changes in muscle metabolism after slaughter (Essen-Gustavsson, 1993). Muscle fibers that are more reliant on glycolytic pathways and that contain less myoglobin (IIb) to store oxygen may shift to anaerobic metabolism earlier, thereby accelerating the rate of postmortem pH decline. It could be hypothesized that a lower IIa:IIb ratio (higher proportion of type IIb fibers) would result in lighter-colored product and more-rapid pH decline.

In the current study, there was a significant correlation of the relative proportion of type IIa to type IIb fibers with the quality characteristics of color (subjective color, Table 3, and Hunter L, Table 4), firmness, and drip loss (Table 3), indicating that products with a higher percentage of IIb fibers could have a greater propensity to be lighter in color, be less firm, and have greater drip loss. Product that is less firm and that has a higher drip loss is often associated with more-rapid pH decline (Bowker, et al., 1999; Lonergan et al., 2001). Although there was not a significant correlation between the ratio of IIa/IIb fibers and ultimate pH (Table 5), prerigor pH decline was not measured, so the relationship between early pH decline and fiber type cannot be determined in this study. There was also a significant correlation of the IIa:IIb ratio with the carcass characteristics of 10th rib backfat and loin eye area. These data suggest that there could be a tendency for carcasses with a greater amount of type IIb fibers in the loin to have less 10th-rib backfat and to have slightly larger loin eyes and for the product to be lighter in color, less firm, and have higher drip loss. However, the magnitude of these relationships was not high, indicating that other factors also contribute to these characteristics. Larzul et al. (1997) found very similar phenotypic corrleations of the percentage of type IIb fibers with average backfat (0.14) and L* values (0.18).

Relationships Among Carcass Measurements and Chemical Characteristics

Carcass weight was significantly positively correlated with 10th-rib backfat, loineye area, residual glycogen, lactate concentration, and glycolytic potential (Table 4). Tenth-rib backfat was most highly correlated with loineye area (–0.57) and percentage lipid in the loin (0.45). Loineye area was also significantly correlated with percentage lipid in the loin (–0.27). Similar relationships were seen by Cameron (1990). These data indicated that selection for less backfat might result in carcasses with larger loineyes and a lower percentage lipid in the loin.

Percentage lipid in the loin was positively and moderately correlated with Hunter L-values, such that product that had a higher percentage of lipid could be expected to have a higher Hunter L-value (lighter-colored product) (Table 4).

Correlations Between Muscles

Often it is of interest to know whether pH or color measurements made in the longissimus have the potential to be predictive of the pH or color of the ham. In this population of pigs, the pH of the semimembranosus was significantly correlated with ultimate pH measures in the loin (Table 5). The magnitude of the correlation was moderate, indicating some predictive value. Hunter L-values measured at 24 h postmortem in the semimembranosus were also significantly correlated with the Hunter L-values in the loin at 24 and 48 h postmortem (Table 5). Again, the magnitude of the correlation was only moderate, indicating moderate reliability in predicting the color of one muscle based on the color of the another.

Implications

Meat quality traits are complex and are influenced by many factors. This fact makes the prediction of these traits difficult, especially when attempting to develop improvement strategies for pork quality. Knowing the relationships between numerous quality traits is therefore important if progress is to be made. This study is unique in the scope of the quality traits that were examined. There were significant correlations between many quality traits that are important for both palatability of the fresh product and for processing factors. These data suggest that changes in some meat quality traits can affect many other meat quality attributes. In addition, there were many sig-

Table 5. Correlations between pH values and Hunter L-values of the longissimus muscle and the semimembranosus

Item	24-h loin pH	48-h loin pH	Loin Hunter L, 24 h	Loin Hunter L, 48 h	Semimembranosus Hunter L, 24 h
Semimembranosus pH, 24 h[a]	**0.47** (0.0001)	**0.42** (0.0001)	–0.002 (0.962)	**–0.16** (0.0003)	**–0.18** (0.0001)
Semimembranosus Hunter L, 24 h	**–0.21** (0.0001)	**–0.10** (0.0262)	**0.30** (0.0001)	**0.31** (0.0001)	

[a]Upper row = phenotypic correlations. Bold values indicate significant correlations. *P*-values for difference from zero in parentheses.

nificant correlations between biochemical traits, instrumental measures of quality, and sensory characteristics. Therefore, the phenotypic correlations reported in this study yield important information that can be used to aid in directing future studies aimed at elucidating the underlying biological mechanisms behind the development of many quality traits.

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