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Meat and Muscle Biology™

Cooking End-Point Temperature and Muscle Fiber Composition Influence the Cooked Meat Quality of Boer Goats

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Abstract: This research aimed to understand the effect of different muscle fiber characteristics and cooking temperature on important quality attributes of goat meat, particularly tenderness and water-holding capacity. To achieve this aim, 3 important muscles, namely *longissimus thoracis et. lumborum* (LTL), *psoas major* (PM), and *semimembranosus* (SM), were obtained from 10 castrated 1 y old Boer goats (live weight of 43 ± 2.95 kg). The muscles were measured for quality (cooking loss and Warner-Bratzler shear force [WBSF]), structural (shrinkage measured using caliper), and protein conformation changes (differential scanning calorimetry [DSC]) during heating up to 80°C, using a consistent heating rate across cooking and DSC (10°C/min). Two staining procedures were conducted: determination of the oxidative or glycolytic metabolism of the muscle by nicotinamide adenine dinucleotide tetrazolium reductase staining and acidic staining for acidic myosin adenosine triphosphatase at pH 4.35. The PM muscle had the highest number percentage of type I fibers ($P < .001$), while the LTL muscle had the lowest percentage of type I fibers. The LTL muscle had a higher ($P < .05$) number precentage of type IIB fibers than the other 2 muscles, with PM having the lowest. The PM had the lowest ($P < .01$) number percentage of type IIA fibers, followed by LTL and SM. Ageing and cooking temperature increased ($P < .001$) cooking loss in both LTL and SM, while muscle type had no significant effect on cooking loss. The WBSF and hue (h) values were negatively correlated ($P < .05$) with the percentage of type I fibers. Cooking temperature plays a critical role, with higher temperatures leading to increased toughness and shrinkage. DSC results suggested that cooking goat meat to below 60°C may help retain tenderness.

Keywords: cooking loss, muscle fiber type, shrinkage, tenderness, thermal denaturation, WBSF
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Introduction

Between 2008 and 2018, the global goat population increased by 15.9%, while sheep and cattle numbers increased by 9.3% and 5.2% respectively (Meat & Livestock Australia, 2020). Over the past 2 decades, farmed Boer goats have gained worldwide recognition as a high-quality meat-purpose breed due to their availability in Australia, New Zealand, North America, and other parts of the world (Pophiwa et al., 2017). Boer goats have excellent body conformation, fast growth rates, and good carcass and meat quality, making them the premium goat breed for meat production (Brand et al., 2018). Boer goats and their crosses can have a dressing percentage 2–5% higher than less muscled or nondefined goat breeds (Meat & Livestock Australia, 2020).

Meat quality attributes, such as texture, juiciness, flavor, and visual appeal, hold significant importance for consumers. The tenderness of the meat is primarily determined by the connective tissue, myofibrils, and their interactions, which can vary among different

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muscles (Warner et al., 2021). The goat carcass consists of over 100 different muscles with different properties, which affect processing characteristics and could influence consumer acceptability. In the retail sector, there has been a growing trend to segregate muscles based on their meat quality characteristics, allowing for better marketing according to consumer preferences. However, compared to cattle and sheep, there has been limited research and understanding of goat meat quality and grading for quality, mainly due to a lack of previous interest in this area. Thus, there is a need for research and investigation to enhance the knowledge and grading techniques specific to goat meat quality. By doing so, it will be possible to meet consumer demands and foster the development of a strong global goat meat industry. The muscle baseline data generated are hypothesized to play a crucial role in making informed decisions to support muscle-specific marketing strategies, which have the potential to enhance consumer acceptance of goat meat (van Wyk et al., 2022). Extensive research has demonstrated that muscle and fiber type significantly influence meat quality, particularly in water-holding capacity (WHC) and tenderness, assessed using instruments and sensory analysis (Vaskoska et al., 2020). While there are limited reports on the impact of muscle and fiber type on goat meat tenderness, insights can be drawn from studies conducted on other ruminants such as cattle and sheep (Totland and Kryvi, 1991; Rhee et al., 2004).

Numerous studies have delved into the relationship between muscle fiber type and tenderness in beef and pork (LeMaster et al., 2023). However, only a few studies are focusing on goat muscle fiber type and meat quality (Kadim et al., 2010; Hwang et al., 2019). Hwang et al. (2019) reported a positive correlation between the number and area percentage of type IIB fibers and Warner-Bratzler shear force (WBSF) in goats. Similar findings have been observed in cattle (Lang et al., 2020; LeMaster et al., 2023). Hwang et al. (2019) showed that in goats, the number and area percentage of type I fibers were highest in the *psoas major* (PM) muscle, followed by the *semimembranosus* (SM), *gluteus medius*, and *longissimus thoracis et. lumborum* (LTL). However, it is worth noting that studies on bovine LTL have reported a positive correlation between the number percentage of type I fibers and WBSF (Seideman et al., 1987), while no effect of fiber type on meat quality was observed in beef by Chriki et al. (2013) and Sazili et al. (2005). Studies examining the influence of fiber type on WHC have primarily focused on analyzing drip loss in raw meat. However, relatively few studies have explored the association between fiber type and cooking loss, which is another important measure of WHC. One notable work in this regard is the study by Kim et al. (2013) on pigs, where both drip loss and cooking loss were investigated in relation to muscle fiber type. The study reported that pig groups with a higher proportion of large-sized type IIB fibers exhibited greater cooking loss and drip loss compared to those with small- and medium-sized type IIB fibers. This study highlighted the relevance of controlling the distribution of fiber types on improving pork quality. Changes in tenderness and WHC during heating or cooking are primarily driven by protein denaturation and shrinkage (Hamm, 1966; Martens et al., 1982; Tornberg, 2005). Therefore, investigating the effect of fiber type on tenderness and cooking loss in relation to protein denaturation during cooking is an area of great interest.

While some research has been conducted in bovine and porcine muscles on the protein denaturation process and its impact on tenderness and cooking loss in different fiber types (Vaskoska et al., 2020), there is a scarcity of studies focusing on the cooking temperature effects in goat meat. Liu et al. (2013) showed that cooking loss and WBSF increased with increase in cooking temperatures in goat meat between 50°C and 80°C. Considering the limited research on the cooking temperature effects on goat meat and the association between fiber type and cooking loss, further research is required to provide valuable insights into optimizing cooking methods for goat meat and enhancing its overall quality. The method of cooking meat and the end-point temperature significantly influence the meat and eating quality of goat meat (Xazela et al., 2011; Liu et al., 2013; Oz et al., 2017). In sheep meat, combining the cut and cooking method is crucial in optimizing eating quality. For cuts such as topside and silverside that have higher collagen and connective tissue content due to constant use in the animal, casserole (wet) cooking methods using low heat and moisture over a period can partially break down these tissues, improving tenderness. On the other hand, tender cuts such as the loin are better suited for grilling, which helps optimize their eating quality (Meat & Livestock Australia, 2019). However, for goat meat, there are no established standards for presenting it to consumers. The current trend in commercial production is to use similar cuts to lamb (Webb et al., 2005; Webb, 2014), but there is a lack of baseline data to guide cooking and presentation choices. Therefore, this study aimed to investigate the effect of muscle type (myofiber characteristics) and cooking temperature on goat meat quality. The study aims to provide insights into determining the optimum cooking temperature for farmed Boer

goats. This research will contribute valuable information to the industry and help establish guidelines for cooking and presenting goat meat to consumers.

Materials and Methods

Animals and slaughter procedure

Ten, 1 y old castrated male Boer goats (see Figure 1) with a mean live body weight of 43.0 ± 2.95 kg were sourced from a commercial farm and transported for 1 h to a processing plant, Cedar Meats, Brooklyn, Victoria. The goats were well-fed and finished with a complete goat diet formulated by Ridley, Victoria, and had a mean hot carcass weight of 20.4 ± 2.33 kg. The goats were kept in lairage for 12 h according to the commercial practice and were provided access to water. Goats were transported using a purpose-built animal transport trailer, and every care was taken to minimize animal stress according to standard practices. All slaughter procedures were followed according to standard commercial operations, including electrical stunning. The ultimate pH (pH_{24}) of LTL muscle was measured after boning at 24 h postmortem using a combined pH and temperature meter (WP-80M, TPS, Brendale, Australia) with a spearhead IJ44C pH probe (TPS, Brendale, Australia) and temperature compensation. The pH probe was calibrated using pH 7.0 and 4.0 buffers.

Muscle collection and experimental treatments

The 3 muscles (LTL, SM, and PM) muscles were obtained 1 d postmortem from both sides of the Boer goat carcasses. The muscles destined for ageing were vacuum packed using a Multivac C100 vacuum packer (Multivac Sepp Haggenmüller SE & Co. KG, Wolfertschwenden, Germany). The muscles from the right side of the carcass ($n = 10$) were aged at 4°C for 7 d (7 d aged) while the other half were not aged (0 d aged).

Meat cutting and cooking were conducted according to Purslow et al. (2016) with slight modifications. Three meat cuboids (5 cm length [L] × 3 cm width [W] × 3 cm height [H]) were randomly obtained from each muscle and allocated to 3 cooking temperatures (60°C, 70°C, and 80°C). Each cuboid was weighed, placed in a plastic bag, and immersed in a temperature-calibrated water bath (Julabo F38; John Morris Scientific, Melbourne, Victoria Australia). Internal temperatures were monitored using temperature probes inserted into the core of the sample (Model 2020, Grant Instruments, Cambridge, UK). Once the samples reached the assigned internal temperature, the bags were taken out immediately and kept in an ice-water bath for 15 min and then stored in a cold room at 2° C overnight. On the next day, meat samples were taken out from the packaging, and excess moisture was absorbed with a paper towel. The weight of each cuboid was then recorded for cooking loss calculation. Purge loss was determined by weighing samples on a scale (Scout SPX 1202, Ohaus Corporation, Parsippany, New Jersey, USA) before and after ageing.

Meat color was measured using Hunterlab Miniscan EZ (model No. 45/0-L, aperture of 31.8 mm; Hunter Assoc. Labs Inc., Virginia, USA) calibrated against white and black reference tiles. Duplicate surface color measurements were taken with D65 illuminant and 10° observer angle. The Internationale de l'Éclairage L^* (lightness), a^* (redness) and b^* (yellowness) values were obtained from the average values of 2 readings on the surface of muscle samples. Psychometric hue

Figure 1. One y old Boer wether goats and their carcasses used in this study. The animals were transported from the farm to the processing plant for 1 h using a covered trailer.

angle (h) and psychometric chroma (C^*) were calculated using the equations outlined by Hunt et al. (1991): $C^* = (a^2 + b^2)^{0.5}$, psychometric hue (degrees) = (arctangent $[b^*/a^*] \times 180/\pi$).

Sarcomere length

Sarcomere length was measured with a laser diffraction unit (custom built by University of New England, New South Wales, Australia). Thin 1-mm slices were shaved from the surface of the frozen sample with a scalpel, placed between 2 microscope slides, and the diffraction distance was measured. The sarcomere length was calculated as in the equation: Sarcomere length = 0.635/SIN (ATAN [X/Y]) (Vaskoska et al., 2020).

X is the diffraction distance of the sarcomere bands; Y is the calibration distance; measured on the device as the distance of the underside of the diffraction surface and the slide holder; SIN is the abbreviation for sine function; and ATAN is the abbreviation for arctangent function. The sarcomere length of a raw sample from each muscle was calculated as the average of 5 to 8 replicate measurements of the diffraction distance.

Total and soluble collagen content

Total and soluble collagen content were determined using the AOAC method 990.26 (Kolar, 1990) for quantification of hydroxyproline as described by Starkey et al. (2015) with some modifications. Pork samples were freeze-dried for 3 d and then powdered using a knife. Water content was calculated using the weights before and after freeze drying. Triplicate of 0.2 g freeze-dried powder was hydrolyzed in 3.5 m H_2SO_4 for 16 h at 105°C. For soluble collagen, 1.0 g of powder was added to 10 mL of water and was heated in a water bath at 80°C for 2 h, with vortexing every 30 min. A standard curve was plotted using a hydroxyproline solution with concentrations of 0, 1.2, 2.4, 3.6, 4.8, and 6.0 µg/mL in H_2O. A conversion factor of 7.25 was used to convert hydroxyproline content to collagen content. Total collagen content was expressed in units of mg/g fresh meat. Collagen solubility was expressed as the percentage of soluble collagen divided by total collagen content.

Histochemical analysis

Histochemical analysis of muscle tissues was performed on 5 randomly selected carcasses ($n = 5$) from each group. Raw muscle samples measuring 1 × 1 × 1 cm were collected and affixed to wooden corks using the optimal cutting temperature compound (Leica, Wetzlar, Germany). These samples were then submerged in iso-pentane cooled with liquid nitrogen and stored at −80°C until further processing for analysis. The frozen cubes were sectioned on a cryostat (model 1860, Leica, Wetzlar, Germany) at −20°C, producing 10 µm thick transverse serial sections that were placed on Superfrost glass slides (Thermo Fischer Scientific, Waltham, Massachusetts, USA). The sections on slides were also kept at −80°C until needed for analysis.

Two staining procedures were carried out on the serial sections. First, nicotinamide adenine dinucleotide tetrazolium reductase (NADHTR) staining was performed to determine the muscle metabolism (oxidative or glycolytic metabolism). The sections were defrosted and incubated at 37°C with NitroBlue tetrazolium and β-bicotinamide adenine dinucleotide in Tris buffer. The second staining procedure involved determining myosin adenosine triphosphatase (ATPase) activity, corresponding to the muscle's contraction speed. This procedure was based on a method by Brooke and Kaiser (1970) and Guth and Samaha (1970). It included an acid preincubation at pH 4.35, which allowed for the best differentiation between fiber types in *cutaneous trunci*. The myosin ATPase stability of slow muscles (and the instability of myosin ATPase of fast muscles) in an acidic environment leads to the formation of cobalt phosphate when combined with cobalt chloride and ammonium sulfide. This, in turn, results in black cobalt sulfide staining in certain muscle fibers. This staining classified black stained fibers as type I, light brown fibers as type IIA, and white fibers as type IIB. The frequency of each fiber type in the section was determined by counting the number of fibers of each type at 5 locations on each section. Fiber number percentage and cross-sectional area (CSA; µm^2) of the muscle fibers were determined using ImageJ software. Fiber number percentage refers to the ratio of the number of each fiber type to the total fiber number counted.

Cooking loss, Warner-Bratzler shear force, and hardness

Cooking loss (%) was calculated as the weight of the cuboids cooked to the specified temperature, relative to the weight of the raw cuboid, as a ratio of the raw cuboid weight and converted to percentage. WBSF was measured on 1 cm^2 (4 cm long rectangular strips) samples, cut from the middle of the raw and cooked goat cuboids with the fibers perpendicular to the blade. A texture analyzer (Ametek Inc., Berwyn, Pennsylvania, USA) was used and set to a speed of 300 mm/min and used a 500 N load cell and an inverted V-blade. The toughness was expressed as WBSF in newtons. Cooking loss

percentage and WBSF of LTL and SM were measured at 60°C, 70°C, and 80°C. However, it was only measured at 70°C in PM due to the limited muscle weight and thickness. Hardness was measured on muscle samples cooked at 70°C using a compression test according to a method previously reported by Warner et al. (2010). A 0.63 cm diameter flat-ended probe was attached to a texture analyzer (LS5 Ametek Lloyd Instruments Ltd., Largo, FL, USA). A total of 5 measurements were taken for each sample and presented as means.

Volume shrinkage

The 12 edges of each muscle cuboid were measured with a digital Vernier caliper (Kincrome, Melbourne, Victoria, Australia) before and after cooking. The volume of the cuboids was calculated based on the assumption that the cuboid has a regular shape, using the averages in each dimension (Vaskoska et al., 2020). Muscle fiber direction was not standardized in the blocks.

Differential scanning calorimetry

On the collection day, approximately 1 g of the sample was collected and stored overnight at 4°C. The following day, 3 subsamples of around 20 mg each were dissected for each sample, corresponding to each carcass. The subsample was placed in an aluminum pan, sealed, and placed in the furnace of the differential scanning calorimeter (model 8000, Perkin Elmer, Waltham, Massachusetts, USA). An empty pan was used as a reference. The heating was conducted with a 1-min isothermal step of equilibration at 25°C, heating steps of 10°C/min to 90°C and a cooling step of 30°C/min. Data were collected from only 9 carcasses because the differential scanning calorimetry (DSC) equipment failed at the time of data collection for 1 carcass.

Statistical analysis

Analysis of pH, sarcomere length, collagen, hardness and color for the muscle characterization was done using analysis of variance (ANOVA) in GenStat (Version 18, VSN International, Hemel Hempstead, UK). pH, sarcomere length, collagen content and color were analyzed with muscle as fixed factor. Physical measurements (WBSF, cooking loss, volume shrinkage) were analyzed by restricted maximum likelihood procedure in GenStat with muscle, ageing, and cooking temperature as fixed effects and carcass number as random effect. The muscle fiber percentage and CSA were analyzed using ANOVA with muscle as fixed factor and carcass as random factor. Multivariate principal component analysis (PCA) was conducted to identify relationships of the shrinkage to WBSF and cooking loss across the muscles in Minitab.

Results

Muscle characterization

The 24 h pH (pH_{24}) of all 3 muscles was in the range of 5.5 to 5.7 (Table 1). PM showed higher ($P < .01$) pH_{24} among the 3 muscles than LTL and SM. A similar trend was observed in sarcomere length, with the longest sarcomeres ($P < .001$) observed for PM (2.57 μm) compared to LTL (1.98 μm) and SM (1.87 μm). However,

Table 1. Effect of muscle on quality characteristics of longissimus thoracis et. lumborum, semimembranosus and psoas major muscles

	N	LTL	SM	PM	SED (Muscle)	*P* Value
pH	10	5.57[a]	5.56[a]	5.71[b]	0.03	.006
Sarcomere length (μm)	10	1.98[a]	1.87[a]	2.95[b]	0.06	<.001
Total collagen content (mg/g wet wt)	9	4.34[a]	6.31[c]	3.41[b]	0.14	<.001
Soluble collagen content (mg/g wet wt)	9	0.41[c]	0.20[a]	0.26[b]	0.13	<.001
Purge loss %	10	6.26	6.76	8.01	0.60	.273
N	10	30.83[a]	34.22[b]	31.85[ab]	1.29	<.05
*L**	10	38.54	37.16	37.96	0.77	.97
*a**	10	15.88[a]	17.87[b]	17.72[b]	0.55	<.001
*b**	10	6.01[ab]	6.84[b]	5.10[a]	0.46	<.01
h	10	36.07[a]	36.02[a]	27.34[b]	1.77	<.001
*C**	10	17.01[a]	19.18[b]	18.81[b]	0.61	<.01

*a**, redness; *b**, yellowness; *C**, chroma; h, hue; *L**, lightness; LTL, *longissimus thoracis et. lumborum*; N, hardness; PM, *psoas major*; SED, standard error of difference; SM, *semimembranosus*.

[a–c]Different superscript capital letters indicate significant difference within row ($p < 0.05$).

the total and soluble collagen content showed a different trend, with higher ($P < .001$) total collagen in SM and soluble collagen content in LTL.

Histochemical analysis

Figures 2A-C illustrate the ATPSase staining in the three muscles based on their ATPase activity. The effect of muscle on CSA and fiber proportion % of the different fiber types are presented in Figure 3A and 3B, the CSA of these muscle fibers decreased in the rank order type IIB > IIA > I in both LTL and SM. However, in PM muscle, CSA of IIA and IIB were comparable but higher than type I. The CSA of type IIA and IIB fiber decreased in the order SM > LTL > PM ($P < .05$). However, the CSA of type I fiber was comparable in both LTL and PM, and it was the highest in SM muscle ($P < .05$). Muscle fiber type composition in the SM, LTL, and PM muscles showed variations. The PM muscle had the highest percentage of type I fibers ($P < .001$), while the LTL muscle had the lowest percentage of type I fibers. The LTL muscle had a higher

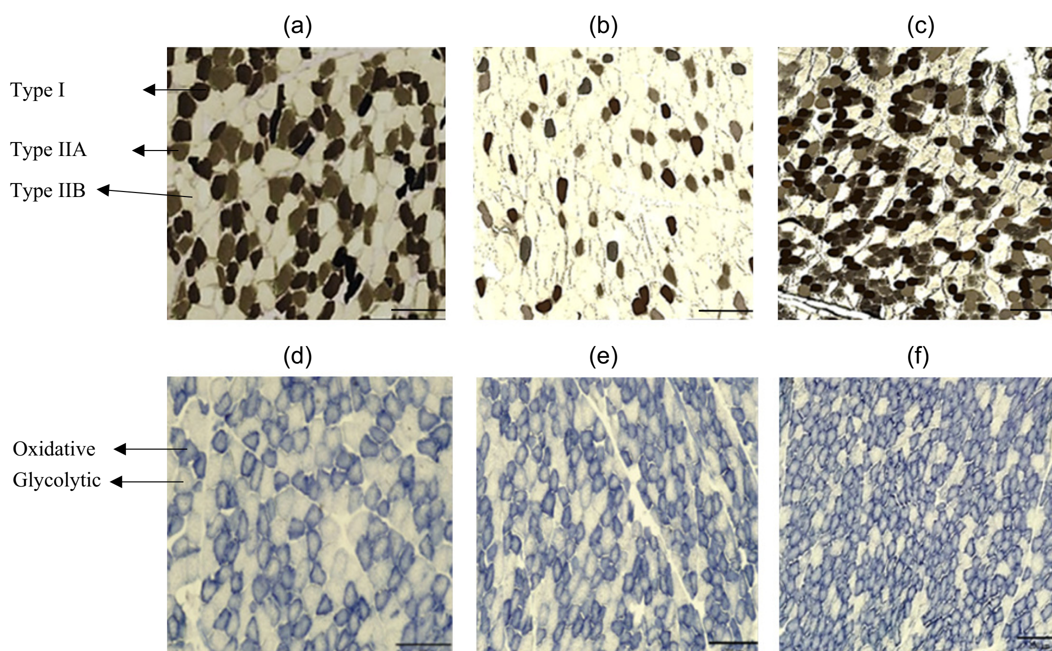

Figure 2. Representative histological images of goat *longissimus thoracis et. lumborum*, *semimembranosus*, and *psoas major* muscles illustrating the staining methods used. (a–c) ATPase staining of transverse sections of LTL (a), SM (b), and PM (c); dark fibers represent slow oxidative type I, light brown fibers indicate intermediate/oxido-glycolytic type IIA, and white fibers denote fast glycolytic type IIB. (d–f) NADHTR staining of transverse sections of LTL (d), SM (e), and PM (f); dark/blue fibers represent oxidative fibers, while light/white fibers indicate glycolytic fibers. NADHTR staining was used for visual illustration purposes only and was not used for statistical analysis of muscle fiber composition, as clear differentiation of 3 distinct fiber types was not possible in these sections. Images were captured using a light microscope at 10× magnification. Scale bar = 200 μm (bottom right). ATPase, adenosine triphosphatase; LTL, *longissimus thoracis et. lumborum*; NADHRT, nicotinamide adenine dinucleotide tetrazolium reductase; PM, *psoas major*; SM, *semimembranosus*.

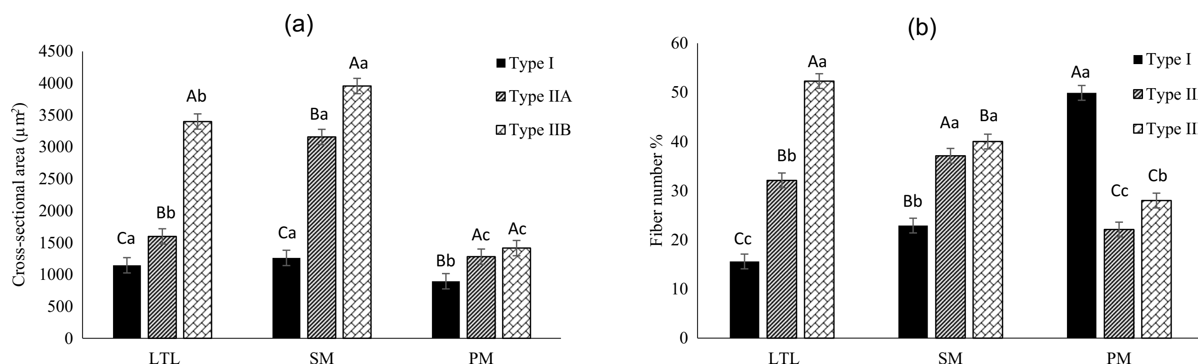

Figure 3. Effect of muscle x fiber type (longissimus thoracis et. lumborum, *semimembranosus*, and psoas major) on myofiber characteristics. (a) CSA (μm^2) and (b) muscle fiber number percentage. Vertical lines bars represent LSD; P < .05. CSA, cross-sectional area; LSD, Least Significant Difference; LTL, longissimus thoracis et. lumborum; PM, psoas major; SM, semimembranosus.

percentage of type IIB fibers than the other 2 muscles, and PM had the lowest ($P < .05$). The PM had the lowest proportion percentage of type IIA and IIB fibers, followed by LTL and SM ($P < .01$). In terms of their oxidative capacity based on NADHTR staining (Figure 2D–F), all 3 muscles were a mixture of oxidative and glycolytic fibers.

Cooking loss, Warner-Bratzler shear force, and volume shrinkage

Figure 4 presents the effect of ageing period and muscle on cooking loss percentage and WBSF. Ageing and cooking temperature increased ($P < .001$) the cooking loss in both LTL and SM, whereas muscle type did not affect cooking loss. There was an interaction between ageing and muscle ($P < .001$) where cooking loss was higher in aged SM compared to LTL. However, this difference between muscles was not evident in 1 d PM muscles. Furthermore, a significant ($P < .001$) effect of muscle, ageing, and cooking temperature ($P < .001$) on the WBSF was observed. Figure 5 illustrates the PCA analysis of WBSF, cooking loss, and volume shrinkage of goat LTL and SM with ageing (1 d and 7 d) and cooking (60°C, 70°C, and 80°C): (a) depicts the score plot labelled by ageing period and cooking temperature, and (b) shows the loading plot corresponding to the PCA analysis in (a).

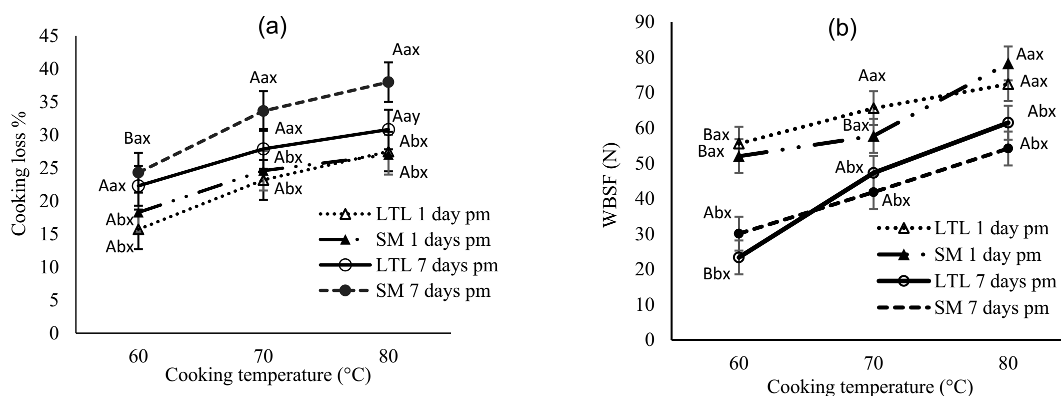

Figure 4. (a) Effect of cooking temperature (60°C, 70°C, 80°C; $P < .001$), ageing (1 d vs 7 d; $P < .001$), and muscle (LTL, SM, PM; $P = .73$), ageing × cooking temperature ($P < .05$), ageing × muscle ($P < .001$) on cooking loss %. (b) Effect of cooking temperature ($P < .001$), ageing ($P < .001$) and muscle ($P = .47$) muscle × ageing × and cooking temperature ($P < .001$) on WBSF (N). LTL, *longissimus thoracis et. lumborum*; PM, *psoas major*; SM, *semimembranosus*; WBSF, Warner-Bratzler shear force.

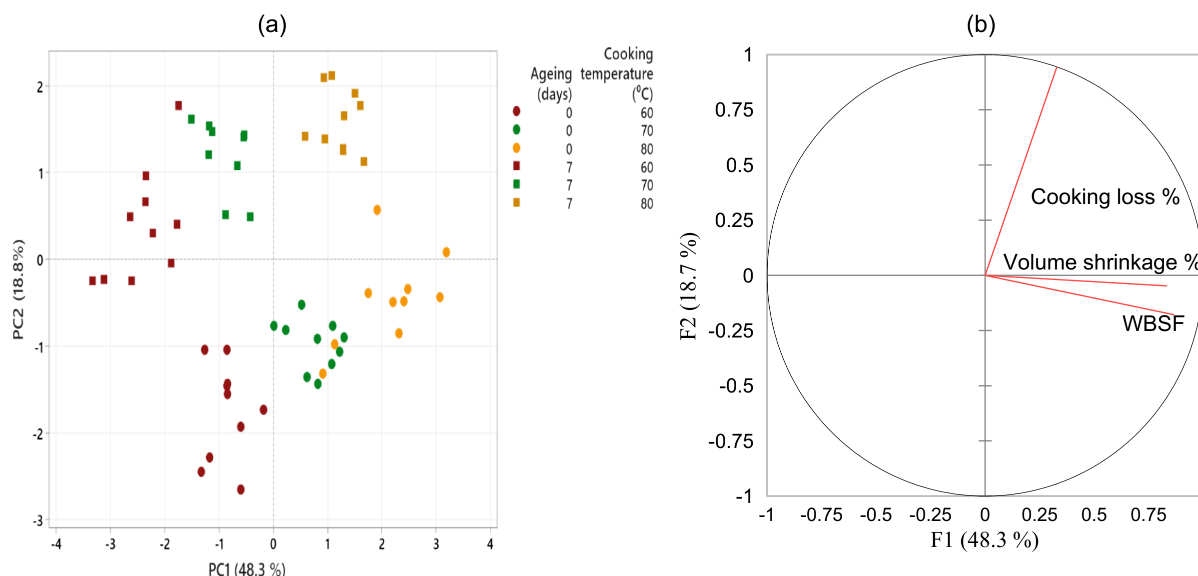

Figure 5. Principal component analysis of Warner-Bratzler shear force, cooking loss and volume shrinkage of goat *longissimus thoracis et. lumborum* and *semimembranosus* with ageing (0 d and 7 d) and cooking (60°C, 70°C and 80°C). (a) Score plot labelled by ageing period and cooking temperature; (b) loading plot corresponding to the PCA analysis in (a) Score plot and (b) biplot corresponding to the PCA analysis. PC, principal component; PCA, principal component analysis; WBSF, Warner-Bratzler shear force.

Relationship between myofiber characteristics and meat quality

The correlations between different muscle fiber types and certain meat quality parameters are presented in Table 2. Specifically, the CSA of all 3 muscle fiber types exhibits negative correlations with pH and a^* values ($P < .05$), while it shows positive correlations with hardness and hue values ($P < .05$). Furthermore, the WBSF and hue values were negatively correlated with the percentage of type I fibers ($P < .05$). These correlations between muscle fiber types and meat quality parameters indicate how specific muscle characteristics influence goat meat's overall quality and attributes.

Differential scanning calorimetry thermogram

The thermograms of LTL and SM showed a similar pattern of 3 major peaks with transitions (T_{max}) at 51°C, 63°C, and 75°C. This is a typical thermogram for meat, and the 3 major peaks can be assigned to myosin, collagen and sarcoplasmic proteins, and actin, respectively. However, PM exhibited 2 major peaks with transitions at 53°C and 75°C and 2 adjacent minor peaks between 60°C and 70°C (Figure 6). Muscle type influenced the transition temperatures/peak values in the 3 major peaks and also the denaturation enthalpy of individual peaks ($P < .01$; see Table 3).

Discussion

Muscle characterization

Across the 3 muscles, PM showed higher pH_{24} compared to LTL and SM. This difference in pH_{24} between the muscles is expected since it is well known that oxidative muscles like PM have premature termination of postmortem glycolysis compared to glycolytic muscles like LTL and usually have a limited pH drop (Bendall and Restall, 1983; Chauhan et al., 2019). The collagen content of the muscles observed was comparable to the values reported previously in Boer goats (van Wyk et al., 2022), with highest total collagen content measured in SM, followed by LTL and PM.

Myofiber characteristics

Only a few studies have investigated goat muscle fiber characteristics and meat quality (Bakhsh et al., 2019; Hwang et al., 2019; Hwang et al., 2017; Rivero et al., 2022). Three muscles (LTL, PM, and SM) compared in this study showed variations in fiber number percentage and CSA, which could be attributed to the different growth rates of the muscle fibers and variable requirements for oxygen diffusion within their cells (Lang et al., 2016). Our findings align with previous research conducted in goats (Hwang et al., 2019; Hwang et al., 2017) and in beef (Ozawa et al., 2000; Kirchofer et al., 2002). These studies reported a high proportion of type IIB fibers in the LTL and SM muscles and higher proportion of type I fibers in the PM muscle. However, these studies on goats have not reported the CSA of different muscle fiber types and, therefore, could not draw inferences from these previous reports. The smaller CSA of the myofibers in the PM muscle relative to LTL and SM muscles is consistent with previous studies in cattle (Lang et al., 2016; Kirchofer et al., 2002), where the variations in fiber sizes were correlated with exercise and muscle type.

Table 2. Pearson correlation coefficients I between histochemical characteristics and meat quality traits for longissimus thoracis et. lumborum, semimembranosus and psoas major muscles (n = 5)

	Type I	Type IIA	Type IIB	Type I	Type IIA	Type IIB
pH	−0.02	−0.14	−0.12	−0.42**	−0.49**	−0.50**
WBSF	−0.50*	−0.29	−0.32	0.61**	0.67**	0.64**
Hardness	−0.16	0.17	0.03	0.51**	0.54**	0.47**
Cooking loss	0.12	0.22	0.20	0.01	0.08	0.09
*L**	0.06	0.19	0.25	0.28	0.19	0.25
*a**	0.39	0.29	0.27	−0.45*	−0.43	−0.41*
*b**	−0.02	0.06	−0.08	−0.03	−0.08	−0.04
*C**	0.28	0.22	0.21	−0.41*	−0.39*	−0.36
h	−0.41*	−0.17	−0.27	0.52**	0.46*	0.51**

a^*, redness; b^*, yellowness; C^*, chroma; h, hue; L^*, lightness; WBSF, Warner-Bratzler shear force.

*$P < .05$.

**$P < .01$.

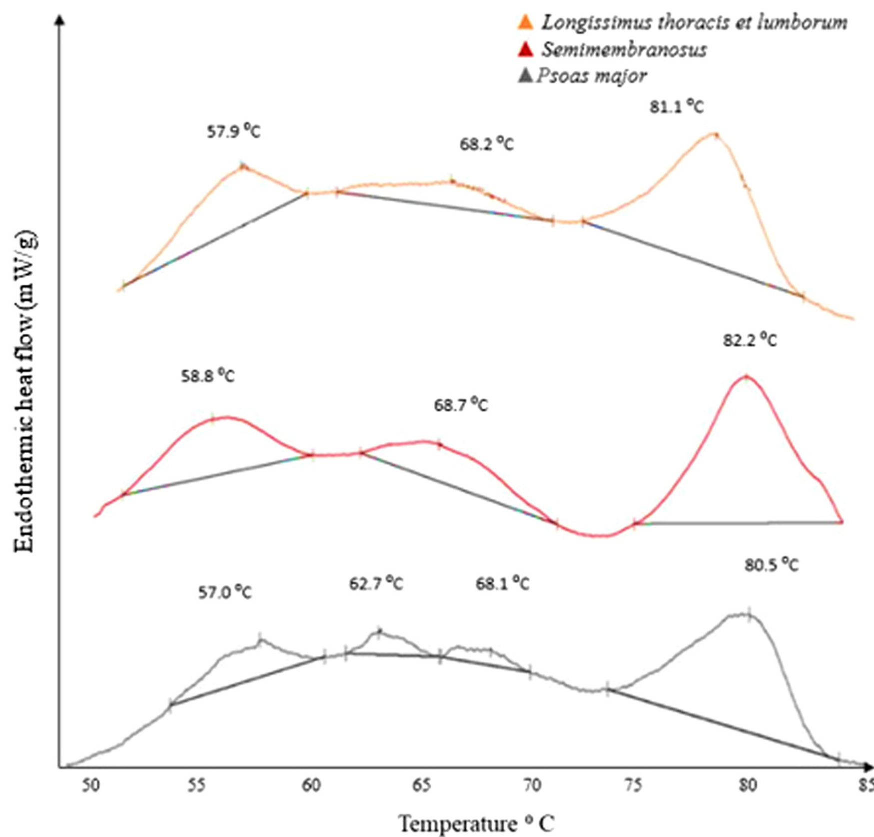

Figure 6. Differential Scanning calorimetry thermograms of longissimus thoracis et. lumborum, semimembranosus and psoas major muscles at a heating rate of 10°C/min. Numbers over peaks represent the T_{max} for 1 muscle.

Table 3. Effect of muscle (*longissimus thoracis et. lumborum*, *semimembranosus* and *psoas major*) on the peak denaturation temperature (T_{max}, °C) and denaturation enthalpy (ΔH, J/g) and of the major differential scanning calorimetry peaks on the thermograms of with heating at a rate of 10°C/min

	T_{max} °C					Enthalpy ΔH (J/g)				
Peak	LTL	SM	PM	SED	*P* Value	LTL	SM	PM	SED	*P* Value
I	57.9[a]	55.1[b]	56.9[a]	0.43	<.001	0.22[a]	0.25[a]	0.12[b]	0.02	.004
II			62.7							
III	68.1[a]	66.6[b]	68.2[a]	0.35	.002	0.20[a]	0.23[a]	0.02[b]	0.06	.010
IV	81.1[a]	79.5[b]	82.6[c]	0.20	<.001	0.53[a]	0.54[a]	0.38[b]	0.03	.002

LTL, longissimus thoracis et. lumborum; PM, psoas major; SED, standard error of difference; SM, semimembranosus.

Carcass replication N = 6.

Means without a common superscript are significantly different ($P < .05$).

[a–c]Different superscript capital letters indicate significant difference within row ($p < 0.05$).

Relationship between myofiber characteristics and meat quality traits

Overall, myofiber characteristics and meat quality traits observed in this study align with previous studies that have compared meat quality of various muscle groups (Hwang et al., 2017; Rhee et al., 2004; Gruber et al., 2006; Vaskoska et al., 2020). Our study revealed that the LTL and SM muscles exhibited higher WBSF values and hardness than the PM muscle. This could be attributed to variations in the CSA and composition of muscle fiber types. Hwang et al. (2019) previously showed that muscles containing more type I fibers exhibited increased tenderness. However, there are studies in beef (Ozawa et al., 2000; Seideman et al., 1987) and pork (Ryu and Kim, 2005; Karlsson et al., 1993) that reported a positive association between type

I fiber number percentage and toughness in the LTL muscle. The discrepancy in tenderness among muscles such as the PM and the LTL and SM can be attributed to the variation in muscle fiber size, where the PM has relatively smaller fibers, and LTL and SM have larger fibers (Jurie et al., 2007; Oury et al., 2010).

Differences in collagen content also contribute to variations in tenderness among muscles. In this study, we have observed a positive correlation between collagen content and WBSF, which aligns with a previous study on beef (Torrescano et al., 2003). Several studies indicate that the composition of muscle fiber types significantly impacts collagen content and subsequently influences meat tenderness (Kovanen et al., 1984; Chriki et al., 2012). Kovanen et al. (1984) observed that slow-twitch muscles contain higher collagen levels than fast-twitch muscles. However, the relationship between collagen content and fiber type composition in livestock species remains unclear (Lefaucheur, 2010). More recently, Chriki et al. (2012) found a negative correlation among the percentage of slow oxidative fibers and total collagen as well as insoluble collagen, while the percentage of fast oxido-glycolytic and fast glycolytic fibers showed positive correlations with total collagen and insoluble collagen.

Numerous research groups have reported results in goats (Bakhsh et al., 2019; Hwang et al., 2019; Hwang et al., 2017) and beef (Strydom et al., 2000; Maltin et al., 2003), showing a positive correlation between beef tenderness and the percentage of type I fibers, while noting a negative correlation with the percentage of type IIB fibers. In contrast to our study, Chriki et al. (2013) discovered a negative correlation between the proportion of fast glycolytic muscle fibers and WBSF, and Ryu and Kim (2005) observed a positive correlation between the percentage of type I fibers and WBSF in porcine muscles. These discrepancies may be attributed to variations in ageing and proteolysis processes among different muscle fiber types. Previous studies have suggested that type I fibers have a lower calpain to calpastatin ratio compared to type IIB fibers and that proteins such as troponin-T and desmin in type IIB fibers are more prone to degradation (Ouali and Talmant, 1990; Muroya et al., 2010). It is commonly reported that type I and type IIA fibers contribute to the redness of beef due to their higher myoglobin content than type IIB fibers (Lefaucheur, 2010). Our study demonstrated that the redness value was positively correlated with the number percentage of type I, and lightness was positively correlated with type IIB, consistent with the findings of Hwang et al. (2017) in Korean native black goats.

Relationship between cooking temperature, cooking loss, shrinkage and Warner-Bratzler shear force in aged and unaged meat. Cooking of meat leads to the contraction of myofibrillar and sarcoplasmic proteins and the shrinkage and solubilization of connective tissue (Liu et al., 2013). Therefore, cooking loss of meat is the result of the protein denaturation caused by heat during cooking, which ultimately results in a decrease in the meat's ability to retain water (Tornberg, 2005; García-Segovia et al., 2007; Vaskoska et al., 2020). It has been observed that as cooking temperatures increase within the range of 60°C to 80°C. Both the LTL and SM muscles experience an increase in cooking loss, WBSF, and volume shrinkage. Liu et al. (2013) attributed this increase in cooking loss and related WBSF to the thermal denaturation of myosin (40–60°C), actin (66–73°C), and the shrinkage of collagen (56−62°C) in goat SM muscle. In contrast, cooking-related tenderization is often associated with collagen solubilization, whereas ageing-related tenderization is related to proteolysis of myofibrillar proteins such as titin, nebulin, and desmin (Koohmaraie and Geesink, 2006). Vaskoska et al., 2020) comprehensively explored the relationship among shrinkage, cooking loss, and WBSF in different bovine and porcine muscles.

In our study, aged meat showed a higher cooking loss in LTL and SM muscles. Although it is widely established that aged meat exhibits higher WHC compared to unaged meat in its raw state, it seems that the water content bound within raw aged meat is more prone to being released during the cooking process compared to water in unaged meat (Purslow et al., 2016). Purslow et al. (2016) related this to the sarcoplasmic proteins in aged meat, which would be expelled with water during cooking. Furthermore, 'lower shrinkage in aged meat could be related to the cytoskeletal proteins degraded during ageing, making the cell and myofibrillar matrix less able to hold water after ageing. The positive association between cooking loss and volume shrinkage with WBSF is shown using the PCA score plot and loading plot, where 48.3% of the variance of the data is separated based on the cooking temperature treatment.

Differential scanning calorimetry thermogram

To the best of our knowledge, this is the first study examining the application of DSC to understand the changes in meat proteins during cooking and goat meat quality. Hence, the thermogram outcomes obtained in

this study can potentially be compared to the findings of earlier DSC studies conducted on beef (Purslow et al., 2016; Vaskoska et al., 2020). DSC studies have demonstrated that different muscle proteins require different levels of heating energy for denaturation during the cooking process (Martens et al., 1982; Purslow et al., 2016; Tornberg, 2005). The thermograms consisted of 3 major endothermic peaks between 50°C and 80°C in LTL and SM muscles like other species, which could be attributed to the thermal denaturation of myosin (40–60°C), collagen (56−62°C), and actin, (66−73°C) respectively (Egelandsdal et al., 1991; Palka and Daun, 1999). The observed cooking loss, shrinkage, and WBSF in our study could be associated with the thermal denaturation of these proteins between 50°C and 80°C. Unlike the other 2 muscles, PM showed 2 peaks between 55°C and 70°C. Studies have shown that during cooking between 50°C and 80°C, muscle fibers shrink in 2 directions: transversely and longitudinally, resulting in increased cooking loss and WBSF. Vaskoska et al., 2020) showed that in bovine muscles (at whole meat and fiber level), myosin and endomysium denaturation overlap with the transverse shrinkage, which usually has an onset between 45°C and 55°C, and the longitudinal shrinkage was observed to be highest at 80°C, which corresponded to the DSC peak that is usually associated with actin denaturation. It is also likely that titin denaturation is encompassed in the actin denaturation peak (Pospiech et al., 2002). The influence of muscle on variations in denaturation enthalpy points to the potentially different thermal denaturation patterns in other muscles. Moreover, there was an additional peak in the PM muscle, unlike LTL and SM, between 60°C and 70°C. This could not be clearly investigated as the muscles used comprised of mixed fiber type rather than pure fibers. However, future studies considering muscles consisting of pure fiber types, like *masseter* and cutaneous *trunci*, and hybrid fibers could help to better explain the mechanism. Vaskoska et al., 2020) showed that the myosin II isoform has greater thermal sensitivity in bovine muscles than type I isoform. Higher denaturation enthalpy indicates higher thermal denaturation of muscle protein. The peak corresponding to actin denaturation, between 75°C and 85°C, showed comparatively higher denaturation enthalpy in all 3 muscles. The WBSF was the highest between 70°C and 80°C in our study, indicating an optimum cooking temperature below 70°C to 75°C in goat meat to reduce the toughening during cooking because between 60°C and 70°C collagen solubilization and associated tenderization occurs. This could be related to the collagenous tenderization theory (Laakkonen et al., 1970) and myofibrillar toughness (Lehmann and Schindler, 1907).

Conclusion

The variations in muscle fiber composition and CSA of type I, IIA, and IIB muscle fibers influence the meat quality of Boer goats. A greater sarcomere length and a lower total collagen content could be related with the tenderness in PM muscle. The cooking end-point temperature is a critical factor influencing the quality of cooked goat meat. As the cooking temperature rises, WBSF, cooking loss, and volume shrinkage increase, leading to tougher meat. Analyzing the contribution of different muscle fiber types to the variations observed between muscles will provide deeper insights into the factors influencing the meat quality of goats. This knowledge can further contribute to developing strategies for optimizing goat meat eating quality and enhancing consumer satisfaction.

Conflicts of Interest

The authors declare no conflict of interest.

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Author Contributions Conceptualization

A.R. and S.S.C.; methodology, A.R., R.D.W; F.R.D., and S.S.C.; writing—original draft preparation, A.R.; writing—review and editing, A.R., F.R.D., R.D.W., B.J.L., and S.S.C., supervision, S.S.C., F.R.D., B.J.L; and R.D.W. All authors have read and agreed to the published version of the manuscript.

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