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Carcass and meat quality of Nellore cattle (*Bos taurus indicus*) belonging to the breeding programs

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ABSTRACT

The objective of this study was to estimate and describe phenotypic traits for carcass and meat quality in Nellore cattle belonging to the breeding programs. Data from 718 Nellore animals participated in the Delta Gen, CRV Paint and Nelore Qualitas breeding programs were used. Meat quality traits were measured and the data were analyzed. The following means and standard deviations of the meat quality traits were obtained: shear force (SF = 5.7 ± 1.3 kg), myofibril fragmentation index (MFI = 32.0 ± 15.3), cooking loss (CL = 27.7 ± 3.1%), intramuscular lipid content (ILC = 0.9 ± 0.5%), backfat thickness (BFT = 4.2 ± 1.4 mm), marbling score (MS = 2.6 ± 0.36), rib eye area (REA = 72.8 ± 7.35 cm^2) and instrumental color (lightness (L* = 27.9 ± 2.7), redness (a* = 12.4 ± 1.86), yellowness (b* = 5.5 ± 1.0)). Significant phenotypic correlations were observed between BFT and MS (0.2314), and between MS and ILC (0.1308). A negative and significant correlation was found between SF and MFI (-0.5525); however, the correlation with MFI was low in animals with SF values higher than 6 kg. In principal component analysis (PCA), the first four eigenvalues of the matrix of direct additive genetic variance explained 61.26% of the total additive genetic variance in the meat quality traits. The most important meat quality traits in PC1 were a*, b* and CL. PC2 was characterized by MFI and color (a* and b*), PC3 by MS, BFT and L* and PC4 by ILC, L* and b*. Furthermore, BFT was positively associated with MS, SF and CL, and SF was negatively associated with MFI. The present study suggests that muscle growth and backfat thickness were satisfactory; however, intramuscular fat deposition and meat tenderness still require more attention from the breeding programs.

1. Introduction

The national cattle herd, which mainly consists of Zebu (*Bos taurus indicus*) and crossbred animals, has enabled Brazil to become the second largest producer and the largest exporter of beef in the world (United States Department of Agriculture, 2020). Despite the importance of these animals for the Brazilian production system, the meat of Zebu cattle usually is believed to be less tender in comparison to the subspecies *Bos taurus taurus* (Rodrigues et al., 2017; Lage et al., 2012). This inconsistency in tenderness explains the reduced interest in Zebu beef (Picard et al., 2014).

Tenderness is considered the most important meat quality trait; however, other traits such as color, marbling, cut size, amount of intramuscular and subcutaneous fat and palatability are also valued by consumers. In addition, with improvements in living standards and consumption levels, people have higher demands for meat quality (Wan et al., 2016). In livestock production, the variability in the quality of the meat produced compromise global competitiveness. Hence, beef cattle farmers must provide high-quality meat in order to ensure the continuous growth of the industry. Within this context, genetic improvement of carcass and meat quality traits in the Nellore breed becomes essential for the beef industry (Gordo et al., 2018).

The improvement of traits requires the selection of animals with favorable genotypes and phenotypes in the breed. In Brazil, organized breeding programs of Nellore bulls were started in the 1980s. There are currently 10 established Nellore breeding programs in the country

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(Carvalheiro, 2014). These programs, in partnership with universities, research institutes and private companies have allowed the generation of phenotypic data for genetic evaluations and animal selection to improve meat quality traits in Nellore cattle (Carvalheiro, 2014). Thus, studies evaluating the meat quality traits of Nellore cattle belonging to these breeding programs are necessary to demonstrate the genetic progress of the breed. Within this context, the objective of the present study was to investigate the carcass and meat quality of Nellore cattle belonging to the breeding programs.

2. Material and Methods

2.1. Experimental animals and sample collection

The experiment was conducted in accordance with animal welfare guidelines according to State Law No. 11.977 of the State of São Paulo, Brazil. All animal procedures were approved by the ethics committee of the Faculty of Agrarian and Veterinarian Science, São Paulo State University (UNESP). Data from 718 contemporaneous uncastrated male Nellore aged 20 - 24 months and finished in the feedlot for 90 - 100 days were used. The animals belong to different farms registered in breeding programs established for the genetic improvement of the Nellore breed in Brazil, such as Delta Gen, CRV Paint and Nelore Qualitas. The animals were sent for slaughter in different months of 2013 and were slaughtered in accordance with guidelines for the Humane Slaughter of Cattle. During slaughter, the carcasses were properly identified. Next, the carcasses were cooled for 24 h and 2.54 cm thick *Longissimus thoracis* muscle samples were collected between the 12th and 13th rib of the left half-carcass of each animal, vacuum packaged and sent to the School of Veterinary Medicine and Animal Science (FMVZ), Unesp, Botucatu, SP, Brazil, for meat quality analysis.

2.2. Meat quality measurements

Rib eye area (REA, cm^2) was determined by the quadrant method and backfat thickness (BFT) was measured with a caliper (in mm). The marbling score (MS) was evaluated visually using the United States Department of Agriculture (USDA) grading system, which assigns a score from 1 to 10, where 1 = practically devoid; 2 = traces; 3 = slight; 4 = small; 5 = modest; 6 = moderate; 7 = slightly abundant; 8 = moderately abundant; 9 = abundant, and 10 = very abundant. Meat color was determined in the CIELab color space (L*, lightness; a*, redness; b*, yellowness) using a Chroma Meter CR-400 (Konica Minolta Sensing, Inc., Tokyo, Japan). The unit was calibrated using a white standard plate and color readings were taken at three locations of the *Longissimus thoracis* muscle sample after 30 min at 1 - 3°C and the average of these measurements was then calculated.

Meat samples were cooked in a pre-heated oven at 170°C until they reached an internal temperature of 71°C. The cooking temperature was controlled by DT-612 digital thermometer (ATP Instrumentation, Ashby-de-la-Zouch, United Kingdom), inserted into the geometric center of each sample to monitor their internal temperature. Next, the samples were cooled for 12 h at 1°C for the measurement of shear force (SF). After refrigeration, 1.27 cm diameter cylinders were cut longitudinally from the center of the sample in the direction of the muscle fiber (Wheeler, Koohmaraie and Shackelford, 1995). The cylinders were cut with a Salter Warner-Bratzler Shear Force device with a capacity of 25 kg at a velocity of 20 cm/minute. The tenderness value was calculated by the arithmetic mean obtained of eight cylinders per sample. Cooking loss (CL) was determined as the weight difference between raw and cooked meat (pre- and post-cooking).

Intramuscular lipid content (ILC) was determined using a gravimetric method with cold extraction (Bligh and Dyer, 1959). *Longissimus thoracis* muscle samples (3 g) were used for extraction of total lipids with chloroform and methanol. The chemical analysis for determination of the myofibril fragmentation index (MFI) was adapted of the described by Culler et al. (1978). *Longissimus thoracis* muscle samples (3 g) were homogenized with buffer (100mM KCl, 20 mM potassium phosphate (pH 7), 1 mM EDTA, 1 mM $MgCl_2$ and 1 mM NaN_3) at 2 °C in an Ultra-turrax (Marconi - MA102/E) at 18,000 rpm and then centrifuged at 1000 x *g* for 17 min. The protein was quantified using Biuret method and the absorbance readings were taken at 540 nm wavelength in a spectrophotometer. In the determination of MFI, samples were prepared with buffer for a protein concentration of 0.5 mg/mL and read by spectrophotometry at 540 nm. The MFI value was obtained by the following calculation: MFI = Absorbance × 200..

2.3. Statistical analyses

The data were analyzed by MIXED procedure of with the SAS statistical program (SAS Institute, Cary, NC, USA, 2011). The data consistency analysis for phenotypic traits was performed and included the fixed effect of contemporary groups and the age at slaughter as covariate. The contemporary groups for meat quality traits were defined as farm, year of birth, management group at yearling and slaughter day. For all traits studied, contemporary groups with records outside the interval given by the mean of the group plus or minus three standard deviations were discarded. Additionally, Pearson's correlation coefficient was applied to determine the correlations among variables.

Principal component analysis (PCA) of the meat quality traits was performed using the Statistica 7.0 software to reduce the number of variables and to identify any latent structures in the data. The quality parameters obtained for each meat sample (REA, BFT, ICL, MS, L*, a*, b*, CL, SF, and MFI) were used as independent variables in PCA. Animal's scores in the first four principal components (PC1 to PC4) explained 61.26% of the total variance and were considered in the present study.

3. Results

The descriptive statistics of the meat quality traits were investigated and are presented in Table 1. The size of the *Longissimus thoracis* muscle determined by average REA was 72.8 ± 7.35 cm^2. The BFT showed value of 4.2 ± 1.4 mm, that is within the standards required by the industry. However, ILC and MS were considered low with values of 0.9 ± 0.5% and 2.6 ± 0.36, respectively. A significant and positive phenotypic correlation was observed between MS and BFT (0.2314; $P < 0.01$) and between ILC and MS (0.1308; $P < 0.05$) in Nellore cattle (Table 2).

Color is a trait that reflects meat freshness and influences the purchase decision of consumers. Analysis of instrumental colors in the present study showed lightness (L*) of 27.9 ± 2.7, redness (a*) of 12.4 ± 1.86 and yellowness (b*) of 5.5 ± 1.0. The CL showed a high value of 27.7 ± 3.1%. High variability in meat tenderness, as evaluated

Table 1
Descriptive statistics for meat quality traits in *Longissimus thoracis* muscle of Nellore cattle.

Variables*	Number of observations	Mean ± SD	Min - Max	CV%
REA (cm^2)	718	72.8 ± 7.35	46.0 - 100.0	10.6
BFT (mm)	718	4.2 ± 1.4	1.2 - 11.0	21.9
ILC (%)	718	0.9 ± 0.5	0.18 - 4.3	22.9
MS	718	2.6 ± 0.36	2.0 - 4.2	12.3
L*	718	27.9 ± 2.7	19.4 - 36.5	9.9
a*	718	12.4 ± 1.86	6.4 - 20.4	19.1
b*	718	5.5 ± 1.0	0.96 - 8.6	17.4
CL (%)	718	27.7 ± 3.1	16.4 - 40.1	12.9
SF (kg)	718	5.7 ± 1.3	2.0 - 11.2	22.7
MFI	718	32.0 ± 15.3	21.8 - 89.1	14.2

REA = rib eye area; BFT = backfat thickness; ILC = intramuscular lipid content; MS = marbling score; L = lightness; a* = redness; b* = yellowness; CL = cooking loss; SF = shear force; MFI = myofibril fragmentation index.

Table 2
Phenotypic correlation among meat quality traits in *Longissimus thoracis* muscle of Nellore cattle belonging to the breeding programs.

	REA	BFT	MS	SF	L*	a*	b*	ILC	MFI	CL
REA	-	0.0483	0.1180*	-0.0923*	-0.0546	0.2234**	0.1240*	-0.0055	0.0124	0.0626
BFT		-	0.2314**	0.0154	0.0965*	-0.0229	0.0548	0.0203	-0.0474	0.0481
MS			-	0.0671	0.1133*	-0.0459	0.0633	0.1308*	-0.1004*	0.0763*
SF				-	-0.1040*	0.0020	-0.0388	-0.1029*	-0.5525**	0.2839**
L*					-	-0.2661	0.0980*	0.0110	0.0143	-0.0203
a*						-	0.7183**	0.0955*	-0.0193	0.2578**
b*							-	0.0671	-0.0056	0.2195**
ILC								-	0.0720*	0.0142
MFI									-	-0.1583**
CL										-

REA = rib eye area; BFT = backfat thickness; MS = marbling score; SF = shear force; L* = lightness; a* = redness; b* = yellowness; ILC = intramuscular lipid content; MFI = myofibril fragmentation index; CL = cooking loss.
Number of observations = 718 animals.
* = P< 0.05; ** = P< 0.01

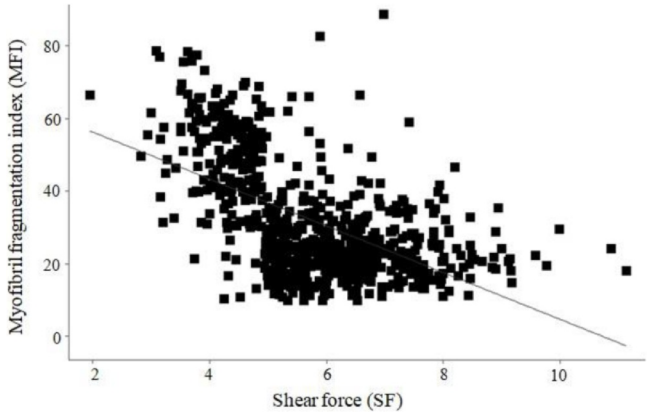

Fig. 1. Distribution of shear force (SF) and myofibril fragmentation index (MFI) of the *Longissimus thoracis* muscle of Nellore cattle (*Bos indicus*).

by shear force measurement, was observed in the Nellore cattle studied, with an SF value of 5.7 ± 1.3 kg (range: 2.0 - 11.2 kg) and MFI of 32.0 ± 15.3 (range: 21.8 - 89.1). Furthermore, there was a significant and positive phenotypic correlation between SF and CL (0.2839; P< 0.01). Thus, meat that presented greater SF value presented higher CL and less proteolytic activity. The distribution of SF and MFI values of each animal and the relation between this meat tenderness traits can be observed in the Fig. 1. The MFI value, frequently determined for expressing the level of protein degradation during *postmortem* storage, has been shown to be correlated with SF values (-0.5525; P< 0.01).

The PCA using meat quality traits generated four principal components (PC) with eigenvalues exceeding 1.0 (Table 3). The first four PCs explained 61.26% of the total variance in meat quality traits. The first principal component (PC1) explained 19.8% of total variance. The most important meat quality traits in PC1 were a*, b* and CL, followed by REA and SF.

The second principal component (PC2) explained 17.12% of total variance, and was characterized by MFI and strongly represented by color (a* and b*), and followed by ILC and REA. The third component (PC3) explained 13.57% of total variance and was characterized by MS, BFT and L*. Furthermore, BFT was positively associated with MS and, to a lesser extent, with ILC. Finally, the fourth component (PC4) explained 10.72% of total variance and was characterized by ILC, L* and b*. The results of PCA obtained by plotting the meat quality traits are shown in the Fig. 2 (PC1 *vs.* PC2 and PC1 *vs.* PC3). Finally, BFT was positively associated with MS, SF and CL. Furthermore, SF was negatively associated with MFI in the present study.

Table 3
Principal component analysis and coefficients of the eigenvalues of meat quality traits of Nellore cattle.

Variables*	PC1	PC2	PC3	PC4
REA (cm^2)	0.23	0.15	0.21	-0.52
BFT (mm)	0.07	-0.10	0.54	0.08
ILC (%)	0.05	0.23	-0.10	0.56
MS	0.09	-0.21	0.58	-0.24
L*	-0.13	-0.01	0.49	0.51
a*	0.60	0.26	-0.13	-0.05
b*	0.55	0.25	0.13	0.20
CL (%)	0.40	-0.20	-0.12	0.17
SF (kg)	0.20	-0.61	-0.20	0.07
MFI	-0.20	0.57	0.09	-0.07
Eigenvalues	1.98	1.71	1.36	1.07
Variance explained	19.83%	17.14%	13.57%	10.72%

REA = rib eye area; BFT = backfat thickness; ILC = intramuscular lipid content; MS = marbling score; L = lightness; a* = redness; b* = yellowness; CL = cooking loss; SF = shear force; MFI = myofibril fragmentation index.
Number of observations = 718 animals.

4. Discussion

The REA represents the cross-sectional area of *Longissimus thoracis* muscle and is an important carcass trait in meat quality evaluations. This trait is a measure of level of muscle development of the animals, carcass yield and, especially, the proportion of prime cuts that are affected by multiple factors, including slaughter weight and genetic group (Correia et al., 2016). Results similar to the present study have been reported by Miguel et al. (2014) for feedlot-finished Nellore cattle aged 24 - 27 months (79.18 cm^2). Fidelis et al. (2017) obtained a REA of 75.7 and 78.4 cm^2 in Nellore cattle (mean bodyweight of 550 kg) with high and low residual feed intake, respectively. However, Sant'anna et al. (2019) found a lower REA (68.28 cm^2) in animals aged 23 months and Bonin et al. (2015) reported a value of 61.24 cm^2 for feedlot-finished Nellore cattle aged 21 - 24 months. Analyzing data from 11,786 animals, Zuin et al. (2012) showed high variability in REA of 21.86 to 114.1 cm^2. Thus, Nellore cattle have adequate muscling, but this trait shows high variability. The variability in REA can be explained by genetic factors and differences in cattle selection programs, environmental factors, management, and feeding programs (pasture or feedlot). The *PLAG1* region is associated with REA in Nellore cattle and indicates a strong genetic correlation between REA and birth weight (Pereira et al., 2016). The results of this study suggest that Nellore cattle selected for muscle growth and meat quality, when reared in intensive production systems commonly show high REA value between 70 and 80 cm^2.

Backfat thickness is important to protect the carcass against cold shortening during chilling and the Brazilian slaughterhouse industry

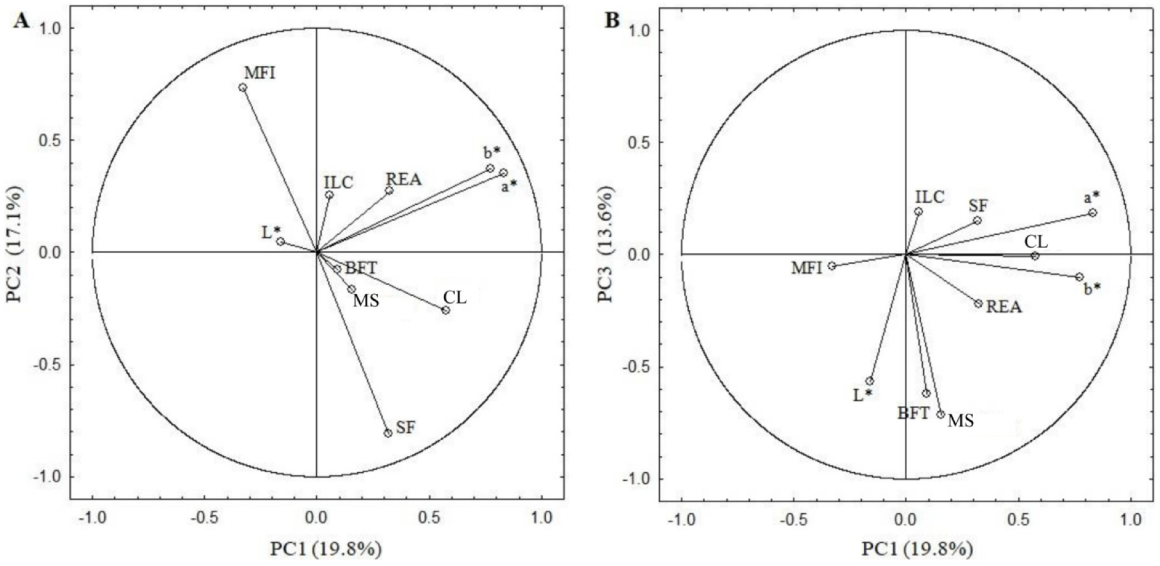

Fig. 2. Principal component analysis indicating correlations between meat quality traits in *Longissimus thoracis* muscle of Nellore cattle. A. Principal component 1 *vs.* 2 (PC1 *vs.* PC2). B. Principal component 1 *vs.* 3 (PC1 *vs.* PC3). Shear force (SF); myofibril fragmentation index (MFI); cooking loss (CL); intramuscular lipid content (ILC); backfat thickness (BFT); marbling score (MS); rib eye area (REA); lightness (L*); redness (a*); yellowness (b*).

requires 3 mm of BFT as a minimum standard for carcasses (Dolezal et al., 1982; Malheiros et al., 2015). However, a BFT > 6.0 mm may cause economic losses for slaughterhouses and animal producers, due to the greater accumulation of adipose tissue in the pelvic, renal and visceral regions. Our results corroborate the findings of Fidelis et al. (2017) who observed value 4.08 and 4.42 mm in Nellore cattle with high and low residual feed intake, respectively. In contrast, Sant'anna et al. (2019) found a BFT of 5.65 mm in another study on Nellore aged of 24 months. In addition, Malheiros et al. (2015) and Baldassini et al. (2017) observed a high genetic variability of the BFT in a population of Nellore cattle, as was also observed in the present study.

Marbling score and ILC are very important meat quality traits in ruminants, which are associated with superior quality meat products, mainly because of their effect on flavor and juiciness (Ladeira et al., 2018). Our results corroborate the findings of Baldassini et al. (2017) who observed a mean ILC of 0.85% in 1652 Nellore bulls. The MS obtained in the present study also corroborates the results observed by Sant'anna et al. (2019) and Magalhães et al. (2018) in the Nellore breed, who used the same MS grading system as our study. The differentiation and proliferation of adipose cells in ruminants starts to be affected during prenatal life by maternal nutrition (Ladeira et al., 2018). In addition, during finishing, marbling depends on starch digestion and glucose metabolism and the creation of nutritional alternatives is therefore important to increase these metabolic processes (Ladeira et al., 2018). Finally, the present results about ILC and MS in skeletal muscle suggest that Nellore animals tend to deposit a lower amount of intramuscular fat. Moreover, these traits show high variability, even in Nellore cattle participating in breeding programs.

A significant and positive correlation between MS and BFT and between ILC and MS was observed. The present results corroborate the findings of Baldassini et al. (2017) who found a correlation of 0.16 between ILC and BFT in the same breed. In contrast, Pflanzer and de Felício (2011), reported a higher correlation (0.79) between ILC and MS in Nellore cattle (n = 60). The mechanisms of how back fat and marbling are deposited in cattle are not entirely clear. The adipocytes of back fat and marbling show morphological, physical and metabolic differences (Miller et al., 1991; Smith et al., 1998), and the G protein-coupled receptor (GPR43) can provide information about adipose tissue (Chung et al., 2016). However, BFT and marbling are complex traits that are influenced by several genes and difference in the gene expression of transcriptional factors may affect the deposition of adipose tissue in *Bos indicus* and *Bos taurus* (Campos et al., 2016; Smith et al., 2009; Teixeira et al., 2017). According to the results observed in the present study, intramuscular fat deposition is low in Nellore cattle. This low deposition possibly is due to the different metabolic pathways involved in lipid metabolism in *Bos indicus* and *Bos taurus* (Tizioto et al., 2013).

A bright cherry-red beef is considered acceptable, while dark colors may prevent the purchase of the product. Analysis of the instrumental color of meat in the present study showed low L* (27.9 ± 2.7) and b* (5.5 ± 1.0) values. Similar L* values (28.0 and 29.1) were reported by Fidelis et al. (2017) for Nellore cattle with high and low residual feed intake, respectively. However, these authors observed higher a* and b* values when compared to the present study. In a recent study Sant'anna et al. (2019), also observed higher L* (36.77) and b* (11.77) values in Nellore cattle. The instrumental colorimetric values (L*and b*) detected in this study are lower than the patterns obtained by Holman et al. (2016) who studied the relationship between instrumental colors and consumer perception. According to Olivera et al. (2013), redness is the most important color parameter for fresh meat and a high a* value was obtained in the present study, in agreement with the results observed by Sant'anna et al. (2019). However, taken together, the L*, a* and b* values found in the present study were lower than those commonly observed in Nellore cattle. According to Young and West (2001), uncastrated males generally have darker beef, a fact that may have contributed to the meat color found in the present study. In addition, this trait is influenced by genetics as reported by Papaleo Mazzucco et al., 2016, who found L*, a* and b* values higher than 36.69, 20.23 and 10.27, respectively, in different *Bos taurus* crossbreeds. Cafferky et al. (2019) also observed higher instrumental color values in *Bos taurus* (> 41.68, 13.61 and 10.67, respectively). Nevertheless, dark-cutting beef still occurs worldwide (Mahmood et al., 2017; Zhang et al., 2018; Ramanathan et al., 2020). The mechanisms related to meat color are still unclear. Many *antemortem, rigor mortis* or even *postmortem* factors influence the concentration and chemical state of pigments and consequently meat color (Park et al., 2007). Thus, understanding all mechanisms responsible for production of dark beef is paramount to the industry worldwide (Apaoblaza et al., 2020).

For example, the process of converting muscle to meat (*rigor mortis*) depends on the type of muscle fiber and may have a significant impact on meat color (Picard and Gagaoua, 2020). In Nellore bulls,

Chardulo et al. (2019) found a negative and positive association between L* and MyHC-I (type I fibers) and between L* and MyHC-IIa (type II fibers), respectively. Thus, muscles containing higher percentages of type I fibers have lower lightness (L*) values. Type I fibers compete with myoglobin for oxygen, reducing its availability and thus affecting the meat color determination (Picard and Gagaoua, 2020). On the other hand, a predominant oxidative fiber type can promote mitochondrial degeneration and meat discoloration (Ramanathan et al., 2020). This fact might explain the lower L* values of Nellore bulls observed in the present study and the darker meat of these animals when compared to *Longissimus thoracis* from cattle produced in the United States, as reported by McKeith et al. (2016) and English et al. (2016). However, the determination of meat color seems to be more complex than expected as it also depends on the biomolecular interaction between myoglobin, mitochondria, metabolites, and lipid oxidation (Ramanathan et al., 2020), processes that may differ between *Bos indicus* and *Bos taurus*.

Cooking loss is due to water evaporation and drip loss of water and fat. This trait is an important factor in studies assessing tenderness since it can affect meat yield, palatability, and consumer acceptability. The present results corroborate the findings of Nascimento et al. (2016) who observed 29.2 and 28.6% of CL in Nellore cattle with efficient and inefficient residual feed intake, respectively. Gouvêa et al. (2020) also observed high CL in the Nellore breed (25.9 - 27.7%), while Gesteira et al. (2019) found low CL in Nellore supplemented with condensed tannins (14.1 – 20.8%). In contrast, Rossi et al. (2016) observed CL values of 36.9 and 38.3% in *L*ongissimus muscle of Nellore cattle receiving different treatments with ground soybean and starch. Custódio et al. (2019) demonstrated a CL of 32.4% in Nellore bulls. Considering our results and the above-mentioned studies, the CL of Nellore beef shows high variability. CL has been linked to transverse and longitudinal shrinkage of myofibrils and protein and collagen denaturation, events that are responsible for the large amounts of water loss during cooking (Dominguez-Hernandez et al., 2018). Thus, the microstructure of meat undergoes structural changes influencing meat quality (Tornberg, 2013), since, during muscle fiber shrinkage, water and other components such as fat and solubilized protein are expelled, an effect that might be related to meat tenderness evaluated by SF.

Tenderness is one of the most important phenotypic traits of beef quality, being related to multifactors during the life of the animal such as breed, muscle tissue and environmental condition, which influence the *antemortem, rigor mortis* and *postmortem* periods. High variability in meat tenderness is observed among Nellore populations, which usually include animals with tender and tough meat. In a recent study, Malheiros et al. (2018) identified three experimental groups, moderately tender meat (3.5 kg), moderately tough meat (5.8 kg), and very tough meat (8.2 kg) in a population of Nellore cattle. Custódio et al. (2019) and Sant'anna et al. (2019) also observed high variability in the Nellore breed (mean 6.78 kg; mean 6.05 and range: 1.79 – 11.35 kg, respectively). Recently, Rodrigues et al. (2020) reported SF of 9.76 kg in *Longissimus lumborum* muscle of Nellore cattle 48 h *postmortem*. High and low SF values were observed in the present study; nevertheless, the meat was classified as tough (mean 5.7 kg).

The MFI is an indicator of *postmortem* enzymatic proteolysis and a useful tool to assess tenderness variations (Aroeira et al., 2020; Lee et al., 2020). This index reflects the integrity of muscle fibers and their skeletal proteins, in which the degradation of the sarcomere I-band and weakening of the Z-line, which is considered the link between myofibrils, result in muscle fiber fragmentation (Taylor et al., 1995). Furthermore, a higher MFI indicates increased damage of the internal structure of myofibrils. Chardulo et al. (2019) reported MFI between 41.6 and 58.8 in Nellore cattle; however, lower values were observed in the present study (Table 1). In a recent study Muniz et al. (2020), observed Nellore cattle belonging to the Nelore Qualitas breeding program with low MFI (15.74 ± 2.14; n = 10) and with high MFI (56.16 ± 6.87; n = 10). Many studies have demonstrated the relationship between myofibrillar proteolysis and the beef tenderizing process (Aroeira et al., 2020, 2016). However, a direct comparison of MFI with the literature is often difficult because this index is influenced by several factors such as breed, storage, and homogenization process (Onopiuk et al., 2018). According to our results Lage et al. (2012) also observed in Nellore, ½ Simmental x ½ Nellore and ½ Angus x ½ Nellore phenotypic correlation of average negative magnitude (-0.35) between SF and MFI. Baldassini et al. (2017), showed significant correlation of negative magnitude (-0.29) in Nellore cattle (*Bos indicus*) and Culler et al. (1978) showed a significant negative correlation of high magnitude in *Bos taurus* cattle. However, our results imply that the differences in MFI become smaller as the SF value increases (> 6 kg), possibly because of the decrease in myofibrillar fragmentations in tough meat. Thus, this approach allowed us to clarify that MFI could be a good indicator of tenderness in Nellore cattle; however, the relationship between SF and MFI tends to be lower in animals with an SF higher than 6 kg.

Principal component analysis was conducted to visualize the relationships among meat quality traits as REA, BFT, ILC, MS, color (L*, a* and b*), CL, SF and MFI. The eigenvector loadings and the relevance of each scatter plot for the four main PCs expressed the PC correlated with the original variables. The correlated variables were explained by the same PC, and demonstrated that the lower correlated variables were explained by different PCs. The first four PCs in the present study explained 61.26% of the total variation. Our results corroborated the findings reported in a recent study by Sant'anna et al. (2019), in which four PCs explained 66.74% of the total variance in carcass and meat quality traits of Nellore cattle. In contrast, using a dataset of chicken meat, Chen et al. (2016) extracted three PCs from statistical analysis, which explained 87.29% of the total variance. No study has so far reported a total variance higher than 80% for the first three PCs in Nellore cattle, possibly because of the variability in meat quality traits.

The most important meat quality traits in PC1 were a* and b*. These results suggest a high cumulative variance for beef color. In the study of Giaretta et al. (2018), the first PC explained 34.7% of variance and was positively correlated with L*, a* and b*. Ma et al. (2017) also found the first PC to account for 59.82% of the total variance and suggested color parameters to be one of the most important indicators of meat quality. Furthermore, this trait is very important for meat quality because consumers classify the beef using its visual appearance (Hughes, Kearney and Warner, 2014).

The PC2 was characterized by MFI and strongly represented by color (a* and b*), followed by the ILC and REA traits. Thus, again the redness a yellowness coloration was represented. REA also has been considered a trait of great importance, because represents the edible portion of beef carcass. PC3 was characterized by MS, BFT and color (L*) and, PC4 was characterized by ILC, L* and b*.

Principal component analysis is a very effective multivariate approach to obtain a synthetic judgment of meat quality. The PCA result of this study corroborates the findings reported by Baldassini et al. (2017) for *Longissimus thoracis* muscle of Nellore cattle. For carcass traits, Boligon et al. (2013) showed that three principal components were sufficient to model the genetic variation in 14 traits studied in Angus breed. However, carcass traits show a high degree of correlation and a small number of PCs are sufficient to model the covariates matrix. Thus, PCA may provide valuable information about meat quality and in the present study the first four PCs were related to one or two traits that make up the instrumental color of meat, demonstrating the importance of this trait for beef quality.

Among multivariate procedures, PCA is an effective and simple method to obtain explanations of the variance in meat quality traits. Thus, the plot of meat quality PC1 *vs.* PC2 and PC1 *vs.* PC3 can be explained according to Cañeque et al. (2004), where the proximity of traits shows a positive correlation, 180°C are negative correlation and 90°C are independent. In the present study, colors a* and b* were positively correlated and closer to PC1. Similar results were observed by

Cañeque et al. (2004) for meat quality of Manchego lambs.

Positive associations were observed between BFT and MS and between SF and CL. Chen et al. (2016), also observed positive correlations between SF and CL by PCA in chicken meat. In the present study, animals with lower SF values had a higher MFI. These results corroborate the findings of Baldassini et al. (2017) who studied different Nellore populations participating in the same breeding programs as the animals of the present study. This indicates, phenotypically, which traits should be evaluated in accordance with each study proposal for beef quality in the Nellore breed. However, PCA can be an alternative approach to facilitate simultaneous selection for all traits of interest, to allow better description of the population studied using a relatively small number of uncorrelated variables, and to better explain relationships between different meat quality traits by permitting visual interpretation of the data represented in two-dimensional scatter plots.

5. Conclusion

Our results demonstrate that the selection adopted in Nellore animals provided satisfactory muscle growth and backfat deposition. However, intramuscular fat deposition and meat tenderness traits still require more attention from the Nellore cattle breeding programs in Brazil. In addition, the instrumental meat color of this breed is considered dark and principal components analysis indicated that this trait is important for meat quality in Nellore cattle belonging to the breeding programs.

Author contributions

Malheiros, Enriquez-Valencia and Chardulo elaborated the Project, analysed the data and wrote the draft of the manuscript. Silva and Oliveira verified the analytical methods and supervised the findings of this work. Albuquerque and Curi contributed to the discussions and to drafting the final version of the manuscript.

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Supplementary materials

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