Selection Criteria for Meat Production Based on the Morphometry of Morada Nova Lambs: A Systematic Approach

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Abstract

The objective of this study was to characterize the meat production potential of *Morada Nova* lambs from different genetic groups using morphological and zoometric data, performance and carcass characteristics. A total of 24 non-castrated male lambs from two genetic groups were used: *Morada Nova* red (M_{NR}) and *Morada Nova* F_1 red x *Morada Nova* white (M_{NF_1}) breed, with an initial mean body weight of 16.9 ± 3.43 kg and an average age of four months were distributed in a completely randomized design. Evaluations of morphometric data and zoom indices, performance and carcass characteristics were measured and calculated. Univariate and multivariate techniques were used to differentiate and reduce the number of variables, to group them and then develop and validate a sheep meat production index. Only 12 differences in the 29 morphometric measurements and zoometric indices analyzed were observed ($P < 0.05$). Furthermore, only 7 of the 28 quantitative and qualitative characteristics of the carcass were greater ($P < 0.05$) in M_{NF_1} lambs. The yields of commercial cuts and the physical-chemical characteristics and qualitative measurements of the carcass were similar ($P > 0.05$) between the genetic groups. All groups of variables, except the cut yield, have discriminatory power ($P < 0.05$) with the highest classification percentages for body morphometry (91.3%) and zoometric indices (95.7%). The four identified factors, which together explain more than 85.0% of the total data variation, were renamed in the following order of importance: morpho-economic (38.5%), morpho-productive (18.8%), morpho-commercial (17.5%), and equilibrium (11.0%). The heat map showed the suitability in the morpho-commercial and morpho-economic factors for M_{NF_1} lambs, while the M_{NR} lambs showed emphasis for the equilibrium factor. Thus, the Sheep Meat Morphometric Index (S_{MMI}) resulted in the following equation

$$S_{MMI} = \frac{AI \times 0.771 + CH \times 0.759 + RH \times 0.878 + TPRI \times 0.876 + BI \times 0.550 + CW \times 0.905}{100}$$

In which: A_I is the anamorphosis index; C_H is chest height; R_H is rump height; T_{PRI} is the thoracic perimeter relation index; B_I is body index; and C_W is chest width. The application and validation of the developed index showed superiority ($P < 0.001$) for meat production in the crossed lambs. M_{NR} and M_{NF_1} lambs have high thoracic development, compact character and aptitude for meat production. Lambs crossed between genetic groups of the M_N breed are another sustainable option for sheep production in drylands. It is recommended that the S_{MMI} be used as a tool for morpho-productive selection criteria in breeding programs in the M_N breed, as well as other small native breeds.

Introduction

The Brazilian semi-arid region has traditionally raised sheep with a total of 68.5% of the national effective herd [Brazilian Institute of Geography and Statistics (*IBGE*, 2018)], with the potential for semi-intensive exploitation in sheep meat farming mainly using native breeds and their crosses to increase meat production (Castro et al., 2020; Silveira et al., 2021a). Among these breeds, *Morada Nova* (M_N) is one of the main genetic resources of hair sheep in the Brazilian semi-arid region, being recognized for its

resistance to gastrointestinal endoparasites (Ferreira et al., 2019), adaptability to the thermal environment of the semi-arid region (Leite et al., 2018; 2020), productive potential as a maternal race in terminal crossbreeding (Landim et al., 2021), fertility without seasonal influence (Moura et al., 2019), carcasses with fatty acid profiles with potential benefit to human health (Lage et al., 2020) and excellent productive potential and skin quality (Vasconcelos-Filho et al., 2021; Alencar et al., 2021).

The Brazilian Association of Sheep Breeders (*Associação Brasileira de Criadores de Ovinos - ARCO*) recognizes the genetic record of two genetic groups of the M_N breed: red and white hair. These present genetic differentiation between themselves, being considered distinct genetic groups (Ferreira et al., 2014). However, there is population fragility with the native breeds due to extinction risk, low effective number of the herd and increased inbreeding rate caused by the indiscriminate introduction of exotic breeds (Nunes et al., 2020). Specifically, the creation of the M_N breed is still undervalued in production systems, with the white genetic group being empirically recognized by farmers as “not adapted” to the thermal environment of the Brazilian semi-arid region, and the red genetic group for its small size. Thus, conducting a survey on the breeding pattern and meat production potential of this breed is essential to encourage the sustainable insertion of these animals in sheep production systems (Lobo, 2019).

A tool used to determine the breeding pattern is by means of body biometrics, which is performed from metric measurements on the animal's body *in vivo*. This simple tool is applied in commercial herds and/or in nuclei to preserve genetic resources in order to assist in zootechnical characteristic studies. With the association of these measures from different body regions, it is possible to generate zoom indices which identify the aptitude and productive potential of the animals, defining the breeding pattern and ability for commercial exploitation (Guimarães, 2018), in addition to relating these indicators to the performance and carcass characteristics. The diversity of this information requires adopting a systematic approach to explore the relationship and identify the main predictor variables for studies of this nature. Multivariate analysis techniques are useful tools for relating sets of indicators (Silveira et al., 2021b) and to develop indexes which assist in decision-making for animal selection and adaptability (de Vasconcelos et al., 2020).

To the best of our knowledge, there is no information on characterizing the potential for meat production using zoomometric measures and indices, nor are there any studies evaluating the performance using the white M_N breed genetic group crossbred with the red (M_{NR}). Therefore, this study aimed to characterize the meat production potential of M_{NR} and $M_N F_1$ lambs using morphological and zoometric data, performance and carcass characteristics.

Material And Methods

Experiment site

The study was conducted at the Research Center for Nutrition of Small Ruminants at the Experimental Farm of the State University Vale do Acaraú (UVA), located in Sobral, Ceará, Brazil (3° 36" S, 40° 18" W

and 56 m asl). The region's climate is Bsh (B - Dry, S - Semi-arid, low h-latitude) according to the Köppen Climate Classification (Alvares et al., 2013).

Animals, experimental design and diet

A total of 24 non-castrated male lambs from two genetic groups were used: Morada Nova red (M_{NR}) and F_1 Morada Nova red x Morada Nova white (M_{NF_1}) with an average initial body weight of 16.9 ± 3.43 kg and an average age of four months distributed in a completely randomized design. The lambs were fed a standard isoproteic and isoenergetic diet during the experimental period according to the nutritional requirements recommended by the National Research Council (NRC; 2007) for lambs of late maturity in the finishing phase with a predicted weight gain of 200 g day^{-1} . Water and mineral salt were supplied *ad libitum*.

Measurements and morphometric indices in vivo

Morphometry was measured in the last week prior to slaughtering the animals with a tape measure and a biometric rod adapted according to (Bianchini et al., 2006; Araújo et al., 2014; Rezende et al., 2014). The lambs were kept in the correct upright position on a horizontal concrete floor without slope during the measurements. Thus, the withers height (W_H), rump height (R_H), chest height (C_H), thoracic depth (T_D), chest width (C_W), body length (B_L), and chest girth (C_G) were measured. The morphometric measurements were combined to elaborate conformation indices, aptitudes and productive and genetic potential according to (Contreras et al., 2011; Silva-Jarquin et al., 2019; Ramos et al., 2019). The indices with their respective equations were: 1) Body index (B_I): body length divided by thoracic perimeter (longilinear animals have $B_I > 0.90$; medium-length $0.86 \leq B_I \leq 0.88$; and short-lived animals $B_I < 0.85$); 2) Relative body index (R_{BI}): ratio of body length to withers height; 3) Thoracic perimeter relation index (T_{PRI}): chest circumference divided by withers height; 4) Anamorphosis index (A_I): thoracic perimeter squared divided by withers height, multiplied by 100; 5) Body capacity index "1" (B_{CI} "1"): corresponding to the quotient between weight and body length; 6) Body capacity index "2" (B_{CI} "2"): corresponding to the quotient between weight and thoracic perimeter; 7) Withers-rump relation index ($W-R_{RI}$): withers height divided by rump height; in which: values equal to 1 describe an animal with thoracic and pelvic limbs of the same height (balance); 8) Body side index (B_{SI}): withers height divided by body length, multiplied by 100. This index provides an understanding of the general shape of the animal's body, meaning if it is long and leggy or short, also indicating production capacity; and 9) Thoracic body index (T_{BI}): ratio given by dividing body length and withers height by withers height and chest depth, multiplied by 100.

Slaughter and carcass characteristics

The lambs were slaughtered at approximately seven months of age. The animals were fasted on a solid diet for 16 hours and then weighed prior to slaughter. The slaughter procedure was carried out following the rules of the Industrial and Sanitary Inspection of Products of Animal Origin (*RIISPOA - Regulamento*

da *Inspeção Industrial e Sanitária de Produtos de Origem Animal*) (Brazil, 2017). Then, the non-carcass components were eviscerated and weighed. After obtaining the carcasses, the pH 0 hour after slaughter was measured using a portable digital pH meter (Testo 205, *São Paulo*, Brazil) provided with a glass electrode, calibrated with pH 7.0 and pH buffer solution 4.0. The carcasses were identified and weighed to determine the hot carcass weight (H_{CW}). The empty body weight (E_{BW}) was determined according to Silva Sobrinho, (2001). Then, the carcasses were packed in plastic bags and sent to a cold chamber (4°C for 24 hours). After this period, the cold carcass was weighed and the pH 24 hours after slaughter was determined. The cooling weight loss [$C_{WL}\%$] = $(H_{CW} - C_{CW}) \times 100/H_{CW}$], in which: H_{CW} = hot carcass weight (kg) and C_{CW} = cold carcass weight (kg). The cuts and carcass composition were longitudinally sectioned using a cold saw (G Paniz SF248, *Rio Grande do Sul*, Brazil), and the left half carcasses were divided into six commercial cuts: leg, shoulder, rib, breast, neck, and loin. These cuts were individually weighed to determine their respective yields (%). In addition, subcutaneous fat thickness (S_{FT}) was measured using a 200 mm digital caliper (ZAAS-01.0013, *São Paulo*, Brazil) (Silva Sobrinho, 1999). Finally, the loin eye area of the *Longissimus lumborum* (L_L) muscle exposed on the 12th thoracic rib was calculated using the geometric method.

Qualitative analysis of the carcass

Conformation, finishing and evaluation of perireneal fat were determined by visually evaluating the carcass according to the methodology described by Cezar and Souza (2007). For conformation, a score of 1 was given for poor conformation to 5 as very good according to the musculature and adipose tissue deposition in relation to the skeleton. Meanwhile, finishing was classified into five categories (score 1 = very thin and 5 = very fat) according to the subcutaneous fat amount and distribution in the chilled carcass. A score of 1 to 3 was assigned for perireneal fat assessment according to the amount of fat in the abdominal cavity around the kidneys (1 = left kidney without fat cover; 2 = fully coated left kidney and the right partially; and 3 = both are covered by a thick layer of fat).

Morphometric measurements and carcass indexes

The morphometric measurements were obtained from the carcass and were carried out as recommended by Cezar and Souza (2007). The morphometric measurements were: carcass external length (C_{EL}), carcass chest girth (C_{CG}), leg length (L_L), leg girth (L_G), arm length (A_L), arm girth (A_G), carcass internal length (C_{IL}), carcass internal width (C_{IW}). The carcass indexes and their equations were: 1) Arm compactness index (A_{CI}): the quotient between the shoulder weight and the arm length; 2) Leg compactness index (L_{CI}): relationship between the shank weight and the leg length; 3) Carcass compactness index (C_{CI}): the relationship between the cold carcass weight and the internal carcass length; and 4) Carcass economic index (C_{EI}): $[(\text{Hot carcass yield} \times 0.25 + \text{Loin eye area} \times 0.15 + \text{Leg yield} \times 0.1 + \text{Loin yield} \times 0.1 + \text{Subcutaneous fat thickness} \times 0.1 + \text{Carcass compactness index} \times 0.09 + \text{Conformation} \times 0.05 + \text{finish} \times 0.05) / (\text{Cooling weight loss} \times 0.05 + \text{age} \times 0.06)] \times 100$.

Statistical analysis

All analyzes were processed and analyzed using the SPSS® software statistical package (Chicago, USA, 2012). The six consecutive steps are described below:

1st Step (Assumptions): All continuous variables met the assumptions of the analysis of variance (ANOVA) on univariate normality by the Shapiro-Wilk test ($P > 0.05$) (Shapiro et al., 1965) and homoscedasticity of the variances by the Levene test (Levene, 1960).

2nd Step (Simple effect): The data were submitted to ANOVA followed by Tukey's means test ($P < 0.05$) for all continuous variables. The effect of genetic groups at two levels (M_{NR} and M_{NF_1}) was considered in the linear mode of ANOVA. The Kruskal-Wallis non-parametric analysis ($P < 0.05$) was used for qualitative carcass variables which did not present a normal distribution using the median as a measure of central tendency.

3rd Step (Differentiation): Canonical discriminant analysis (C_{DA}) was used to differentiate genetic groups into 9 groups: *I.* body morphology, *II.* zoometric indices; *III.* carcass and muscle; *IV.* carcass morphometry; *V.* carcass indices; *VI.* carcass performance; *VII.* commercial cuts; *VIII.* cut yield; and *IX.* mix of variables (all variables simultaneously). The homogeneity of multivariate covariance matrices was assessed using Box's M statistical test ($P > 0.05$). The discriminant function significance was determined using the Wilks' Lambda statistic ($P < 0.05$). The main discriminating characteristics between genetic groups was identified by the highest value of the standardized coefficient of the canonical discriminating function ($r > 0.50$).

4th Step (Identification of variables): A factor analysis (F_A) was performed to identify the most relevant characteristics in meat production for the evaluated genetic groups. The analysis was initially performed for each group of characteristics in a similar way to that described in the C_{DA} . After identifying the main variables within each group of characteristics, an F_A was performed to extract the factors. The number of extracted factors followed the Kaiser criterion (eigenvalues > 1 ; (Kasier, 1960) with orthogonal rotation (varimax method). The factors were renamed according to the importance of the factor weights of the variables within each factor ($> \pm 0.50$). The model adequacy was assessed using Kaiser-Meyer-Olkin statistical test ($KMO = 0.59$) and the significance by Bartlett's sphericity test ($P < 0.05$).

5th Step (Clusters): The definition of the potential for each genetic group according to the renamed factors was performed through the hierarchical cluster analysis (HCA). Ward's method (Ward, 1963) and Euclidean distance were used to measure similarity. Next, individual eigenvalues of the M_{NR} and M_{NF_1} lambs were used in the regression method to generate the matrix. From these, the average factor score by genetic group was generated and for each renamed factor in Step 4. As a complementary analysis, the result of the grouping was plotted using a heatmap generated using the HeatMapper software program (Babicki et al., 2016).

6th Step (Development of an aggregate index): The Sheep Meat Morphometric Index (S_{MMI}) was created to facilitate identifying lamb selection to provide greater potential for meat production. The morphometric characteristics and zoom indices which integrated the index were selected according to the commonality of each characteristic in the F_A . The S_{MMI} was built from the factor weights of the variables as performed by de Vasconcelos et al., (2020) using morphometric measurements, zoom indices and productive characteristics. An ANOVA between genetic groups was performed followed by a means comparison by the Tukey test ($P < 0.001$) to validate and apply the S_{MMI} .

Results

Differences ($P < 0.05$) were observed in only 12 of the 29 variables for the body morphometric characterization and zoometric indices (Table 1). The zoometric indices (B_l , T_{PRI} , A_l , B_{Sl} , T_{Bl}) classify both genetic groups as longitudinal, compact biotype, prone to meat production ability and respiratory capacity. Differences were observed ($P < 0.05$) for the anamorphosis index (A_l) and thoracic body index (T_{Bl}). Regarding the carcass measurements and indexes: carcass chest girth, arm length, carcass inner width, and carcass compactness index were heavier ($P < 0.05$) in the crossbred lambs.

Regarding the productive and physico-chemical characteristics of the carcass, commercial cuts and cut yields (Table 2), only 7 of the 28 variables differed between genetic groups, observing a higher value ($P < 0.05$) for M_{NF_1} lambs. Regarding these variables, the fasting live weight, hot carcass weight, rib eye area and rib, loin and flank weights stood out. Cut yields and carcass physicochemical characteristics were similar ($P > 0.05$) between genetic groups. Qualitative characteristics (conformation, finishing and evaluation of perirenal fat) did not show an effect on genetic groups ($P < 0.05$).

The C_{DA} showed that it is possible to differentiate M_{NR} from M_{NF_1} lambs from the groups of the 9 clusters (Table 3). The zoometric indices were the group of variables which had the highest percentage of correctly classified cases (C_{CC}) in their group of origin, followed by morphometry. The mix of variables in the simultaneous assessment of all variables belonging to the discriminating groups pointed out that T_{Bl} , leg yield, C_G and rib weight are the main predictor variables to differentiate purebred lambs from crossbred. The yield of the cuts in isolation did not show any power to differentiate ($P = 0.092$) the genetic groups.

The eigenvalues and commonality of the variables distributed in the factors are shown in Table 4. High commonality values (> 0.90) were obtained in the ranked variables of C_{WL} , T_{PRI} , A_l and C_{El} , while the other variables had values > 0.70 . The first four factors explained 85.90% of the total variation in the data, in which the first factor retained 38.5% of the total variance, and constituted the variables with the highest factor load, being renamed morpho-economic. There was a positive association between C_{Cl} , L_{EA} , R_H , C_H , T_D , C_W , A_l and C_{El} , but negative with C_{WL} . Higher coefficients in the morpho-productive factor were obtained by C_Y , C_{WL} and T_{PRI} , with 18.8% of the explained variance. The factor associated with the commercial characterization was composed of two variables with greater load (Leg Y. and B_l). Finally, the

equilibrium factor was given by the list of variables which met the analysis assumptions (> 0.5), and that it was not possible to allocate these variables in the first three factors due to their compared low factor load.

The heat map (Figure 1) demonstrated the dynamics of the genetic groups based on the four factors extracted, thus revealing the productive potential of each group, in which the $M_N F_1$ lambs showed aptitude in the morpho-commercial and morpho-economic aspects (positive value of Z -scores) and M_{NR} showed a high association for the balance factor. There was also the formation of two clusters: (i) morpho -economic and morpho-commercial; and (ii) morpho-productive and equilibrium.

The S_{MMI} resulted in the following equation:

$$S_{MMI} = \frac{AI \times 0.771 + CH \times 0.759 + RH \times 0.878 + TPRI \times 0.876 + BI \times 0.550 + CW \times 0.905}{100}$$

The application and validation of the S_{MMI} is shown in Figure 2, in which crossbred lambs presented greater ($P < 0.001$) potential for meat production.

Discussion

The morpho-functional and productive characterization of the M_N breed is non-existent, since the morphological evaluation is limited to considerations about breeding pattern and is only used in promotional events, fairs and exhibitions organized by breeders' associations. This study assesses the productive potential of the M_N breed through morphometric, zoometric, productive data and carcass characteristics using a systematic approach with successive multivariate techniques for different objectives.

Our main findings were: (i) zoometric analyzes show the capacity for morpho-productive classification of lambs from the two genetic groups of the M_N breed; (ii) the zoometric indices and body morphometry are the main factors responsible for differentiation between the genetic groups evaluated in the study; and (iii) the S_{MMI} has potential in the area of selection criteria for conservation programs and genetic improvement of small native sheep breeds.

The morphological indices used in this study were able to characterize the phenotypic and production potential of M_N lambs using the T_{PRI} , A_i , B_{CI} "1" and B_{CI} "2" variables, enabling the classification of breeding groups in high thoracic development, ability to produce meat, weight gain, feeding efficiency and breathing capacity, infusing greater breed rusticity and adaptability for both genetic groups. These characteristics are in agreement with other studies which evaluated adaptability and productive potential of the M_N breed, especially the red variety which has greater potential for meat production (Melo et al., 2018; Rezende et al., 2018; Leite et al., 2020), in addition to breaking paradigms about the low adaptability of white M_N to the semi-arid environment, as already reported by Leite et al., (2018; 2020).

We emphasize that the breathing capacity of the M_N breed is an important adaptive characteristic, since the main mechanisms of heat dissipation during the hottest periods of the day are through transferring sensitive and latent heat through the respiratory tract as observed by (Fonsêca et al., 2019), and in studies of biothermic rhythmicity (Façanha et al., 2020) and caloric management (Ferreira et al., 2020) in native breeds of small ruminants.

The superiority observed in some morphometric and productive characteristics in crossbred lambs are justified by the fact that this crossbreed brought together intrinsic characteristics of the white group, meaning that we still observe the result of the heterosis process and complementarity of characteristics between genetic groups, even within the same breed. This is mainly because the M_{NW} breed is larger when compared to the M_{NR} (Nunes et al., 2020). Therefore, it is inferred that the crossing between the genetic groups of the M_N breed is another alternative to increase the carcass weight resulting in greater cuts, especially noble ones (rib, loin and breast), but with similar cut yields indicating proportionality between carcass and non-carcass components within the two genetic groups. This result may be a peculiar characteristic of using the M_N breed in crossbreedings, since Landim et al. (2021) observed similarities between the cut yields in pure M_N lambs when compared to crossbred *Rabo Largo* $\times$ M_N and *Santa Inês* $\times$ M_N lambs.

The thoracic body index developed *a priori* was fundamental for the survey of phenotypic diversity between the genetic groups. This is because there were combinations of morphometric measurements which express high responses with the profile and productive aptitude of a certain animal (B_L , W_H and T_D) for its development. Studies indicate the great importance of the T_D measurement due to the close relationship with digestive capacity and rusticity (Santos, 2019).

The direct relationship between S_T and C_{WL} (Table 2) is associated with the carcass quality during the final post-slaughter process, since the cover fat has the main objective to act as a thermal insulator in cooling the carcass, thus providing less loss of weight during the maturation process (Nascimento et al., 2018; Landim et al., 2021). However, S_T was not sufficient to maintain thermal insulation for the evaluated genetic groups, exceeding the extremity considered adequate ($C_{WL} < 7\%$; Oliveira et al., 2017).

The discrimination in only one canonical discriminating function (Table 3) for the nine selected groups is explained because the genetic groups (white and red) belong to the same breed, which reduced the discriminatory variance shared between the genetic groups. Even the cut yields do not have an isolated capacity to discriminate genetic groups, which is justified by the similarity between yields (Table 2). The shank yield showed discriminatory power between the genetic groups when all variables were simultaneously analyzed. However, this characteristic acted in a complementary way to the others (T_{BL} , C_G and rib weight) to classify 87.0% of the lambs in their group of origin. It is emphasized that adopting the mix of variables is important to identify the main predictor variables for inclusion in genetic breeding programs for native breeds, especially small breeds due to the lack of research.

The higher classification rates observed when the zoometric indices and body morphometry were partially analyzed are justified by the higher values in the characteristics related to the thoracic part and the height of the crossbred lambs (Tables 1 and 2), which infer in the efficiency response from the productive point of view, i.e. the ability to gain weight and intake dry matter, which justifies the higher performance of these animals. In contrast, the lowest rates were observed in carcass performance and indexes, as the effect of crossbreeding between genetic groups did not influence most carcass variables (Melo et al., 2018; Ramos et al., 2019). The discrimination of the thoracic perimeter when evaluating the carcass morphometry is explained because this characteristic is a predictor of live weight at slaughter (Castro et al., 2012), for which both variables were higher in $M_N F_1$ lambs.

In this study, the potential for meat production was assessed by factor analysis, in which the characteristics linearly associated with each other were distributed through their respective loads, making it possible to compose factors with biological and economic interpretation. The first factor grouped a larger number of variables including those which indirectly affect the final carcass characteristics, and therefore acted in the economic scope of meat production. This factor also pointed out that C_{WL} is the single factor which most compromises the economic index, since losses due to cooling interfere with the carcass weight and quality, and consequently reduce its price. For (Landim et al., 2017; 2021), an alternative to increase C_{WL} is the use of the *Rabo Largo* breed in terminal crossbreeding.

The C_{EI} inferred greater explanatory power due to the four factors extracted, in addition to having a high correlation with the A_i , which is considered an important indicator of meat production (Sabbioni et al., 2016). Therefore, if there is selection in the M_N breed for this morphological index, there will indirectly be a positive influence on the economic aspect. Considering the variables of greatest importance and association within the first factor, it is observed that it is possible to carry out sheep selection through measurements and zoometric indices, indirectly resulting in the carcass traits, which in principle would only be analyzed after slaughter.

The second factor associated characteristics which exert great influence on the productive potential of the M_N breed. It is possible to predetermine the digestive capacity and weight gain of a given animal using T_{PRI} (Nunes et al., 2020), while C_Y can be used in sheep farming in response to the relative percentage of meat to be marketed, as lambs generally have high yields and small variations between biotypes (Oliveira et al., 2018).

The factor associated with commercial characterization, which in turn is directly related to the animal's production capacity, and consequently greater body and carcass weight, has a direct influence with $LegY$, as this variable has the greatest quantitative representation of a sheep carcass (McManus et al., 2008; Trindade et al., 2018). The chest height indicates the stature of the animal, and it is recommended to raise small sheep for the *Caatinga* biome since the availability of food during the dry period of the year is mostly located in herbaceous extract (Nunes et al., 2020). In addition, animals with a compact profile and small to medium body structure should be chosen if the breeder intends to raise animals for meat production with a high capacity for weight gain (Ramos et al., 2019).

The grouping plotted on the heat map clarified the specificities for meat production of the genetic groups. $M_N F_1$ lambs presented superiority in the productive, commercial and economic aspects, while the M_{NR} lambs were balanced. Moreover, Issakowicz et al. (2016) report that the lower meat production potential for the M_{NR} breed when compared to other native sheep breeds is related to the small size of this breed group; however, morpho-productive characterizations are useful approaches to circumvent this limitation, as they identify the main characteristics related to the productive potential and use them as a selection criterion. The cluster formed by the morpho-economic and morpho-commercial factors is justified by their direct relationship between factors, while the balance was related to the morpho-productive factor, especially with emphasis on the crossbred lambs due to their greater production when compared to the purebred lambs.

The S_{MMI} suggests that sheep obtained by crossbreeding the white and red genetic groups of the M_N breed have a greater potential for meat production when compared with M_{NR} lambs, demonstrating the importance of the white genetic group participating in terminal crossbreeding. Finally, this work identified predictive morphological parameters for meat production with the creation of an aggregate index obtained from the variables with greater participation in the multivariate analysis. This index presents itself as an early and practical selection criterion for meat production in native lambs, and can be used in breeding programs for sheep and by farmers, since biometrics is a simple and easy tool to perform. It is also expected to contribute to the recovery process of the MN white breed variety, as its use has been shown to be favorable in sheep meat production.

Conclusions

$M_N V$ and $M_N F_1$ lambs present high thoracic development, compact character and aptitude for meat production. Traits such as T_{Bl} , Leg Y., C_G and rib weight were generally the most important for differentiating the genetic groups of the M_N breed. The successive adoption of multivariate techniques demonstrated greater potential for meat production for $M_N F_1$ lambs, with this crossbreeding being another alternative to increase sustainable sheep production in the Brazilian semi-arid region. It is recommended that M_{MI} be used as a tool for morpho-productive selection criteria in M_N breeding programs, as well as for other small native breeds.

Declarations

Conflict of interests

None

Declaration of animal rights

All clinical procedures and examines were approved by the Ethical Committee Use Animals from State University of Acaraú Valley (Protocol nº 002.10.020.UVA.504.02.).

Authors' contributions

Conceptualization: [Genilson Cesar Alves], [Aline Vieira Landim], [Wilder Hernando Ortiz Vega] [Hélio Henrique Araújo Costa]; Methodology: [Wilder Hernando Ortiz Vega] [Aline Vieira Landim]; Statistical analysis: [Robson Mateus Freitas Silveira], [Wilder Hernando Ortiz Vega]; Writing - preparing the original draft: [Genilson Cesar Alves]; Writing – review and editing: [Robson Mateus Freitas Silveira], [Wilder Hernando Ortiz Vega] [Aline Vieira Landim]; Supervision: [Aline Vieira Landim].

Consent to publish

The authors state that all human participants in the research provided consent for the publication of the data.

Data availability

Data will be made available on request

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Tables

Table 1

Mean and standard deviation of measurements and morphometric indices *in vivo* and in the carcass of the *Morada Nova* red breed (M_{NR}) lambs and crossbred with the white (M_NF_1)

Traits	Genetic groups		P-Value
	M _{NR}	M _{NF₁}	
Slaughter weight	26.3 ± 4.0 ^b	30.7 ± 3.9 ^a	= 0.0016
<i>Morphometry in vivo (cm)</i>			
Withers height (W _H)	58.2 ± 4.7	61.3 ± 3.0	= 0.067
Rump height (R _H)	58.4 ± 4.2 ^b	62.8 ± 3.4 ^a	= 0.013
Chest height (C _H)	28.5 ± 1.6 ^b	31.1 ± 1.7 ^a	< 0.001
Thoracic depth (T _D)	29.7 ± 3.9	30.2 ± 1.6	= 0.730
Chest width (C _W)	16.1 ± 1.2 ^b	17.5 ± 1.0 ^a	= 0.010
Body length (B _L)	64.4 ± 2.8 ^b	67.3 ± 2.9 ^a	= 0.025
Chest girth (C _G)	67.7 ± 4.2 ^b	72.5 ± 2.9 ^a	= 0.004
<i>Zoometric index</i>			
Body index (B _I)	94.7 ± 5.0	93.2 ± 2.0	= 0.399
Relative body index (R _{BI})	110.5 ± 6.0	110.2 ± 2.9	= 0.896
Thoracic perimeter relation index (T _{PR})	116.6 ± 5.1	118.1 ± 3.7	= 0.465
Anamorphosis index (A _I)	79.2 ± 5.9 ^b	85.9 ± 4.7 ^a	= 0.012
Body capacity index "1" (B _{CI} "1")	0.41 ± 0.05	0.45 ± 0.04	= 0.052
Body capacity index "2" (B _{CI} "2")	0.38 ± 0.04	0.42 ± 0.03	= 0.052
Withers-rump relation index (W-R _{RI})	0.99 ± 0.02	0.97 ± 0.03	= 0.112
Body side index (B _{SI})	90.7 ± 5.1	90.78 ± 2.4	= 0.982
Thoracic body index (T _{BI})	56.1 ± 2.2 ^a	52.4 ± 2.1 ^b	= 0.002
<i>Morphometric (cm) and Carcass e index</i>			
Carcass external length (C _{EL})	53.0 ± 2.9	53.1 ± 3.6	= 0.921
Carcass chest girth (C _{CG})	62.5 ± 4.1 ^b	67.0 ± 2.9 ^a	= 0.013
Leg length (L _L)	27.6 ± 2.4	30.3 ± 3.7	= 0.072
Leg girth (L _G)	33.0 ± 2.2	34.0 ± 3.6	= 0.473

Arm length (A_L)	23.4 ± 2.1^b	26.0 ± 2.7^a	= 0.031
Arm girth (A_G)	18.5 ± 1.7	17.3 ± 3.2	= 0.315
Carcass internal length (C_{IL})	42.5 ± 3.9	42.1 ± 6.5	= 0.854
Carcass internal width (C_{IW})	17.4 ± 2.4^b	19.3 ± 1.3^a	= 0.046
Arm compactness index (A_{CI})	0.043 ± 0.0	0.044 ± 0.0	= 0.806
Leg compactness index (L_{CI})	0.071 ± 0.01	0.076 ± 0.01	= 0.358
Carcass compactness index (C_{CI})	0.30 ± 0.05^b	0.36 ± 0.07^a	= 0.045
Carcass economic index (C_{EI})	18.8 ± 0.51	19.3 ± 0.59	= 0.066

^{ab} Different letters in the same columns indicate significant differences by the Tukey test ($P < 0.05$).

Table 2.

Mean and standard deviation of productive and physical-chemical characteristics of the carcass, commercial cuts and yields of cuts in the *Morada Nova* red breed lambs (M_{NR}) and crossbred with the white ($M_N F_1$)

Variables	Genetic groups		P-Valor
	M _N R	M _N F ₁	
Age at slaughter (days) [‡]	111.8 ± 4.2	113.4 ± 6.0	0.500
Shrunk body weight (kg) [‡]	26.3 ± 4.3b	31.0 ± 4.3a	0.028
<i>Productive and physicochemical of carcass</i>			
Hot carcass weight (H _{CW} ; kg) [‡]	13.0 ± 2.2 b	15.6 ± 2.3 a	= 0.021
Cold carcass weight (C _{CW} ; kg) [‡]	12.9 ± 2.2	15.2 ± 2.6	= 0.052
Right half of the carcass weight (R _{HCW} ; kg) [‡]	6.1 ± 0.9 b	7.2 ± 1.1 a	= 0.031
Hot carcass yield (H _{CY} ; %) [‡]	49.6 ± 1.6	50.5 ± 1.7	= 0.231
Loin eye area (L _{EA} ; cm ²) [‡]	9.86 ± 1.3 b	11.54 ± 1.7 a	= 0.028
Subcutaneous fat thickness (S _{FT} ; mm) [‡]	1.33 ± 0.19	1.24 ± 0.34	= 0.504
Cooling weight loss (C _{WL} ; %) [‡]	7.9 ± 1.3	6.7 ± 1.2	= 0.055
pH:			
0 hour after slaughter [‡]	6.7 ± 0.18	6.9 ± 0.25	= 0.130
24 hours after slaughter [‡]	6.0 ± 0.13	6.1 ± 0.25	= 0.117
Carcass temperature			
Initial (I _T ; °C) [‡]	31.1 ± 3.2	29.2 ± 1.0	= 0.100
Final (F _T ; °C) [‡]	6.9 ± 0.6	6.3 ± 0.9	= 0.131
<i>Commercial cuts: Weight (kg)</i>			
Leg [‡]	1.94 ± 0.35	2.20 ± 0.34	= 0.116
Shoulder [‡]	1.01 ± 0.16	1.16 ± 0.25	= 0.141
Rib [‡]	0.59 ± 0.07 _b	0.72 ± 0.11 a	= 0.006
Loin [‡]	0.59 ± 0.09 b	0.71 ± 0.10 a	= 0.015
Breast [‡]	1.49 ± 0.32 b	1.83 ± 0.27 a	= 0.023
Neck [‡]	0.46 ± 0.12	0.55 ± 0.13	= 0.124

<i>Yields (%)</i>			
Leg [¥]	31.8 ± 0.97	30.6 ± 1.79	= 0.092
Shoulder [¥]	16.73 ± 2.32	16.09 ± 1.87	= 0.508
Rib [¥]	9.82 ± 1.15	10.08 ± 0.55	= 0.523
Loin [¥]	9.71 ± 0.89	9.95 ± 0.89	= 0.567
Breast [¥]	24.38 ± 2.89	25.48 ± 1.10	= 0.280
Neck [¥]	7.52 ± 1.10	7.72 ± 1.05	= 0.688
Medidas qualitativas da carcaça [⊠]			
Finish [‡]	2.50 – 0.63	2.50 – 1.00	= 0.628
Conformation [‡]	2.50 – 0.75	3.25 – 0.63	= 0.350
Perirenal fat (P _F) [‡]	2.50 – 0.63	2.50 – 0.63	= 0.999

^{¥ ab} Different letters on the same columns indicate significant differences by Tukey's test ($P < 0.05$).

[‡] Different same on the same columns indicate significant differences by Kruskal-Wallis test ($P < 0.05$).

[⊠] Resultados apresentados para esse grupo de variável é mediana – intervalo interquartil (IQR)

Table 3

Canonical discriminant analysis for carcass characteristics, morphometry and zoometric indices in *Morada Nova* red breed lambs (M_{NR}) and crossbred with the white (M_{NF1})

Group of discriminating variables	C_{CC} ¹	Classification by genetic group ² (%)		Variance Explained (%)	Lambda de Wilks ³ (<i>P</i> -value)	Main Traits ⁴
	(%)	MN _{RED}	M _N F ₁			
Body morphometry	91.3	90.9	91.7	100	0.008	C _H , C _G , C _W , R _H
Zoometric index	95.7	90.9	100.0	100	0.023	B _I , T _{PR} , A _I , T _{BI}
Evaluation of carcass and muscle	65.2	81.8	50.0	100	0.049	L _{EA} , P _F
Carcass morphometric	73.9	63.6	83.3	100	0.013	C _{GC}
Carcass index	56.5	63.6	50.0	100	0.045	C _{CI}
Performance and carcass	60.9	54.5	66.7	100	0.021	H _{CW}
Commercial cuts (kg)	65.2	72.7	58.3	100	0.022	Rib; Loin
Cut yield (%)	69.6	81.8	58.3	100	0.092	Leg Y.
Mix of variables	87.0	90.9	83.3	100	0.027	T _{BI} , Leg Y., C _G , Rib

¹ Total percentage of cases correctly classified: C_{CC} = cases correctly classified.

² Percentage of cases correctly classified by genetic group.

³ Statistic test: Canonical functions (F_{C1}) with $P < 0.05$ of Wilks' Lambda were considered significant.

⁴ Main traits of the groups: C_H = chest height; C_G = chest girth; C_W = chest width; R_H = rump height; B_I = body index; T_{PR} = thoracic perimeter relation index; A_I = anamorphosis index; T_{BI} = thoracic body index; L_{EA} = loin eye area; P_F = perirenal fat; C_{GC} = carcass chest girth; C_{CI} = carcass compactness index; H_{CW} = hot carcass weight; Leg Y. = leg yield

Table 4. Factor analysis for carcass productive characteristics, morphometry and zoometric indices in *Morada Nova* lambs.

Variables	Factors ¹				Commonality
	Morpho - Economic (1)	Morpho – Productive (2)	Morpho commercial (3)	Equilibrium (4)	
Carcass compactness index (C _{CI})	0.809	-0.252	-0.093	-0.022	0.727
Loin eye area (L _{EA})	0.789	-0.235	-0.108	0.408	0.819
Hot carcass yield (H _{CY})	0.318	0.659	0.572	0.042	0.865
Cooling weight loss (C _{WL})	-0.914	0.155	-0.280	0.037	0.940
Leg yield (Leg Y)	-0.131	0.205	0.589	-0.627	0.800
Rump height (R _H)	0.878	-0.287	0.025	-0.149	0.877
Chest height (C _H)	0.759	-0.149	0.233	0.354	0.778
Chest girth (C _G)	0.649	-0.433	-0.143	-0.458	0.839
Chest width (C _W)	0.905	0.030	-0.141	-0.096	0.849
Body index (B _I)	-0.480	-0.424	0.550	0.383	0.860
Thoracic perimeter relation index (T _{PRI})	-0.001	0.876	-0.386	0.090	0.925
Anamorphosis index (A _I)	0.771	0.494	-0.339	-0.018	0.954
Carcass economic index (C _{EI})	0.677	0.452	0.512	0.114	0.938
Partial variance. %	38.50	18.80	17.50	11.00	-
Total variance	38.50	57.30	74.80	85.90	-

¹ Factor loads in bold indicate greater participation of the variable in the respective factor.

Figures

Figure 1

Heat map of the main components for productive carcass characteristics, morphometry and zoomometric indexes in Morada Nova breed red lambs (MNR) and crossbred with the white (MNF1). Note: Positive Z-score values show a positive association between genetic groups (lines) and factors

Figure 2

Boxplot of Sheep Meat Morphometric Index (SMMI) of the Morada Nova breed red (MNR) and crossbred with the white (MNF1). Note: Means followed by different letters are statistically different by the Tukey test ($P < 0.001$).