HISTOLOGICAL, PHYSICAL, AND CHEMICAL FACTORS OF VARIOUS LAMB MUSCLES

A Thesis

by

TARA ELIZABETH TSCHIRHART

Submitted to the Office of Graduate Studies of
Texas A&M University
in partial fulfillment of the requirements for the degree of

MASTER OF SCIENCE

December 2003

Major Subject: Animal Science

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Approved as to style and content by:

Jeffrey W. Savell (Chair of Committee)	Daniel S. Hale (Member)
Joe D. Townsend (Member)	John McNeill (Head of Department)

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ABSTRACT

Histological, Physical, and Chemical Factors of Various

Lamb Muscles. (December 2003)

Tara Elizabeth Tschirhart, B.S., Texas A&M University

Chair of Advisory Committee: Dr. Jeffrey W. Savell

Muscles (n = 18) were dissected from each side of twenty lamb carcasses. Muscles from the right sides of the carcasses were used to determine weight, length, width, minimum and maximum thickness, objective color measurements, water-holding capacity (WHC), pH, total collagen content, sarcomere length, and fat and moisture content. Muscles from the left sides of the carcasses were aged for seven days and used to determine percent cook loss, and Warner-Bratzler shear force values.

The *M. teres major* was lightest ($P < 0.05$) in weight and smallest in surface area, while the *M. longissimus lumborum* was heaviest ($P < 0.05$) in weight, and the *M. serratus ventralis* was largest in surface area. *M. adductor* and *M. semimembranosus* were found to be the darkest in color ($P < 0.05$), while the *M. latissimus dorsi* and *M. tensor fasciae latae* were the lightest ($P < 0.05$). *M. triceps brachii* had the highest WHC and the *M. longissimus lumborum* the lowest. The *M. teres major* and *M. serratus ventralis* had the highest ($P < 0.05$) pH values. The *M. infraspinatus* was found to have the highest collagen content (9.00 mg/g) and the *M. psoas major* revealed the longest sarcomere lengths (3.06 μm). *M. serratus ventralis* possessed the highest ($P < 0.05$) percent fat and the lowest moisture content. *M. serratus ventralis* had the lowest cook

loss (17.1%) and *M. supraspinatus* had the highest (25.6%). Of the muscles sampled, the *M. serratus ventralis* was found to have the lowest shear force value (21.8 newtons) and the *M. semimembranosus* had the highest (42.6 newtons).

Based on the findings of these data, it is likely to conclude that certain muscles may be suitable for individual muscle applications while others may not be suitable or may pose certain palatability problems.

DEDICATION

This thesis is dedicated to my fiancé, Craig Hoelscher. I thank you for everything you have done for me that has helped me to get to this point today. Your love, support, understanding, and encouragement has helped to make this process a lot easier for me. I thank you for the person you are, the person you have helped me to become, and the person you encourage me to be, myself, on an everyday basis. Thank you and I love you very much.

I also dedicate this work to my parents, Bonnie Crenwelge and DeWane Tschirhart, and to my brother, Todd Tschirhart. Thank you for always encouraging me to go to college as a child and for always having faith in me and all that I have tried to accomplish. You have both been wonderful parents, and you have helped to lay the foundation on which I continue to grow today. Todd, I could not ask for a better big brother. Although I have always wanted to come to Texas A&M, you helped make the transition a better one for me and served as guidance along the way. You have been an excellent role model for me in the past and continue to be one today. For all that you all have taught me about life and about living – thank you and I love you all dearly.

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I extend a special thanks to Dave McKenna and Andy King for all that they have done in helping me prepare and complete this project. You both have served as a wealth of knowledge and mentor to me, and I could not have done this without your help. Special appreciation also goes out to my fellow graduate students, Pat Mies, Kyle Pfeiffer, John Ellebracht, Jason Behrends, and Barret Kolle, who have provided support and manual labor to the completion of this project.

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I cannot go without mentioning the person that sparked my interest in meat science many years ago. Chance Brooks, thank you for being a great teacher, exceptional coach, and most importantly, a good friend. You did so much to encourage my learning and motivate me toward success.

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CHAPTER I

INTRODUCTION

In the past decade, there has been a 9.1 kg per person increase in meat and poultry consumption in the United States. During that same time period, lamb consumption has decreased by 20% (Market Solutions, 2002), and a 29% decrease in lamb demand has been seen over the last 20 years (Schroeder, Marsh & Mintert, 2000). Currently, lamb accounts for less than half of one percent of the 100 kg of meat and poultry consumed by Americans each year (Market Solutions, 2002). Ward, Trent, and Hildebrand (1995) found that there are many factors that affect meat purchases; among these factors are taste, quality, color and appearance, tenderness, convenience and cooking ease, level of fat, economic value, nutritional content, and variety of meat preparation and packaging. Consumer reports and market analyses have indicated that the decrease in demand and consumption of lamb products has been due to cuts containing high fat content, lack of versatility among products, and perceived inconsistency in overall meat quality (Hopkins & Considine, 1998). In a study on consumer perceptions of lamb as compared to other meats, lamb was found to be ranked last among seven meats for taste, convenience, ease of cooking, and overall preference behind beef, chicken, pork, turkey, fish, and veal (Ward et al., 1995). The report also noted that the factors most likely to increase lamb consumption are high and consistent quality of products, lower prices, meal recipes, and cooking instructions. If there is

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This thesis follows the style and format of *Meat Science*.

going to be a long-term survival in the lamb industry, it is important that this trend be reversed and that the industry finds more innovative ways to market and cater its products to consumers.

In July 2002, the Agricultural Marketing Service issued an assessment collection and remittance regulations for the Lamb Promotion, Research and Information Program (Mattingly & Cox, 2002). With such a program in place, the lamb industry can expect to benefit from a muscle profiling study that characterizes various attributes of stand alone muscles such as tenderness, color, water-holding ability, and compositional characteristics.

Information gathered in this study will serve as a valuable resource for facilitating increased demand in lamb consumption. By doing so, it will offer information to aid meat processors in adding value and consistency to lamb products in the marketplace. The objective of this study was to characterize individual muscles within the lamb carcass in order to better classify muscles and enhance marketing potential.

CHAPTER II

LITERATURE REVIEW

Industry of Change

As the United States continues to grow and change every year, so do the American consumer's demands and expectations. U.S. consumption patterns have changed dramatically over the past 25 years and there are a variety of factors responsible for these changes. Health issues, consumer preferences, relative prices, more convenient products, smaller households, more two-worker households, and an increase in ethnic diversity are but a few of the forces driving changes in consumption patterns (Hamilton, 1988; USDA, 1998). The past 25 years has seen dramatic shifts in meat consumption in the Unites States. In 1970, red meat accounted for 74 percent of the total meat consumption and poultry only accounted for 19 percent. By 1997, poultry increased to 34 percent of the total meat consumption and red meat fell to 58 percent (USDA, 1998).

Studies in the past have focused on identification and classification of various muscles in the beef carcasses, however, as consumer attitudes continue to change, the meat industry must continue to change with them (Belew, Brooks, McKenna, & Savell, 2003; Ramsbottom, Strandine & Koonz, 1945). According to Schroeder et al. (2000), the beef industry has halted its twenty-year decline through a multi-faceted strategy. Recent trends within the beef industry have emphasized characterizing the traits of individual muscles within the carcass. Through such research, underutilized and inappropriately cut muscles have been identified thus allowing for new innovative marketing potential (Johnson et al., 1988; Johnson & Calkins, 1999). Jones, Burson, and

Calkins (2001) completed a comprehensive muscle profiling project for the beef industry that evaluated individually dissected muscles for tenderness, color, and processing characteristics. Following this extensive research, Jones, Burson, Devine, Schafer, and Poday (2000) began a muscle profiling project for the pork industry and have compositionally identified muscles throughout the pork carcass. There has been no extensive research done that solely focuses on identification of individual muscles in the lamb carcass and classification of those muscles for individual characteristics.

In order to maximize utilization of individual lamb muscles, those factors that influence a consumer's perception of quality and palatability must be explored. Some of the factors influencing quality and palatability include: tenderness, water-holding capacity, color, muscle pH, collagen content, muscle fat, and moisture content.

Tenderness

Multiple components factor into the overall tenderness of a muscle, and because tenderness is so multi-faceted, each component is muscle dependent. Collagen content, sarcomere length, intramuscular lipid content, cooking rate, and final internal temperature are among some of the factors affecting tenderness. In beef sarcomere length is the major contributor of tenderness in the *M. psoas major*, connective tissue content is the major determinant in the *M. gluteobiceps* and *M. semimembranosus*, and proteolysis is the major contributor of tenderness in the *Longissimus* (Koohmaraie, Kent, Shackelford, Veiseth & Wheeler, 2002).

Collagen Content & Solubility

Collagen is one form of connective tissue that can affect both muscle tenderness and quality. Structural units within collagen form intermolecular crosslinks, which are relatively unstable in young animals when exposed to denaturing conditions. However, as the crosslink bridges grow older in maturing animals, they become more stable and heat resistance, and cooking causes less disruption (Marsh, 1977).

In discussing the effects of collagen on meat tenderness, total collagen content or "quantity" and percent soluble collagen or "quality" must both be taken into consideration. Smith and Carpenter (1970) reported strong positive relationships between ovine muscle tenderness and total collagen concentrations. Cross, Smith, and Carpenter (1972) found percent soluble collagen to have a low but significant correlation to tenderness ($P < 0.05$) and a significant ($P < 0.01$) negative relationship with chronological age when evaluating individual muscles from ovine leg steaks. Significant differences were found between leg muscles with the *M. semimembranosus* and *M. semitendinosus* having a mean collagen content of 4.2 mg/g, *M. gluteobiceps,* 5.3 mg/g, and *M. vastus lateralis*, 7.2 mg/g. Differences also were seen between these muscles in percent soluble collagen with 7.0%, 7.5%, 10.4%, and 7.3% for the *M. semimembranosus*, *M. semitendinosus*, *M. gluteobiceps*, and *M. vastus lateralis*, respectively.

Cross, Carpenter, and Smith (1973) reported that more youthful cattle had significantly higher percentages of soluble collagen than did more mature cattle. Collagen solubility decreased in the *Longissimus dorsi* muscle with increasing age from

10.4 % to 9.4% and finally to 4.2% with increasing maturity age from “A” to “B” and “E,” respectively (Herring, Cassens, & Briskey, 1967). Tenderness values were found to be similar in “A” and “B” maturity and were found to be significantly higher than “E” maturity. Panel tenderness scores were positive and highly correlated to collagen solubility for the *Longissimus dorsi* (r = 0.77) and the *M. semimembranosus* (r = 0.81), however, were negative and not significantly related to collagen content (r = -0.42 and r = -0.48, respectively).

McKeith, De Vol, Miles, Bechtel, and Carr (1985) reported that there were significant differences in total collagen content in various beef muscles ranging from the *M. psoas major* (3.23 mg/g) to the *M. infraspinatus* (17.81 mg/g). *Longissimus dorsi* muscles in beef were found to have among the lowest values for total collagen content as well as highest percentage of soluble collagen when compared to the *M. rectus femoris, M. gluteobiceps, M. semitendinosus*, and *M. semimembranosus* (Cross et al., 1973). However, *Longissimus dorsi* muscles were rated low in tenderness by subjective panel scores and by shear force values, and thus it was concluded that collagen contributed little to the observed toughness.

Jeremiah and Murray (1984) reported that anatomical location along the longitudinal axis of the *Longissimus dorsi* had no effect on concentration of soluble or insoluble collagen, total concentration of collagen, or overall tenderness. However, it was noted that percent soluble did differ with anatomical location.

Contractile State

Locker (1960) was the first to suggest that the contractile state of the muscle, measured in sarcomere length, was related to tenderness. Since then, it has become generally accepted that these changes in sarcomere length or shortening have a significant effect on overall meat tenderness. Herring, Cassens, and Briskey (1965b) reported that muscles with longer sarcomeres have low resistance to shear and therefore are more tender. Though shortening is not solely responsible for a reduction in muscle tenderness, it is suggested that in a "good" muscle, such as the M. *psoas major*, where the effect of connective tissue is small, the contractile state of the muscle and long sarcomere lengths may be particularly significant in the ultimate tenderness (Herring et al., 1965b; Locker, 1960; Marsh & Leet, 1966).

When exposed to cooler temperatures during the pre-rigor state, red muscle fibers are stimulated to contract and shorten (cold-shortening), and if not physically prevented, will contract by half or more of their initial length (Marsh, 1977). Marsh and Leet (1966) reported that minimum shortening occurs at approximately 15°-20°C and as temperature increases or decreases from this point, shortening increases. Similarly, Locker and Hagyard (1963) observed minimum shortening (less than 10%) occurred in the 14° to 19°C range and maximum shortening (47.7%) occurred at 0°C. Marsh and Leet (1966) again noted that a decrease of up to 20% of the initial muscle length did not exert a significant effect on tenderness in beef *M. sternomandibularis* muscle. However, toughening increased rapidly after this point until it reached its peak shear point at 40% shortening. As shortening increased to 55 to 60%, samples became more tender and

were similar to that of the < 20% shortened samples. Thus, it was concluded that excessive toughness occurred from samples that had shortened in intermediate amounts while those that had shortened by low or very high amounts remained relatively tender. It has also been found that shortening in the *M. sternomandibularis* muscle can vary greatly due to high variability in animals, in that at 2°C, the greatest amount of shortening was 62% while the smallest was 31% (Locker & Hagyard, 1963).

Beef muscles excised pre-rigor being free to contract, are less tender than muscles excised post-rigor. When comparing stretched and "free" pre-rigor excised muscles to the control post-rigor excised muscles, Herring et al. (1965b) reported that the *M. psoas major* contracted by 50% of its initial control length (sarcomere lengths 1.8 μm vs. 3.5 μm) in "free" samples, and when stretched, sarcomeres were between 2.1 μm and 2.4 μm for 5°C and 1°C, respectively. Even after stretching, muscles could not achieve initial length or sarcomere length after being excised. Post-rigor excised muscle was found to have lower shear force values and higher panel ratings than "free" or restrained samples at both 1°C and 5°C in almost every case. Conversely, *M. semitendinosus* muscle was found to have longer sarcomeres in pre-rigor excised, stretched muscle than the "free" or control samples. However, post-rigor muscles were found to be more tender than pre-rigor "free" or restrained samples with shear force values of 13.7 and 37.2 for post-rigor, 19.8 and 13.1 for pre-rigor "free," and 30.7 and 16.9 for restrained muscles at 1°C and 5°C, respectively. These findings contrast those of Marsh and Leet (1966), who found that the prevention of shortening by physical restraint eliminated the toughening effect entirely. In another study on beef

M. semitendinosus, it was revealed that sarcomere lengths between 2.0 µm and 3.25 µm indicated very little change in shear force, while sarcomere lengths below 2.0 µm indicated significant differences (Herring, Cassens, Suess, Brungardt, & Briskey, 1967.)

Smith and Carpenter (1970) and Cross et al. (1972) reported that sarcomere length was significantly related to ovine muscle tenderness ($P < 0.05$) and ($P < 0.01$), respectively. Cross et al. (1972) observed that the *M. semitendinosus* and *M. rectus femoris* were assigned the highest panel ratings for tenderness while the *M. semimembranosus* was assigned the lowest. The *M. semitendinosus* also was found to have longer sarcomeres than the *M. gluteobiceps,* M. *vastus lateralis, M. rectus femoris*, and *M. semimembranosus* ($P < 0.05$).

Locker (1960) suggested that some of the variations in sarcomere length may be due to strains induced on muscles during vertical suspension. Herring, Cassens, and Briskey (1965a) later looked at differences in carcass vertical suspension as compared to horizontal placement and found a greater range in sarcomere lengths of those vertically suspended than those horizontally placed (3.6 µm to 1.8 µm and 2.7 µm to 2.0 µm, respectively). Vertical suspension was found to increase sarcomere length in the *M.* p*soas major, M. latissimus dorsi*, and *M. rectus femoris*, while it shortened sarcomere length in the *Longissimus dorsi*, *M. gluteus medius, M. adductor, M. gluteobiceps*, and *M. semitendinosus* muscles. Differences in sarcomere length between sides were found to be highly related in shear force values ($r = -0.80$, $P < 0.01$).

Fat & Moisture Content

Intramuscular fat (marbling) content also has been shown to have an effect on overall tenderness and palatability. In a comparative study of thirteen beef muscles, McKeith et al. (1985) reported that the four muscles with the highest fat content: *M. infraspinatus* (7.7 %), *M. longissimus thoracis* (6.8 %), *M. longissimus lumborum* (6.1 %), and *M. psoas major* (5.9 %), were rated as the most tender and most flavorful, suggesting a positive relationship between fat content and palatability. The *M. psoas major*, *M. infraspinatus* and *M. longissimus lumborum* also were found to have the lowest shear force values as well (2.64 kg, 3.28 kg, and 3.46 kg, respectively). In the same study, the *M. infraspinatus*, *M. psoas major*, *M. longissimus lumborum*, and *M. longissimus thoracis* were found to have among the lowest percent moisture (72.6 %, 72.3 %, 71.5 %, and 71.5 %, respectively).

In evaluating the relationship between marbling score, fat content, and percent moisture, Brackebusch, McKeith, Carr, and McLaren (1991) found similar results. Slight differences were seen between ranking of muscles and percent fat due to carcass and muscle selection. Muscles with the highest fat content were as follows: *M. spinalis dorsi*, *M. serratus ventralis, M. rectus abdominis, M. infraspinatus, M. psoas major*, and *Longissimus dorsi* (16.0%, 14.5%, 14.4%, 10.4%, 10.2%, and 8.6%, respectively). These six muscles were also found again to have the lowest percent moisture. As marbling increased, fat content increased linearly ($P < 0.001$) and moisture decreased linearly ($P < 0.05$).

Smith and Carpenter (1970) reported similar trends noting that increased percentages of intramuscular fat, accompanied by decreased percentages of moisture, were associated with higher overall palatability when analyzing roasts and chops from the lamb leg, loin, and rib areas. In another study, a significant relationship was found between marbling and shear force values for some lamb leg muscles, however, low correlations observed in panel scores indicated that marbling is not an important indicator of tenderness (Jeremiah, Smith, & Carpenter, 1971).

Tatum, Smith, and Carpenter (1982) reported that each of the palatability attributes was positively related to marbling and their relationships were highly significant. However, it was noted that large differences in marbling would be required to cause detectable changes in palatability; therefore, factors other than marbling are more closely related to overall palatability. Despite the low degree of association, marbling would be relatively effective in identifying beef steaks with "desirable" versus "undesirable" palatability because steaks with slight or higher degrees of marbling were rated 92, 99, and 92% desirable for overall tenderness, flavor desirability, and overall palatability, respectively (Tatum et al., 1982). Gault (1985) noted that "marbling perhaps, influences palatability only to a certain level, with very little improvement beyond this level."

In a study evaluating marbling effects on beef loin steaks in three different geographical locations, Savell et al. (1987) found that there were no substantial differences in overall desirability values of steaks with slightly abundant to small amounts of marbling in San Francisco, Kansas City, or Philadelphia. However,

Philadelphia was slightly lower in desirability values for the high slight, low slight, and traces marbled steaks, whereas values were very similar for San Francisco and Kansas City. The cause of this difference is speculated to be partially due to the higher internal temperature in which consumers in Philadelphia cooked their steaks. It is also noted that consumers in different cities may have different tastes for beef and therefore geographical differences may play an important role in how consumers react to marbling.

Cooking Method, Degree of Doneness, and Cooking Loss

Meat can be prepared using a variety of different temperature and cooking method guidelines. While it is important that some meat products are cooked until color pigments change or to a designated internal temperature, other meat products can be cooked to the consumer's desired degree of doneness. Most often cooking method is cut specific. Aberle, Forrest, Gerrard, and Mills (2001) defined a dry-heat cookery method to be that which uses hot, dry air over a shorter period of time, and is suggested to be used for more tender cuts. A moist-heat cookery method is that which uses moisture and low temperatures over a longer period of time, and is suggested to be used on tougher cuts with larger amounts of connective tissue. While options exist in the preparation of meat products, it has been shown that cooking method and final internal temperature have a direct impact on overall tenderness and palatability (Lorenzen et al., 1999; Neely et al., 1999; Savell et al., 1999).

Davey and Gilbert (1974) identified two distinctly separate phases of toughening with increasing cooking temperature. The first toughening phase involved the

contractile muscle system of actomyosin and occurred between 40 and 50°C. During this phase, a three-to four-fold toughening was seen due to myofibrillar denaturation. Another change occurring in parallel with this phase and occurring around 43 to 44°C is the change in meat color from red to brown. A second phase, responsible for toughening to double again, occurred between 65 and 75°C and involved connective tissue components. Three distinct muscle changes occurred during the second phase of toughening - collagen shrinkage, muscle shrinkage, and weight loss. The authors noted that weigh loss closely paralleled shrinkage and attribute this to the compression of myofibrils from shrinking collagen, the driving force in squeezing fluid out of the muscle.

Similar results were previously reported by Schmidt and Parrish (1971) in that increased internal temperature increased the tenderness of the connective tissue components in meat. However, with progressive heating, a decrease in tenderness occurred due to hardening and drying effects of myofibrillar proteins due to fluid loss.

Palatability and cooking loss has been shown to be impacted by an increase in cooking internal temperature. Cross, Stanfield, and Koch (1976) reported panel scores for the juiciest beef steaks to be those cooked between 60 and 70°C, which resulted in the least weight lost during cooking. Cooking losses increased substantially after the internal temperature reached 70°C. As internal temperature increased from 60° to 80°C, tenderness decreased. Only when temperature increased to 80°C was maximum toughness and panel unacceptability achieved; however, as temperature increased further to 90°C, an increase in tenderness was observed. Parrish, Olson, Miner, and Rust (1973)

reported increased cook losses with increased temperatures as well as a significant difference in WBS values as temperatures reached 80°C. Steaks broiled to 60°C were reported to have a 25% moisture loss while those broiled to 82°C had a 40% loss. Little differences were seen in shear values of steaks cooked to 60, 71, or 82°C, however, panel scores for those cooked to 60°C were higher than those cooked to 71 and 82°C for tenderness and flavor (Gilpin, Batcher, & Deary, 1965). Griffin, Savell, Smith, Rhee, and Johnson (1985) found that cooking losses for lamb roasts increased as temperature increased from rare to well-done. An average additional loss of 6.4% and 6.2% was seen as temperature increased from 60 to 70°C and 70 to 77°C, respectively, given this, cooking loss increased by 0.5% for every additional one minute of cooking time.

Parrish et al. (1973) reported that final internal temperature had a greater impact on overall palatability than did intramuscular fat. Regardless of the amount of marbling, the most desirable beef rib steak was obtained when cooked to an internal temperature of 60°C and as temperature increased, palatability decreased. Much of the same results were acquired from Gilpin et al. (1965) when it was noted that the amount of marbling in the *Longissimus dorsi* and *M. semitendinosus* muscles was not associated with tenderness, juiciness, and flavor scores of the beef rib steaks or eye of round steaks. They also reported that the relationship between cooking loss and marbling was inconsistent. Rib steaks from high marbled carcasses had the greatest percentage of cook loss when broiled to 82°C; on the other hand, eye of round steaks had the greatest percentage of cook loss from carcasses with low marbling cooked to 60°C. Thus, it was

concluded that differences in panel scores for steaks were primarily due to cut and degree of doneness.

Lorenzen et al. (1999), Neely et al. (1999), and Savell et al. (1999) all found that cooking method and degree of doneness affect overall like, tenderness, juiciness, flavor desirability, and flavor intensity in consumer ratings of beef top loin steaks, top round steaks, and top sirloin steaks. Consumers were selected from Houston, Philadelphia, Chicago, and San Francisco and were asked to cook steaks to their preference using one of eleven cooking options. Neely et al. (1999) reported that top round steaks were most commonly cooked to well done, and consumer overall like ratings were highest when cooked to medium rare or less degrees of doneness or to very well degrees of doneness. However, overall like ratings were lower than those of top loin and top sirloin steaks, which may be due to the higher degree of doneness. The cooking methods that yielded the highest consumer ratings were braise, simmer, stew, or stir-fry, the majority of which are less harsh than dry heat methods. It was also reported that Houston rated top round steaks higher for all attributes than did the other cities, and that differences in cooking methods may be the cause of this occurrence.

Somewhat similarly, Lorenzen et al. (1999) found that overall like ratings by consumers were highest in beef top loin steaks when cooked to medium rare or less degree of doneness and that consumers preferred medium or well done over medium well. Outdoor grilling was the most commonly used cooking method, however, indoor grilling, broiling, and pan-frying also were frequently used. Grilling methods provided for interesting results in that consumers from Chicago rated indoor grilling among the

highest and Houston among the lowest. For outdoor grilling, Houston, Chicago, and Philadelphia rated outdoor grilling among the highest and San Francisco among the lowest.

In studying beef top sirloin steaks, Savell et al. (1999) found that most consumers cooked steaks to at least well done and that satisfaction greatly depended on cooking method used. Outdoor grilling and broiling were the most commonly used cooking methods, however, when cooked by these methods to well done or greater degrees of doneness, they received among the lowest palatability ratings. Indoor grilling provided for the highest palatability ratings in overall like, tenderness, flavor desirability, and flavor intensity, while pan-frying provided for the juiciest product.

While differences are seen in cook loss, tenderness, juiciness, flavor, and overall palatability, panel tenderness scores for steaks cooked to different internal temperatures seem to be a reflection of an individual's psychological and physiological response to effect of doneness (Parrish et al., 1973). Consumer acceptance and product satisfaction is very dependant on cultural differences, consumer preferences, how a meat product is cooked, and who it is consumed by (Lorenzen et al., 1999; Neely et al., 1999).

Given that consumers have different preferences in cooking method and degree of doneness, Shackelford, Morgan, Cross, and Savell (1991) found that with beef top loin steaks, there is a 50% chance that steaks will rated as "slightly tender" or better when given a shear force less than 4.6 kg (45.11 newtons) and 68% chance when given a shear force less than 3.9 kg (38.25 newtons). When these results were tested against the National Consumer Retail Beef Study (Savell et al., 1987), they were 88.6% and 74.3%

accurate in determining whether or not a steak would be rated as “slightly tender” or better for 4.6 kg (45.11 newtons) and 3.9 kg (38.25 newtons), respectively.

Muscle pH and Water-Holding Capacity

Muscle pH has been identified as a component that has a great impact on quality because of its influence on muscle water-holding capacity and color. Water-holding capacity is affected by the formation of lactic acid and pH during the postmortem period, which causes the reduction in reactive groups on proteins available for water binding. When reduction in reactive groups occurs and the total number of positively and negatively charged groups becomes equal, the pH approaches its isoelectric point (IEP). At the isoelectric point (pH ~5.1), the muscle has its lowest water-holding capacity and from that point, the water-holding capacity increases as the pH moves in either direction (Aberle et al., 2001; Gault, 1985).

Davis, Smith, Carpenter, and Cross (1975) found that pH was significantly related ($P < 0.01$) to sensory panel ratings for juiciness and overall satisfaction in pork loin chops. Smith and Carpenter (1970) reported muscle pH to have a low but significant correlation to lamb leg roast tenderness and overall consumer satisfaction ($r = 0.31$ and $r = 0.23$, respectively).

Aberle et al. (2001) described water-holding capacity as the ability of a muscle to retain naturally occurring or added fluids during application of an outside force such as cooking, cutting, or grinding. Water-holding capacity has a direct effect on shrinkage during storage due to water loss or moisture loss during cooking. Severe water loss can

be detrimental to the overall product quality and may lead to dryness and the perception of toughness.

It is noted that the water-holding ability of meat is based on shrinkage or swelling of myofibrils, and that major tenderizing effects were achieved at approximately 50% maximum swelling (Gault, 1985; Offer & Trinick, 1983). Maximum swelling, resulting in a doubling in muscle volume, was found at pH 3.4 for the *M. longissimus lumborum* and the *M. triceps brachii caput longum* and pH 3.2 for the *M. infraspinatus.* It was found that muscle swelling characteristics appeared to be reflective of connective tissue content. As the *M. longissimus lumborum* and *M. triceps brachii caput longum* are similar in collagen content, they were also found to have the same smooth swelling profile, whereas the *M. infraspinatus*, a high collagen content muscle, was found to erratic in its swelling patterns. Shear force was found at a maximum around the lowest swelling ratio, pH 4.5-5.5, an increase in tenderness became apparent in the range of 4.6-4.1, and maximum tenderness was achieved at pH 3.3. Offer and Trinick (1983) found that as pH was increased from 7 to 9, the myofibrils swelled by approximately 15% in diameter and as the pH was lowered from 7 to 5, they shrunk by a similar amount.

Because of the effect of pH on water-holding capacity, it is said to have a relationship with quality. Two quality problems in pork associated with this cause are known as dark, firm, and dry (DFD), and pale, soft, and exudative (PSE). A high ultimate pH will result in DFD meat or also termed “dark cutter”. The high pH results in a greater water-holding capacity which allows muscle fibers to swell, and therefore

absorb more light, causing a darker color of lean. This quality problem is seen as a severe defect in industry due to its cause of poor consumer appeal in meat product, and is therefore discounted heavily. The second quality problem, PSE, is associated with an extremely low pH (near the isoelectric point) resulting in a lower water-holding capacity. The soft, loosely structured muscle is associated with protein denaturation and a greater reflectance of light, therefore giving it a pale color of appearance. This quality defect is also seen as a severe problem to the industry in that PSE meat is not only unappealing to consumers, but also has very poor processing characteristics (Romans, Costello, Carlson, Greaser, & Jones, 1994).

Smith and Carpenter (1970) reported overall consumer satisfaction scores on lamb rib chops to be significantly correlated with increased water-holding capacity ($P < 0.05$), however, it was not consistently related to overall ovine muscle palatability.

Meat Color

Color greatly influences a consumer's overall perception of meat quality, and therefore, impacts retail purchasing decisions (Carpenter, 1966). Differences in color can be seen between different species, age groups, sex classifications, muscles, and muscle physical activity level (Aberle et al., 2001; Romans et al., 1994). Differences between these factors arise from myoglobin content, which is largely determined by the oxygen needs of a muscle, whereas a higher quantity of myoglobin results in a darker color of lean. Color differences between species, chronological age, and physical activity level are readily apparent when comparing the light color of pork to the bright red color of beef, pale color of veal to the dark color of mature beef, and the light

colored breast muscle in chicken to the dark contrasting color of the leg or thigh. Muscle-to-muscle differences in myoglobin are due to the type of muscle fibers present. Red muscle fibers have a higher myoglobin content than do white muscle fibers, and therefore muscles with a relatively high proportion of red muscle fibers (30-40%) will appear darker in color (Romans et al., 1994).

Color also can be affected by the pH of the muscle; an extremely low pH can result in a lighter color muscle and an extremely high pH can result in a darker color muscle. It was found that darker color was associated with higher juiciness ratings, and lower cook shrink in pork loin chops, however, tenderness is not significantly influenced by color (Carpenter, Kauffman, Bray, & Weckel, 1965). In addition, a flavor preference was not seen between light and dark muscle colors. Janicki, Kortz, and Rozyczka (1967) noted that color lightness in pork was significantly correlated ($P < 0.01$) to water-holding capacity and muscle pH, and Carpenter et al. (1965) found that these lighter colored muscles with lower pH and water-holding capacity resulted in greater losses during cooking. Given these differences, it has been shown that the variability of pH, water-holding capacity, and firmness is much greater in pork than in lamb (Smith and Carpenter, 1970).

CHAPTER III

MATERIALS & METHODS

Lamb Selection and Dissection

Lamb carcasses (n = 20) were purchased from a commercial lamb slaughter facility and shipped to the Rosenthal Meat Science and Technology Center at Texas A&M University. Carcasses were selected from those weighing between 30.5 to 32.7 kg in hot carcass weight. After arrival, carcasses were be ribbed between the 12th-13th rib and the following information was collected by trained Texas A&M personnel: fat thickness, adjusted fat thickness, body wall thickness, ribeye area, leg conformation score, maturity score, and flank streaking score (Table 1). Carcasses were dissected into individual muscles (Table 2). Following dissection, muscles from the left side of the carcass were trimmed free of fat, denuded, vacuum packed (Ultravac Model 2100-D, Koch Equipment, Kansas City, MO) in individual bags (oxygen transmissible rate 3 to 6 $cc/m^2/24$ hr @ 5°C, 0% relative humidity, vapor transmission 0.5-0.6 g/645 $cm^2/24$ hr @ 38°C, 100% relative humidity) and aged approximately seven days in a 2 ± 2°C cooler.

Muscle Dimension

Weights and dimensions, including length, width, minimum thickness, and maximum thickness, were recorded on individual muscles from the left sides of carcasses, and digital images were taken as a visual illustration. Weights were taken using an analytical scale (Model PB3002-S, Mettler Toledo, Switzerland) and minimum and maximum thickness were taken from the thinnest and thickest portion of the muscle using electronic digital calipers (Traceable Model 14-648-17, Control Company,

Table 1
Means, standard deviation, minimum and maximum values for carcass data

Trait	Mean	SD	Minimum	Maximum
Carcass Weight (kg)	30.29	0.82	28.70	31.35
Fat Thickness (mm)	4.83	1.52	2.03	7.62
Body Wall (mm)	23.37	3.81	17.78	31.75
Ribeye Area (cm^2)	17.61	1.55	15.16	20.65
Lean. Maturity[a]	149.50	10.50	140.00	170.00
Skeletal Maturity[a]	157.00	9.79	140.00	180.00
Flank Streaking[b]	11.35	0.81	10.00	13.00
Quality Score[b]	11.35	0.81	10.00	13.00
Confirmation Score[b]	12.30	0.80	11.00	14.00
Quality Grade[b]	11.65	0.67	10.00	13.00

[a] $A^{40} = 140$, $A^{50} = 150$, $A^{60} = 160$, $A^{70} = 170$, $A^{80} = 180$
[b] $Choice^{-} = 10$, $Choice^{o} = 11$, $Choice^{+} = 12$, $Prime^{-} = 13$, $Prime^{o} = 14$

Table 2
Muscles selected for lamb carcass dissection

Muscle
M. adductor
M. gluteobiceps
M. gluteobiceps - distal
M. gluteobiceps - proximal
M. gluteus medius
M. infraspinatus
M. latissimus dorsi
M. longissimus lumborum
M. longissimus thoracis
M. pectoralis profundus
M. psoas major
M. rectus femoris
M. semimembranosus
M. semitendinosus
M. supraspinatus
M. serratus ventralis
M. triceps brachii
M. tensor fasciae latae
M. teres major
M. vastus lateralis

Friendswood, TX). All other dimensions were measured using a ruler. Length was determined to be the longer of the two dimensions, and both length and width were taken across the longest line or diagonal of the muscle.

Cooking

After aging seven days, raw weights were recorded on individual muscles. Whole muscle roasts were cooked in a forced air convection oven (Hobart Corp., Troy, OH), preheated to 177°C for 20 minutes, to an internal temperature of 70°C. Muscles were grouped with those of a similar size to be cooked together. Temperature was checked on smaller muscles approximately five minutes after cooking was started and on larger muscles approximately 10 minutes after cooking. As internal temperature approached desired degree of doneness, internal temperatures were checked more frequently to avoid overcooking. Internal temperatures were monitored in the geographical center of the roasts using an Omega HH501BT thermometer (Omega Engineering, Inc., Stamford, CT). When muscles reached 70°C, they were removed from the oven and allowed to rest at room temperature (approximately 21°C) for approximately 10 minutes. After the cooling period, muscles were weighed and values were recorded. Muscles then were covered in Saran Wrap® and placed in a cooler at 4°C for 18 hours.

S*hear Force Determination*

Fully cooked individual muscles were removed from the cooler and allowed to equilibrate to room temperature (approximately 21°C). Muscles were cut into 2.54 cm thick chops, and four to six sample cores (1.27 cm diameter) were removed parallel to

the muscle fiber orientation. An Instron Universal Testing Machine (Model 1011, Instron Corp., Canton, MA) with a standard v-notch blade attached was used to determine Warner-Bratzler Shear Force (WBS). Maximum force was recorded in newtons and values for individual muscles were calculated by averaging the shear values of each core for each muscle.

Color Space Value

Denuded individual muscles dissected from the right side of the carcass were cut into 2.54 cm thick chops, and the *M. gluteobiceps* was broken into a proximal and distal portion. The *M. serratus ventralis, M. latissimus dorsi, M. pectoralis profundus, M. teres major,* and *M. tensor faciae latae* muscles remained intact. Muscles were allowed to oxygenate for 15 minutes and objective color measurements (L*-, a*-, b*- values) were collected using a Minolta Colorimeter (Model CR-200 Chroma Meter, Minolta Corp., Ramsey, NJ) on three chops selected at random. Color measurements were taken on intact muscles from three different surface locations.

One cylindrical raw core (1.27 cm diameter) was removed from two different chops, and a total of two cores from each muscle were used for determination of water-holding capacity. Two chops were selected randomly and a raw sub-sample was collected to determine sarcomere length. The remaining portion of each chop was bagged, frozen, and used for further analyses.

Water-Holding Capacity

Water-holding capacity was determined by a modified version of the centrifugation method of Jauregui, Regenstein, and Baker (1981). Three pieces of

undried Whatman #3 filter paper and one piece of Whatman #50 were folded with the #50 paper being on the internal surface. Folded filter papers were inserted into a 50 ml centrifuge tube. Raw cores were weighed and placed into the filter paper in the centrifuge tube. Tubes were positioned in a JA-17 centrifuge rotor, and centrifuged at 31,000 × g for 30 minutes at 4°C using an Avanti J-25 centrifuge (Beckman Instruments Inc., Palo Alto, CA). After centrifugation, meat samples were removed from the filter papers and weights were recorded on each sample. Expressible moisture was determined using the following equation:

$$\% \text{ Expressible Water} = \frac{\text{Centrifuged Sample Weight}}{\text{Uncentrifuged Sample Weight}} \text{ X } 100$$

S*arcomere Length*

Sarcomere lengths were determined using the laser method described by Cross, West, and Dutson (1981). Cubed samples (3-5 g) from individual muscles were homogenized in a cold sucrose buffer solution (85.58 g, 0.25 M sucrose, 0.15 g, 0.002 M KCl, pH adjusted to 7.0 and brought to 1 L volume) using a Waring blender (Model 31BL92, Waring Products Division, Dynamics Corp. of America, New Hartford, CT). Three drops of the homogenate were placed in different locations on a microscope slide and each covered with a cover slip. Each slide was scanned under a helium-neon laser (Model 155SL, Spectra-Physics Inc., Eugene, OR) until a diffraction pattern was observed. Distance between the origin and the first order diffraction band was recorded.

Ten readings were taken for each sample and averaged, and samples were done in duplicate.

Sarcomere length was calculated, in μm, using the following formula:

$$\text{Sarcomere length, } \mu m = \frac{.6328 \times D \times \sqrt{(T/D)^2 + 1}}{T}$$

D = Distance in mm from specimen to the diffraction screen; set at 100 mm before taking measurements.
T = Distance in mm from the origin to the first order diffraction band.
λ = 0.6328 = Wavelength of the He-Ne Laser.

Fat and Moisture Determination

The remaining portion of the frozen samples were pulverized in a Waring blender using liquid nitrogen and stored on dry ice until used for further analyses. Percent moisture and fat were determined according to AOAC (1990) approved procedures. Thimbles were made using Fisher Q2 filter paper and were dried in a Thelco convection oven (Model 28, GCA/Precision Scientific, Chicago, IL) for 12 hours. Following the drying period, thimbles were weighed, filled with 2-3 g of pulverized sample, reweighed, and placed in a convection oven for 12 hours at 100°C. Following the drying period, samples were reweighed and moisture content was determined. Thimbles were put into soxhlets and distilled with 1000 ml of petroleum ether and allowed to extract for 12 hours. After extraction, thimbles were again dried at 100°C for 12 hours, reweighed, and fat content was determined. Analysis of the samples was preformed in triplicate. The fat and moisture content were calculated using the following formulas:

$$\% \text{ Moisture} = \frac{\text{Dried Sample Weight}}{\text{Wet Sample Weight}} \text{ X } 100$$

$$\% \text{ Fat} = \frac{\text{Post - Ether Weight}}{\text{Initial Wet Sample Weight}} \text{ X } 100$$

pH Determination

The pH of individual muscles was determined in duplicate by using a glass probed pH meter (Accumet Basic, Fisher Scientific, Pittsburgh, PA). Approximately 3 g of pulverized sample was blended with 30 ml of distilled water until a smooth slurry was formed. The slurry was filtered through Whatman #1 filter paper. The pH probe was calibrated with pH 4 and 7 standard buffer solutions and was placed into the filtrate for 30-60 seconds to allow the electrode to equilibrate.

Collagen Content

Total collagen content was determined by isolating hydroxyproline from individual pulverized muscle samples as described by Hill (1966). Hydroxyproline concentration was determined by using a color reaction as described by Bergman and Loxley (1963) and then converted to collagen content according to the method of Cross, Carpenter, and Smith (1973). Four grams of pulverized sample were weighed into a 50 ml glass centrifuge tube and 15 ml of 12 N HCl were added to each tube. Tubes then were vortexed using a Maxi Mix II (Model M37615, Barnstead International, Dubuque, IA) until HCl coated the entire tube (10-15 seconds), and centrifuge tubes were placed in a convection oven (IsoTemp 500 series, Fisher Series, Pittsburgh, PA) for 18 hours to hydrolyze collagen. After the cooking period, tubes were removed from the oven and allowed to cool under a vented hood. Approximately 500 g of carbon decolorizing agent

were added to each tube and mixed well. The liquid fraction of sample then was filtered through one Whatman #1 filter paper in a vacuum filter attached to a 500 ml Erlenmeyer flask. Seven drops of methyl red indicator were added to the filtered sample before being neutralized using 5 N NaOH. Samples were transferred into a 500 ml volumetric flask, diluted to volume with double distilled water, and were mixed well. Twenty-five to thirty milliliters of the final filtrate were transferred into a 50 ml centrifuge tube and capped. A blank was prepared using 1 ml of double distilled water, and a standard curve was constructed by preparing 0-, 2-, 4-, 8-, and 12- g/ml hydroxyproline standard solutions. One ml of each standard was pipette, in duplicate, into a 15 ml glass culture tube. A 1 ml sample of the final filtrate was pipetted into a culture tube, in duplicate. Each tube received 2 ml of isopropyl alcohol and was vortexed well. One ml of oxidant solution was added to each test tube, vortexed, and allowed to incubate for 4 minutes. Tubes then received 2 ml of Erlich's reagent, were vortexed, and were placed in a water bath for 25 minutes at 60°C to develop color. Tubes were removed and cooled in a running tap water bath for 5 minutes. Samples were read at 558 nm using a Genesys 10 uv spectrophotometer (Thermo spectronic, Rochester, NY). Analysis was performed in triplicate, however, collagen content was not determined on the *M. teres major* or *M. tensor fasciae latae* due to insufficient sample. Percent total collagen values were calculated using the following formulas:

$$\text{Residue mg} = \frac{(\text{Abs.} + \text{y} - \text{intercept})}{\text{slope}}$$

$$\text{Residue} = \frac{(\text{Residue mg} \times \text{ml diluted})}{\text{sample weight}}$$

Residue Collagen = Residue x 7.25

Residue mg/g = Residue Collagen /1000

Statistical Analysis

Data were analyzed using the GLM procedure of SAS (1997). Muscles were tested as the main effect for each factor analyzed. When the main effect was significant ($P < 0.05$), least square means were generated and separated using the PDIFF procedure.

CHAPTER IV

RESULTS & DISCUSSION

Physical Measurements

Wide variation in physical measurements was noted among the eighteen individual muscles (Table 3). Differences ($P < 0.05$) were observed between many of the muscles. On average, the largest muscles identified were the *M. gluteobiceps, M. gluteus medius, M. longissimus lumborum, M. longissimus thoracis,* and *M. semimembranosus*, which would likely be suitable in terms of physical dimensions to be used for a variety of individual muscle applications. While muscles such as the *M. latissimus dorsi, M. pectoralis profundus*, and *M. serratus ventralis* were thin in terms of dimension, they still possessed sufficient surface area, which may allow them to be used in small muscle applications. The *M. adductor, M. infraspinatus, M. psoas major, M. rectus femoris, M. semitendinosus, M. supraspinatus, M. triceps brachii*, and *M. vastus lateralis* were moderate in terms of all physical measurements and may possibly be able to be used in certain applications. Other muscles, however, such as the *M. teres major* and *M. tensor fasciae latae*, may be too small in size and dimension to be used for individual application. Chambers and Bowers (1993) noted size and shape to play an important role in consumer selection and purchasing of meat products. Consumers will likely choose a product that will fulfill a serving size need.

Muscle pH

Muscle pH values are reported in Table 4. The *M. teres major* and *M. serratus ventralis* had a higher ($P < 0.05$) pH than all other muscles. Values for pH are higher

Table 3
Least squares means for physical measurements

Muscle	Weight (g)	Length (mm)	Width (mm)	Min. Thick. (mm)[o]	Max. Thick. (mm)[p]
M. adductor	184.17de	131.35a	59.11def	10.59abc	35.68h
M. gluteobiceps	379.15k	297.80	66.45f	5.93ab	33.58gh
M. gluteus medius	300.30i	172.10cd	102.20j	6.92ab	31.21fg
M. infraspinatus	215.70fg	205.05e	55.82cde	18.42c	27.13e
M. latissimus dorsi	152.60c	248.05f	101.60i	2.61a	11.41a
M. longissimus lumborum	493.50n	275.10g	77.23g	13.5bc	29.49ef
M. longissimus thoracis	345.48j	312.55i	47.79bc	7.62ab	31.87fg
M. psoas major	233.00g	347.60j	42.66ab	5.27ab	23.23d
M. pectoralis profundus	263.65h	370.70k	93.17hi	3.24a	11.90ab
M. rectus femoris	203.25ef	158.60bc	54.53cd	11.18abc	39.45i
M. semimembranosus	403.86l	164.95bc	76.35g	10.42abc	46.88j
M. semitendinosus	170.31cd	183.40d	43.89b	4.94ab	29.42ef
M. supraspinatus	171.48cd	163.60bc	53.21cd	5.84ab	32.35fg
M. serratus ventralis	444.17m	423.25l	117.86k	3.73a	16.03c
M. triceps brachii	335.20j	164.70bc	91.47h	8.65ab	42.37i
M. tensor fasciae latae	91.14b	155.55b	63.19ef	4.96ab	13.78abc
M. teres major	47.08a	141.00a	34.27a	4.98ab	14.89bc
M. vastus lateralis	193.70e	157.85b	78.83g	6.40ab	31.88fg
SEM	7.29	4.92	3.10	3.35	1.15

Within a column, means lacking a common letter differ ($P < 0.05$)
[o] Min. Thick. = Minimum Thickness
[p] Max. Thick. = Maximum Thickness

Table 4
Least squares means for pH[j] and water-holding capacity (WHC)[k]

Muscle	pH	WHC, %
M. adductor	5.99bcde	39.35j
M. gluteobiceps- distal	6.01cde	37.11ghij
M. gluteobiceps- proximal	5.98bcde	38.07ij
M. gluteus medius	5.95abcd	37.70hij
M. infraspinatus	6.30gh	32.44bcd
M. latissimus dorsi	6.31h	29.36a
M. longissimus lumborum	5.93abc	39.70j
M. longissimus thoracis	5.89a	37.55hij
M. psoas major	6.03de	34.75defgh
M. pectoralis profundus	6.20f	29.31a
M. rectus femoris	6.17f	35.60efghi
M. semimembranosus	5.90ab	37.37ghij
M. semitendinosus	6.21fg	31.27ab
M. supraspinatus	6.24fgh	33.43bcdef
M. serratus ventralis	6.45i	31.73abc
M. triceps brachii	6.19f	29.22a
M. tensor fasciae latae	6.02cde	32.72bcde
M. teres major	6.44i	34.75defgh
M. vastus lateralis	6.06e	35.97fghi

Within a column, means lacking a common letter differ ($P < 0.05$)
[j] SEM = 0.03
[k] SEM = 1.08

than those reported by Jones et al. (2001) for beef. Koohmaraie and Wheeler (1994) reported an ultimate pH for the *M. longissimus et lumborum* to be 5.74. This is lower than that of the current study which found the *M. longissimus thoracis* to have a pH value of 5.89 and the *M. longissimus lumborum* a value of 5.93. Braggins (1996) reported that as ultimate pH in lamb increased from low (5.66) to moderate or high (6.26 and 6.81, respectively), overall cooking odor and flavor decreased ($P < 0.05$). It was also noted in that study however, that a general shift in odor and flavor descriptors increased from desirable to undesirable as pH increased.

Water-Holding Capacity

Values associated with water-holding capacity (WHC) are shown on Table 4. The *M. triceps brachii, M, pectoralis profundus*, and *M. latissimus dorsi* were found to have the highest numerical water-holding capacities while the *M. adductor* and the *M. longissimus lumborum* had the lowest. These findings associated with higher water-holding capacity corresponded with those muscles that tended to have a higher muscle pH, and lower water-holding capacity to those with a lower pH. Jones et al. (2001) reported some muscles to have similar WHC to those found in the current study; however, other muscles reported had a higher WHC.

Muscle Color

Muscle color values are shown in Table 5. Muscle L* values revealed that the *M. latissimus dorsi* and *M. tensor fasciae latae* were the lightest ($P < 0.05$) in terms of muscle color and the *M. adductor* and *M. semimembranosus* were the darkest when compared to all other muscles. The *M. supraspinatus* and *M. psoas major* were found to

Table 5
Least squares means for color measurements

Muscle	L*	a*	b*
M. adductor	41.03a	15.41ef	3.93cdef
M. gluteobiceps- distal	42.80b	15.97fgh	3.99cdef
M. gluteobiceps- proximal	43.77cde	16.33gh	4.18defg
M. gluteus medius	43.15bc	16.49hi	4.25efg
M. infraspinatus	46.28gh	16.85ij	3.88bcdef
M. latissimus dorsi	48.09i	14.02ab	3.32ab
M. longissimus lumborum	42.66b	14.67bcd	3.75bcde
M. longissimus thoracis	44.34de	15.57ef	4.22efg
M. psoas major	44.32de	17.39jk	4.40fg
M. pectoralis profundus	46.98h	13.85a	3.04a
M. rectus femoris	45.36fg	15.48ef	3.65bcd
M. semimembranosus	41.10a	15.32def	3.99cdef
M. semitendinosus	46.72h	15.24cde	4.21efg
M. supraspinatus	46.77h	17.74k	4.67g
M. serratus ventralis	46.48h	15.79efgh	4.07bcdef
M. triceps brachii	43.52bcd	15.72efg	3.47abc
M. tensor fasciae latae	48.21i	13.91a	3.92cdef
M. teres major	46.07gh	14.54abc	3.50abc
M. vastus lateralis	44.68ef	16.51hi	4.19defg
SEM	0.34	0.26	0.20

Within a column, means lacking a common letter differ ($P < 0.05$)

have the highest numerical a* values. Although beef muscles differ in numerical L* and a* values as compared to that of the current study, Jones et al. (2001) reported beef rankings in partial agreement with the current findings. Ward et al. (1995) reported color to be among the top three factors affecting consumer purchases for lamb meat.

Sarcomere Length

Differences ($P < 0.05$) were found for sarcomere length (Table 6). The *M. psoas major* had longer sarcomere lengths when compared to all other muscles. This finding is in agreement with Herring et al. (1965a; 1965b) and McKeith et al. (1985). Although not different from one another, the *M. adductor*, *M. gluteobiceps, M. gluteus medius, M. longissimus lumborum, M. longissimus thoracis*, and *M. semimembranosus* had shorter lengths than other muscles. No differences were found between the proximal and distal portions of the *M. gluteobiceps*. While variations in values do exist, muscle rankings for sarcomere length are similar to those reported by Herring et al. (1965a) for beef carcasses. Values reported for sarcomere lengths are similar to those reported by Cross et al. (1972) for the lamb *M. gluteobiceps, M. rectus femoris, M. semimembranosus, M. semitendinosus*, and *M. vastus lateralis* and Wheeler and Koohmaraie (1994) for the lamb *M. longissimus lumborum.*

Collagen Content

Table 6 shows least squares means for total collagen content. The *M. infraspinatus* was found to have higher ($P < 0.05$) total collagen content when compared to all other muscles; however, the standard deviation (3.62) was also the highest. This variation is likely due to the heavy connective tissue sheath running through the muscle.

Table 6
Least squares means for sarcomere length[k] and collagen content[l]

Muscle	Sarcomere length, µm	Collagen, mg/g
M. adductor	1.71a	3.22abc
M. gluteobiceps- distal	1.67a	4.97efg
M. gluteobiceps- proximal	1.72a	5.59fg
M. gluteus medius	1.68a	6.11g
M. infraspinatus	2.30e	9.00h
M. latissimus dorsi	2.87i	4.98efg
M. longissimus lumborum	1.70a	2.64a
M. longissimus thoracis	1.76ab	2.86ab
M. psoas major	3.06j	4.53def
M. pectoralis profundus	2.77h	5.00efg
M. rectus femoris	2.02c	4.31cde
M. semimembranosus	1.70a	3.53abcd
M. semitendinosus	2.43f	3.74abcd
M. supraspinatus	2.18d	5.54fg
M. serratus ventralis	2.14d	4.09cde
M. triceps brachii	2.56g	5.00efg
M. tensor fasciae latae	2.91i	-
M. teres major	2.58g	-
M. vastus lateralis	1.85b	3.91bcde

Within a column, means lacking a common letter differ ($P < 0.05$)
[k] SEM = 0.04
[l] SEM = 0.41

The notably high level of collagen in the *M. infraspinatus* is in agreement with the findings of McKeith et al. (1985) for beef carcasses. Both findings, however, are in disagreement with that of Johnson et al. (1988) who characterized the *M. infraspinatus* as being moderate in total collagen content. Kolle and Savell (2003) found that by removing the heavy connective tissue sheath in the *M. infraspinatus*, the connective tissue content decreased by nearly six percentage points in raw samples (4.73 versus 9.89%) and nearly eight percentage points in cooked samples (5.68 versus 13.22%). The *M. longissimus lumborum, M. longissimus thoracis, M. adductor, M. semimembranosus,* and *M. semitendinosus* were found to be lower ($P < 0.05$) in collagen content than other muscles. These findings are in partial agreement with those of McKeith et al. (1985) who reported four of these muscles to be ranked among the top five. McKeith et al. (1985) reported the *M. psoas major* to be lowest in collagen; however, the findings of this study reported it to be moderate in content.

Fat and Moisture Content

A wide range of values for fat content of the muscles was observed (Table 7). The three muscles found to have a higher ($P < 0.05$) fat content than the others were the *M. pectoralis profundus* (7.47%), *M. latissimus dorsi* (8.45%), and the *M. serratus ventralis* (13.24%). Of the muscles represented in this study, Johnson et al. (1988) found the beef *M. serratus vent*ralis to be ranked the highest (11.3%) in terms of fat content. Whereas, Johnson et al. (1988) and McKeith et al. (1985) found the *M. infraspinatus* to be among the highest ranking muscles in percent fat (7.3 and 7.7%,

Table 7
Least squares means for percent fat[j] and moisture[k]

Muscle	Fat, %	Moisture, %
M. adductor	3.28a	73.69ef
M. gluteobiceps- distal	4.00abcd	73.02de
M. gluteobiceps- proximal	5.89f	72.19cd
M. gluteus medius	3.98abc	73.52ef
M. infraspinatus	3.36a	74.60g
M. latissimus dorsi	8.45h	70.61b
M. longissimus lumborum	4.25bcde	72.97de
M. longissimus thoracis	5.17ef	72.30cd
M. psoas major	6.83g	71.44bc
M. pectoralis profundus	7.47g	71.66c
M. rectus femoris	3.33a	74.93g
M. semimembranosus	3.52ab	73.25e
M. semitendinosus	4.82cde	73.30e
M. supraspinatus	5.29ef	73.66ef
M. serratus ventralis	13.24i	67.69a
M. triceps brachii	5.05def	73.51ef
M. tensor fasciae latae	5.86f	71.72c
M. teres major	4.61cde	72.95de
M. vastus lateralis	3.32a	74.37fg

Within a column, means lacking a common letter differ ($P < 0.05$)
[j] SEM = 0.31
[k] SEM = 0.32

respectively), this study did not find the ranking as high. Fat percentages in the current study were found to be in partial agreement with those reported by Cross et al. (1972) for lamb leg muscles, however, they were lower than those reported by Carpenter, Rice, Crockett, and Snowder (1996) for lambs. Values and rankings were different than those reported by McKeith et al. (1985) and Kolle (2002) for beef muscles.

Least squares means for percent moisture are shown in Table 7. The *M. serratus ventralis, M. latissimus dorsi, M. psoas major, M. pectoralis profundus, M. tensor fasciae latae,* and *M. gluteobiceps*- proximal were ranked numerically as having the lowest percentage of moisture. Conversely, they were all found to have the highest ranking and numerical value for fat content. The *M. adductor, M. vastus lateralis, M. infraspinatus*, and *M. rectus femoris* were found to have the highest percentage of moisture and lowest percentage of fat. The noted inverse relationship between percentage of fat and moisture also was seen in the studies performed on various beef muscles by Brackebusch et al. (1991) and McKeith et al. (1985). Of the muscles in the current study, Johnson et al. (1988) reported the *M. serratus ventralis* to have the lowest moisture content; this is in agreement with the findings in this study ($P < 0.05$). Cross et al. (1972) reported similar findings for lamb leg muscles. McKeith et al. (1985) reported beef values in partial agreement, however, the rankings differed.

Cook Loss

Percent cooking loss was determined on the eighteen muscles (Table 8). The *M. serratus ventralis* was found to have the lowest (17.08%) cooking loss and the *M. supraspinatus* was found to have the highest (25.61%) loss. Shackelford, Wheeler,

Table 8
Least squares means for cook loss[i] and Warner-Bratzler shear force (WBS)[h]

Muscle	Cook loss, %	WBS, newtons
M. adductor	23.72gh	31.58e
M. gluteobiceps-distal[i]	21.10cdef	26.48bc
M. gluteobiceps-proximal[i]	21.10cdef	28.05cde
M. gluteus medius	23.35fgh	30.69de
M. infraspinatus	21.99defg	26.97bcd
M. latissimus dorsi	21.85defg	28.14cde
M. longissimus lumborum	19.19abc	25.60abc
M. longissimus thoracis	18.85abc	23.44ab
M. psoas major	20.00bcd	28.44cde
M. pectoralis profundus	18.16ab	28.73cde
M. rectus femoris	20.53bcde	26.87bcd
M. semimembranosus	24.12gh	42.56f
M. semitendinosus	19.84bcd	31.09e
M. supraspinatus	25.61h	30.60de
M. serratus ventralis	17.08a	21.77a
M. triceps brachii	18.97abc	29.71cde
M. tensor fasciae latae	20.07bcd	30.89de
M. teres major	18.11	26.38bc
M. vastus lateralis	22.69efg	29.42cde

Within a column, means lacking a common letter differ ($P < 0.05$)
[g] SEM = 0.88
[h] SEM = 1.47
[i] *M. gluteobiceps*-distal and *M. gluteobiceps*-proximal are weighed together

and Koohmaraie (1997) reported cooking losses for lamb muscles greater than those found in the current study. In the previous study, scientists used an open electric broiler rather than oven broiling. Wheeler, Shackelford, and Koohmaraie (1996) found that cooking losses were lower when using oven broiling rather than open electric broiling. In a study done by Gilpin et al. (1965), using beef rib steaks with somewhat similar fat and moisture content as the *M. longissimus thoracis* in the current study (5.8 and 5.17 % fat and 70.9 and 72.3% moisture, respectively), a much higher cook loss was reported when cooked using the same method and endpoint temperature. However, in a similar study on beef rib steaks done by Parrish et al. (1973), and with a similar fat (5.34%) and moisture (72.63%) content, cooking losses were similar to those reported in this study.

Warner-Bratzler Shear Force

Rankings in Warner-Bratzler shear force (WBS) differed from those reported by Belew et al. (2003), Johnson et al. (1988), McKeith et al. (1985), and Ramsbottom et al. (1945) for beef muscles. Least squares means for WBS are reported on Table 8. The *M. serratus ventralis* was found to have the lowest numerical WBS value. One of the features associated with this muscle and contributing to its tenderness is its high fat content (Brackebusch et al., 1991; Johnson et al., 1988). The *M. semimembranosus* had a WBS value higher ($P < 0.05$) than all other muscles in the study (42.6 newtons). Belew et al. (2003) reported a similar value (4.53 kg or 44.4 newtons) for beef, and of the muscles represented in this study, the *M. semimembranosus* was ranked at the bottom in terms of tenderness with only the *M. pectoralis profundus* behind it. Johnson et al. (1988) and McKeith et al. (1985) also found the *M. pectoralis profundus* to be ranked

last in tenderness; however, the values have been inconsistent (3.89 and 6.34 kg or 38.4 and 62.2 newtons). Morgan et al. (1991) reported similar results to those of the current study as steaks from the top round were found to have the highest ($P < 0.05$) WBS values (5.23 kg or 51.3 newtons). The WBS values for the *M. triceps brachii, M. supraspinatus*, and *M. psoas major* from the current study (29.7, 30.6, and 28.4 newtons, respectively) are very similar to those (2.9, 3.3, and 3.0 kg or 28.4, 32.4, or 29.4 newtons, respectively) reported for lamb by Shackelford et al. (1997). Belew et al. (2003) and McKeith et al. (1985) reported WBS values in beef to be similar (2.96 and 2.64 kg or 29.0 and 25.9 newtons, respectively) to those reported in the current study for the *M. psoas major*, however, their ranking was much higher.

Shackelford et al. (1991) reported WBS threshold values for beef to be 4.6 and 3.9 kg (45.1 and 38.2 newtons, respectively). At these threshold values, the authors set guidelines for beef based on 50 and 68% confidence intervals, respectively, for overall tenderness ratings of "slightly tender" or better. Using these standards, all muscles in the current study with the exception of the *M. semimembranosus* would be considered "slightly tender" or better based the first threshold value (3.9 kg or 38.2 newtons) and all muscles would be considered "slightly tender" or better based on the second threshold value (4.6 kg or 45.1 newtons).

CHAPTER V

CONCLUSIONS

Based on the findings of this study, it is reasonable to conclude that certain muscles may be suitable for use in individual muscle applications while others may not be. Of the largest muscles studied, *M. longissimus lumborum* and *M. longissimus thoracis* possess many positive attributes, which would make them suitable in individual muscle applications. While the *M. gluteobiceps, M. semimembranosus*, and *M. gluteus medius* may be large in size, they possess some negative characteristics, such as high collagen content and WBS values, which may limit them to applications targeted for their specific palatability problems. Although the *M. serratus ventralis, M. latissimus dorsi*, and *M. pectoralis profundus* are thin in terms of muscle dimension, they possess sufficient surface area and palatability attributes to enable them to be used in certain individual applications. Being intermediate in size, the *M. adductor, M. rectus femoris, M. triceps brachii*, *M. vastus lateralis*, *M. semitendinosus*, and *M. psoas major* revealed both positive and negative attributes that may limit ability to be used in certain applications. *M. infraspinatus* and *M. supraspinatus* may pose problems in individual application due to heavy connective tissue content. While the *M. teres major* and *M. tensor fasciae latae* possess some positive palatability attributes, they are too small in terms of size to be effectively used in individual application.

With a better understanding of individual muscle characteristics, the meat industry may be able to maximize potential from individual muscles to help increase quality and consistency in lamb products. In doing so, this will open many new

opportunities in value-added and new-product development. Further research is needed to evaluate consumer acceptance of individual lamb muscles, and stringent marketing strategies will need to be used in order to change consumer perception of lamb products.

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APPENDICES

Page

APPENDIX 1

Simple statistics for characterization of the *M. adductor*

Trait	Mean	SD	Minimum	Maximum
WBS, newtons[a]	31.48	8.92	15.59	52.17
Cook loss, %	23.72	3.30	17.83	30.38
Sarcomere, μm[b]	1.71	0.13	1.42	1.89
Collagen, mg/g[c]	3.25	1.40	1.47	5.55
Fat, %	3.28	1.46	0.92	7.58
Moisture, %	73.69	1.67	69.67	76.97
pH	6.00	0.25	5.78	6.97
WHC,%[d]	39.35	4.55	31.59	46.97
L*	41.03	1.84	38.31	44.46
a*	15.41	1.81	12.51	18.76
b*	3.93	1.28	1.16	7.15
Weight, g	184.17	18.77	140.84	217.58
Length, mm	131.35	13.35	112.00	154.00
Width, mm	59.11	6.26	51.95	73.77
Min. Thick., mm[e]	10.59	5.89	1.53	21.34
Max. Thick., mm[f]	35.68	5.92	24.19	46.70

[a] WBS = Warner-Bratzler shear force
[b] Sarcomere = Sarcomere length
[c] Collagen = Total collagen content
[d] WHC = Water-holding capacity
[e] Min. Thick. = Minimum Thickness
[f] Max. Thick. = Maximum Thickness

APPENDIX 2

Simple statistics for characterization of the *M. gluteobiceps - distal*

Trait	Mean	SD	Minimum	Maximum
WBS, newtons[a]	26.48	5.49	17.95	37.66
Cook loss, %[g]	21.10	4.48	14.49	26.78
Sarcomere, µm[b]	1.67	0.08	1.51	1.83
Collagen, mg/g[c]	4.97	1.94	2.21	8.26
Fat, %	4.00	1.04	2.48	5.93
Moisture, %	73.02	1.52	68.20	75.43
pH	6.01	0.27	5.68	7.03
WHC, %[d]	37.11	4.61	27.61	44.24
L*	42.80	2.27	38.83	48.22
a*	15.97	1.82	12.81	20.32
b*	3.99	1.38	2.00	7.98
Weight, g[g]	379.15	37.27	323.35	462.40
Length, mm[g]	297.80	14.32	270.00	328.00
Width, mm[g]	66.45	8.75	44.85	81.88
Min. Thick., mm[eg]	5.93	1.76	3.42	9.36
Max. Thick., mm[fg]	33.58	6.35	26.06	49.56

[a] WBS = Warner-Bratzler shear force
[b] Sarcomere = Sarcomere length
[c] Collagen = Total collagen content
[d] WHC = Water-Holding Capacity
[e] Min. Thick. = Minimum Thickness
[f] Max. Thick. = Maximum Thickness
[g] *M. gluteobiceps* – proximal and distal combined

APPENDIX 3

Simple statistics for characterization of the *M. gluteobiceps - proximal*

Trait	Mean	SD	Minimum	Maximum
WBS, newtons[a]	28.05	7.85	15.49	51.38
Cook loss, %[g]	21.10	4.48	14.49	26.78
Sarcomere, µm[b]	1.72	0.11	1.54	1.90
Collagen, mg/g[c]	5.00	1.27	2.01	8.06
Fat, %	5.89	2.52	3.04	11.26
Moisture, %	72.19	2.18	67.21	76.88
pH	5.98	0.26	5.55	6.91
WHC, %[d]	38.07	4.80	28.88	46.72
L*	43.77	2.36	38.31	47.67
a*	16.33	1.63	13.86	19.59
b*	4.18	1.40	1.18	6.54
Weight, g[g]	379.15	37.27	323.35	462.40
Length, mm[g]	297.80	14.32	270.00	328.00
Width, mm[g]	66.45	8.74	44.85	81.88
Min. Thick., mm[eg]	5.93	1.76	3.42	9.36
Max. Thick., mm[fg]	33.58	6.35	26.06	49.56

[a] WBS = Warner-Bratzler shear force
[b] Sarcomere = Sarcomere length
[c] Collagen = Total collagen content
[d] WHC = Water-holding capacity
[e] Min. Thick. = Minimum Thickness
[f] Max. Thick. = Maximum Thickness
[g] *M. gluteobiceps* – proximal and distal combined

APPENDIX 4

Simple statistics for characterization of the *M. gluteus medius*

Trait	Mean	SD	Minimum	Maximum
WBS, newtons[a]	30.69	7.45	17.95	48.15
Cook loss, %	23.35	6.21	7.34	40.94
Sarcomere, μm[b]	1.68	0.04	1.60	1.77
Collagen, mg/g[c]	6.12	2.25	1.91	10.05
Fat, %	3.98	1.26	1.93	6.37
Moisture, %	73.52	1.39	69.48	76.06
pH	5.95	0.20	5.61	6.57
WHC, %[d]	37.70	9.22	10.51	56.82
L*	43.15	2.18	40.26	47.52
a*	16.49	1.55	13.06	18.60
b*	4.25	1.06	2.83	6.05
Weight, g	300.30	28.75	229.97	346.75
Length, mm	172.10	18.38	135.00	222.00
Width, mm	102.20	17.08	39.42	127.95
Min. Thick., mm[e]	6.92	3.12	2.74	13.75
Max. Thick., mm[f]	31.22	8.21	7.78	46.11

[a] WBS = Warner-Bratzler shear force
[b] Sarcomere = Sarcomere length
[c] Collagen = Total collagen content
[d] WHC = Water-holding capacity
[e] Min. Thick. = Minimum Thickness
[f] Max. Thick. = Maximum Thickness

APPENDIX 5

Simple statistics for characterization of the *M. infraspinatus*

Trait	Mean	SD	Minimum	Maximum
WBS, newtons[a]	26.97	4.71	19.81	37.76
Cook loss, %	21.99	3.50	15.69	28.07
Sarcomere, μm[b]	2.30	0.15	2.04	2.49
Collagen, mg/g[c]	9.00	3.62	1.82	13.57
Fat, %	3.36	0.77	2.02	4.93
Moisture, %	74.60	1.27	72.31	77.17
pH	6.30	0.13	6.06	6.55
WHC, %[d]	32.44	10.51	18.62	71.37
L*	46.28	1.79	43.80	49.42
a*	16.85	0.86	15.40	18.97
b*	3.88	0.92	2.54	5.89
Weight, g	215.70	24.32	181.25	261.29
Length, mm	205.05	22.90	172.00	244.00
Width, mm	55.82	12.27	7.43	64.76
Min. Thick., mm[e]	18.42	61.83	2.45	281.00
Max. Thick., mm[f]	27.13	4.60	20.12	38.87

[a] WBS = Warner-Bratzler shear force
[b] Sarcomere = Sarcomere length
[c] Collagen = Total collagen content
[d] WHC = Water-holding capacity
[e] Min. Thick. = Minimum Thickness
[f] Max. Thick. = Maximum Thickness

APPENDIX 6

Simple statistics for characterization of the *M. latissimus dorsi*

Trait	Mean	SD	Minimum	Maximum
WBS, newtons[a]	28.14	5.39	14.81	39.52
Cook loss, %	21.85	4.12	11.84	29.88
Sarcomere, μm[b]	2.87	0.20	2.39	3.22
Collagen, mg/g[c]	4.99	1.67	2.42	7.44
Fat, %	8.45	3.57	4.39	16.11
Moisture, %	70.61	2.51	65.85	75.29
pH	6.31	0.29	5.80	7.15
WHC, %[d]	29.36	7.10	12.52	42.11
L*	48.09	2.16	44.70	52.62
a*	14.03	1.33	11.59	16.14
b*	3.32	1.05	1.46	5.43
Weight, g	152.60	22.74	110.27	186.55
Length, mm	248.05	20.67	218.00	300.00
Width, mm	101.60	16.33	75.50	130.49
Min. Thick., mm[e]	2.61	1.49	1.12	6.93
Max. Thick., mm[f]	11.41	2.73	6.65	15.96

[a] WBS = Warner-Bratzler shear force
[b] Sarcomere = Sarcomere length
[c] Collagen = Total collagen content
[d] WHC = Water-holding capacity
[e] Min. Thick. = Minimum Thickness
[f] Max. Thick. = Maximum Thickness

APPENDIX 7

Simple statistics for characterization of the *M. longissimus lumborum*

Trait	Mean	SD	Minimum	Maximum
WBS, newtons[a]	25.60	9.12	14.32	54.13
Cook loss, %	19.19	4.99	12.41	28.94
Sarcomere, μm[b]	1.70	0.08	1.57	1.85
Collagen, mg/g[c]	2.63	1.53	0.72	6.27
Fat, %	4.25	1.08	2.55	6.47
Moisture, %	72.97	1.39	70.54	75.54
pH	5.93	0.31	5.54	7.07
WHC, %[d]	39.70	9.22	10.51	56.82
L*	48.09	2.16	44.70	52.62
a*	14.67	2.15	11.16	19.24
b*	3.75	1.40	1.85	7.16
Weight, g	493.50	55.91	362.96	611.40
Length, mm	275.10	23.24	227.00	311.00
Width, mm	77.23	23.17	58.35	172.83
Min. Thick., mm[e]	13.05	4.46	6.55	21.51
Max. Thick., mm[f]	29.49	3.60	24.56	36.30

[a] WBS = Warner-Bratzler shear force
[b] Sarcomere = Sarcomere length
[c] Collagen = Total collagen content
[d] WHC = Water-holding capacity
[e] Min. Thick. = Minimum Thickness
[f] Max. Thick. = Maximum Thickness

APPENDIX 8

Simple statistics for characterization of the *M. longissimus thoracis*

Trait	Mean	SD	Minimum	Maximum
WBS, newtons[a]	23.44	4.51	15.40	37.85
Cook loss, %	18.85	5.08	9.63	28.26
Sarcomere, μm[b]	1.76	0.08	1.55	1.88
Collagen, mg/g[c]	2.86	1.34	0.46	6.09
Fat, %	5.17	1.15	3.37	7.60
Moisture, %	72.30	1.71	69.19	76.12
pH	5.89	0.27	5.44	6.76
WHC, %[d]	37.55	6.15	21.24	46.78
L*	44.34	1.87	41.71	48.19
a*	15.57	2.09	12.05	20.07
b*	4.22	1.46	2.44	7.59
Weight, g	345.48	33.30	289.69	410.28
Length, mm	312.55	36.69	238.00	396.00
Width, mm	47.79	5.13	36.97	55.18
Min. Thick., mm[e]	7.62	5.08	1.51	20.76
Max. Thick., mm[f]	31.87	5.94	20.50	49.17

[a] WBS = Warner-Bratzler shear force
[b] Sarcomere = Sarcomere length
[c] Collagen = Total collagen content
[d] WHC = Water-holding capacity
[e] Min. Thick. = Minimum Thickness
[f] Max. Thick. = Maximum Thickness

APPENDIX 9

Simple statistics for characterization of the *M. psoas major*

Trait	Mean	SD	Minimum	Maximum
WBS, newtons[a]	28.44	4.02	21.48	37.07
Cook loss, %	20.00	4.84	13.72	32.03
Sarcomere, μm[b]	3.06	0.22	2.18	3.20
Collagen, mg/g[c]	4.53	2.21	0.90	8.30
Fat, %	6.83	1.19	3.85	8.80
Moisture, %	71.44	1.34	68.11	73.98
pH	6.03	0.14	5.76	6.28
WHC, %[d]	34.75	8.54	3.97	41.31
L*	44.32	2.21	40.20	48.29
a*	17.39	1.58	15.03	20.99
b*	4.40	1.50	1.99	7.92
Weight, g	232.99	31.87	164.27	294.82
Length, mm	347.60	25.72	312.00	406.00
Width, mm	42.66	7.53	30.54	56.58
Min. Thick., mm[e]	5.27	2.73	1.04	10.56
Max. Thick., mm[f]	23.23	6.52	13.54	40.94

[a] WBS = Warner-Bratzler shear force
[b] Sarcomere = Sarcomere length
[c] Collagen = Total collagen content
[d] WHC = Water-holding capacity
[e] Min. Thick. = Minimum Thickness
[f] Max. Thick. = Maximum Thickness

APPENDIX 10

Simple statistics for characterization of the *M. pectoralis profundus*

Trait	Mean	SD	Minimum	Maximum
WBS, newtons[a]	28.73	4.51	17.16	32.45
Cook loss, %	18.16	3.31	11.86	24.38
Sarcomere, μm[b]	2.77	0.14	2.51	2.98
Collagen, mg/g[c]	5.00	1.27	2.01	8.06
Fat, %	7.47	1.87	3.74	11.10
Moisture, %	71.66	1.68	68.46	74.40
pH	6.20	0.28	5.77	6.99
WHC, %[d]	29.31	5.03	19.62	39.11
L*	46.98	2.23	43.84	52.31
a*	13.85	1.68	10.55	17.24
b*	3.04	1.41	0.27	6.34
Weight, g	263.65	29.25	214.36	309.95
Length, mm	370.70	30.34	307.00	440.00
Width, mm	93.17	17.17	65.76	153.00
Min. Thick., mm[e]	3.24	1.17	1.34	5.69
Max. Thick., mm[f]	11.90	2.91	6.48	18.97

[a] WBS = Warner-Bratzler shear force
[b] Sarcomere = Sarcomere length
[c] Collagen = Total collagen content
[d] WHC = Water-holding capacity
[e] Min. Thick. = Minimum Thickness
[f] Max. Thick. = Maximum Thickness

APPENDIX 11

Simple statistics for characterization of the *M. rectus femoris*

Trait	Mean	SD	Minimum	Maximum
WBS, newtons[a]	26.87	5.88	15.49	39.42
Cook loss, %	20.53	5.43	13.26	31.30
Sarcomere, μm[b]	2.02	0.12	1.78	2.19
Collagen, mg/g[c]	4.31	1.52	2.15	7.62
Fat, %	3.33	1.07	1.23	6.10
Moisture, %	74.93	1.57	70.94	77.31
pH	6.17	0.15	5.84	6.43
WHC, %[d]	35.60	5.51	23.48	50.79
L*	45.36	1.75	42.92	48.85
a*	15.48	1.23	13.51	17.78
b*	3.65	0.86	2.54	5.48
Weight, g	203.25	18.76	170.82	241.45
Length, mm	158.60	6.29	151.00	177.00
Width, mm	54.53	9.37	21.72	65.05
Min. Thick., mm[e]	11.18	3.42	4.47	16.29
Max. Thick., mm[f]	39.45	6.13	27.43	48.77

[a] WBS = Warner-Bratzler shear force
[b] Sarcomere = Sarcomere length
[c] Collagen = Total collagen content
[d] WHC = Water-holding capacity
[e] Min. Thick. = Minimum Thickness
[f] Max. Thick. = Maximum Thickness

APPENDIX 12

Simple statistics for characterization of the *M. semimembranosus*

Trait	Mean	SD	Minimum	Maximum
WBS, newtons[a]	42.56	18.73	20.40	85.32
Cook loss, %	24.12	2.77	19.82	30.20
Sarcomere, μm[b]	1.70	0.08	1.54	1.89
Collagen, mg/g[c]	3.53	1.51	1.16	7.06
Fat, %	3.52	1.26	1.57	6.32
Moisture, %	73.25	1.43	69.63	75.83
pH	5.90	0.28	5.53	6.95
WHC, %[d]	37.37	3.34	30.34	42.41
L*	41.10	1.99	37.72	45.25
a*	15.32	1.59	13.27	19.27
b*	3.99	1.11	2.13	6.79
Weight, g	403.86	65.46	163.34	475.40
Length, mm	164.95	18.53	132.00	196.00
Width, mm	76.35	15.78	16.88	94.45
Min. Thick., mm[e]	10.42	4.49	2.66	19.87
Max. Thick., mm[f]	46.88	6.88	30.04	56.13

[a] WBS = Warner-Bratzler shear force
[b] Sarcomere = Sarcomere length
[c] Collagen = Total collagen content
[d] WHC = Water-holding capacity
[e] Min. Thick. = Minimum Thickness
[f] Max. Thick. = Maximum Thickness

APPENDIX 13

Simple statistics for characterization of the *M. semitendinosus*

Trait	Mean	SD	Minimum	Maximum
WBS, newtons[a]	31.09	5.88	15.59	40.80
Cook loss, %	19.84	4.41	11.29	26.14
Sarcomere, μm[b]	2.43	0.18	2.11	2.91
Collagen, mg/g[c]	3.74	1.53	1.67	7.43
Fat, %	4.82	1.76	1.88	8.38
Moisture, %	63.30	1.76	68.14	75.89
pH	6.21	0.31	5.72	7.04
WHC, %[d]	31.27	3.96	23.93	39.36
L*	46.72	2.02	42.99	50.23
a*	15.24	1.17	13.15	17.35
b*	4.21	1.34	2.56	7.39
Weight, g	170.31	15.75	144.98	202.31
Length, mm	183.40	6.27	168.00	195.00
Width, mm	43.89	6.54	23.50	54.44
Min. Thick., mm[e]	4.94	2.01	1.87	9.03
Max. Thick., mm[f]	29.42	4.83	17.73	37.09

[a] WBS = Warner-Bratzler shear force
[b] Sarcomere = Sarcomere length
[c] Collagen = Total collagen content
[d] WHC = Water-holding capacity
[e] Min. Thick. = Minimum Thickness
[f] Max. Thick. = Maximum Thickness

APPENDIX 14

Simple statistics for characterization of the *M. supraspinatus*

Trait	Mean	SD	Minimum	Maximum
WBS, newtons[a]	30.60	5.20	21.28	43.25
Cook loss, %	25.61	3.70	21.17	33.15
Sarcomere, μm[b]	2.18	0.15	1.90	2.43
Collagen, mg/g[c]	5.54	2.32	0.63	9.23
Fat, %	5.29	1.16	2.53	7.30
Moisture, %	73.66	1.10	71.43	75.69
pH	6.24	0.14	6.04	6.54
WHC, %[d]	33.43	4.07	27.30	43.94
L*	46.77	1.86	44.23	50.90
a*	17.74	1.11	15.21	19.59
b*	4.67	0.93	3.33	6.47
Weight, g	171.48	15.82	145.60	223.24
Length, mm	163.60	9.81	146.00	188.00
Width, mm	53.21	10.68	23.62	65.49
Min. Thick., mm[e]	5.84	2.49	2.64	10.38
Max. Thick., mm[f]	32.35	4.63	22.73	42.63

[a] WBS = Warner-Bratzler shear force
[b] Sarcomere = Sarcomere length
[c] Collagen = Total collagen content
[d] WHC = Water-holding capacity
[e] Min. Thick. = Minimum Thickness
[f] Max. Thick. = Maximum Thickness

APPENDIX 15

Simple statistics for characterization of the *M. serratus ventralis*

Trait	Mean	SD	Minimum	Maximum
WBS, newtons[a]	21.87	3.33	13.43	27.16
Cook loss, %	17.08	4.27	9.16	22.68
Sarcomere, μm[b]	2.14	0.21	1.59	2.48
Collagen, mg/g[c]	4.09	1.56	1.24	6.39
Fat, %	13.23	3.55	5.70	19.34
Moisture, %	67.69	2.57	62.07	73.13
pH	6.46	0.22	5.97	6.95
WHC, %[d]	31.73	5.20	21.37	42.21
L*	46.48	1.76	43.05	49.53
a*	15.79	1.14	13.81	17.79
b*	4.08	1.12	1.54	5.85
Weight, g	444.17	48.56	379.01	531.82
Length, mm	423.25	49.43	344.00	505.00
Width, mm	117.86	24.46	43.13	154.88
Min. Thick., mm[e]	3.73	2.53	1.00	9.41
Max. Thick., mm[f]	16.03	2.75	11.10	19.15

[a] WBS = Warner-Bratzler shear force
[b] Sarcomere = Sarcomere length
[c] Collagen = Total collagen content
[d] WHC = Water-holding capacity
[e] Min. Thick. = Minimum Thickness
[f] Max. Thick. = Maximum Thickness

APPENDIX 16

Simple statistics for characterization of the *M. triceps brachii*

Trait	Mean	SD	Minimum	Maximum
WBS, newtons[a]	29.71	5.69	23.44	47.66
Cook loss, %	18.97	3.90	13.45	25.51
Sarcomere, μm[b]	2.56	0.18	2.15	2.87
Collagen, mg/g[c]	5.00	1.80	2.67	9.62
Fat, %	5.05	1.82	1.31	8.97
Moisture, %	73.51	1.43	71.07	76.51
pH	6.19	0.22	5.87	6.59
WHC, %[d]	29.22	5.73	19.82	44.20
L*	43.52	1.17	41.05	45.66
a*	15.71	1.62	12.47	19.23
b*	3.47	1.47	1.31	7.49
Weight, g	335.20	39.21	259.57	393.14
Length, mm	164.70	10.15	148.00	185.00
Width, mm	91.47	19.72	37.48	113.00
Min. Thick., mm[e]	8.65	4.18	3.86	16.15
Max. Thick., mm[f]	42.37	11.76	34.55	86.71

[a] WBS = Warner-Bratzler shear force
[b] Sarcomere = Sarcomere length
[c] Collagen = Total collagen content
[d] WHC = Water-holding capacity
[e] Min. Thick. = Minimum Thickness
[f] Max. Thick. = Maximum Thickness

APPENDIX 17

Simple statistics for characterization of the *M. tensor fasciae latae*

Trait	Mean	SD	Minimum	Maximum
WBS, newtons[a]	30.89	10.59	20.01	67.47
Cook loss, %	20.07	5.44	10.95	28.63
Sarcomere, µm[b]	2.91	0.37	1.80	3.23
Collagen, mg/g[c]	-	-	-	-
Fat, %	5.86	2.37	1.52	10.39
Moisture, %	71.72	2.93	69.38	83.20
pH	6.02	0.21	5.67	6.58
WHC, %[d]	32.72	6.35	15.91	42.45
L*	48.21	2.18	44.36	53.18
a*	13.91	1.78	10.43	17.29
b*	3.92	1.50	1.26	7.38
Weight, g	91.14	9.84	69.31	104.03
Length, mm	155.55	21.36	92.00	188.00
Width, mm	63.19	12.69	27.60	86.44
Min. Thick., mm[e]	4.96	2.80	1.37	10.94
Max. Thick., mm[f]	13.78	3.56	5.21	19.15

[a] WBS = Warner-Bratzler shear force
[b] Sarcomere = Sarcomere length
[c] Collagen = Total collagen content
[d] WHC = Water-holding capacity
[e] Min. Thick. = Minimum Thickness
[f] Max. Thick. = Maximum Thickness

APPENDIX 18

Simple statistics for characterization of the *M. teres major*

Trait	Mean	SD	Minimum	Maximum
WBS, newtons[a]	26.38	6.18	11.08	34.13
Cook loss, %	18.11	4.78	12.11	28.28
Sarcomere, µm[b]	2.58	0.17	2.31	2.98
Collagen, mg/g[c]	-	-	-	-
Fat, %	4.61	1.26	1.77	6.48
Moisture, %	72.95	1.19	71.03	75.33
pH	6.44	0.24	5.89	6.91
WHC, %[d]	34.46	5.00	24.80	43.70
L*	46.07	1.70	43.78	49.83
a*	14.54	1.35	12.71	17.15
b*	3.50	1.11	1.39	5.21
Weight, g	47.08	4.98	40.22	57.43
Length, mm	141.00	12.79	116.00	167.00
Width, mm	34.27	3.41	27.91	40.62
Min. Thick., mm[e]	4.98	2.81	0.39	12.33
Max. Thick., mm[f]	14.89	2.87	10.57	19.53

[a] WBS = Warner-Bratzler shear force
[b] Sarcomere = Sarcomere length
[c] Collagen = Total collagen content
[d] WHC = Water-holding capacity
[e] Min. Thick. = Minimum Thickness
[f] Max. Thick. = Maximum Thickness

APPENDIX 19

Simple statistics for characterization of the *M. vastus lateralis*

Trait	Mean	SD	Minimum	Maximum
WBS, newtons[a]	29.42	4.71	21.57	49.23
Cook loss, %	22.69	4.33	15.42	31.12
Sarcomere, μm[b]	1.85	0.12	1.65	2.05
Collagen, mg/g[c]	3.92	1.41	1.60	6.72
Fat, %	3.32	1.18	1.57	6.75
Moisture, %	74.37	1.81	68.22	77.67
pH	6.06	0.20	5.79	6.66
WHC, %[d]	35.97	4.73	25.39	45.06
L*	44.68	1.68	42.59	48.59
a*	16.51	1.29	14.60	19.80
b*	4.19	0.92	2.79	6.29
Weight, g	193.70	57.05	20.96	238.26
Length, mm	157.85	9.46	140.00	171.00
Width, mm	78.83	13.54	29.31	99.81
Min. Thick., mm[e]	6.40	2.41	1.39	10.01
Max. Thick., mm[f]	31.88	5.64	21.79	42.18.

[a] WBS = Warner-Bratzler shear force
[b] Sarcomere = Sarcomere length
[c] Collagen = Total collagen content
[d] WHC = Water-holding capacity
[e] Min. Thick. = Minimum Thickness
[f] Max. Thick. = Maximum Thickness

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