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Predicting the chemical composition of the body and the carcass of hair sheep using body parts and carcass measurements

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ABSTRACT

Determination of the chemical composition in the body and carcass of ruminants is important for both nutritional requirement studies and the meat industry. This study aimed to develop equations to predict the body and carcass chemical composition of hair sheep using the chemical composition of body parts, carcass measurements and shrunk BW as predictors. A database containing 107 individual records for castrated male hair sheep ranging from 24 to 43 kg BW was gathered from two body composition studies. The empty body, carcass and body parts were analyzed for water, ash, fat and protein contents (%). The body parts used to estimate body and carcass composition were fore leg, hind leg and 9–11th rib section. The carcass measurements used were leg length, thoracic circumference, hind circumference, hind width, thoracic width, thoracic depth and chest width. Each model performance was evaluated using a leave-one-out cross-validation. Multiple regression analysis considering the study as a random effect revealed that body parts in association with carcass measurements were significant for predicting the chemical composition in the body of castrate male sheep. However, the use of the chemical composition of hind leg produced the best models for predicting the ash and fat contents in the empty body, whereas the water and protein contents in the empty body were better predicted when using the chemical compositions of 9–11th rib section and fore leg, respectively. Multiple regression analysis also revealed that most body parts were suitable for predicting the carcass composition, except for 9–11th rib section whose chemical composition did not produce significant prediction equations for ash and protein carcass contents. The use of the chemical composition of hind leg in association with carcass measurements produced the best models for predicting the water and fat contents in the carcass, while the ash and protein contents in the carcass were better predicted when using the chemical composition of fore leg. In conclusion, precision, accuracy and goodness-of-fit of the equations drove the selection of the chemical composition of hind leg and carcass measurements in a multivariate approach, as the most suitable predictors of the chemical composition of the body and carcass of hair sheep. However, the chemical composition of fore leg may be used as well. The developed equations could improve the accuracy of the empty body and carcass composition estimations in sheep, optimizing the estimation of nutrient requirements, as well as the carcass quality evaluation for this species.

Implications

This study showed for the first time, that combination of the chemical composition of body parts, carcass measurements and shrunk BW in a multiple regression equation, can predict the body and carcass composition (water, ash, fat and protein) of castrated male hair sheep from 24 to 43 kg BW. The developed equations may assist nutritional requirement experiments of hair sheep, reducing economic expenses in body chemical analyses. Also, these may be helpful for the sheepmeat industry to optimize carcass nutritional quality.

Introduction

The development of quick and reliable methods to determine the body and carcass chemical composition in ruminants may help to produce more accurate nutritional recommendations and to optimize the carcass quality to meet market preferences (Sahlu et al., 2004; National Research Council [NRC], 2007; Bernabéu et al., 2017). Although the direct method (i.e., chemical analysis of the body tissues) is the most reliable option for determining body and carcass composition, it is expensive, time-consuming and laborious (Fernandes et al., 2008).

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To overcome these limitations, alternative methods (e.g., linear measurements, carcass specific gravity, ultrasound and dilution techniques) have been developed for estimating body and carcass composition (Crooker et al., 1997; Resende et al., 2017). However, most of these methods have a high cost, their responses are limited to fixed experimental conditions and it has shown inconsistent repeatability (Fernandes et al., 2008; Bell et al., 2018; Moro et al., 2020).

The use of the chemical composition of body parts for predicting the body and carcass composition of ruminants was proposed for the first time by Hankins and Howe (1946), who showed that chemical composition of 9, 10 and 11th ribs section is significantly correlated with carcass composition in beef cattle. This promoted the development of further studies who showed that different body parts (e.g., neck, fore leg, ribs, loin) and carcass measurements may be accurate predictors of the body and carcass composition in large (Marcondes et al., 2012; Ribeiro and Tedeschi, 2012) and small (Fernandes et al., 2008; Lambe et al., 2009) ruminants, considering these variables as independent regressors. However, to date, no methods have yet published to predict the major chemical compounds (i.e., water, ash, fat, and protein) in the body and carcass of hair sheep, using the chemical composition of body parts and carcass measurements in a multivariate approach.

Body and carcass chemical composition are significantly associated with animal growth and BW (Marcondes et al., 2015; Almeida et al., 2016). Hence, we hypothesize that the combination of the chemical composition of different body parts, carcass measurements and shrunk BW (**SBW**) in a multiple regression equation may produce reliable predictions of the body and carcass composition in hair sheep. Therefore, the objective of this study was to develop multiple regression equations to predict the empty body and carcass chemical composition of castrated male hair sheep using the chemical composition of body parts, carcass measurements and SBW as regressors.

Material and methods

Database

A database containing 107 individual records of body and carcass chemical composition of castrated male hair sheep ranging from 24 to 43 kg BW was constructed (Table 1). This database merged data from 2 studies: Santos et al. (2016, $n = 44$) and Luz et al. (2017, $n = 63$), in which the BW of sheep ranged from 27.7 to 42.5 and 23.6 to 41.3 kg, respectively. The studies were conducted at the small ruminant facilities of the Universidade Federal Rural da Amazônia (Parauapebas Campus, PA, Brazil). The lambs received diets with different proportions of roughage:concentrate: 40:60 (Luz et al., 2017) and 50:50 (Santos et al., 2016). Metabolizable energy (Mcal/kg DM) and CP (g/kg DM) of the diets ranged from 2.20 to 3.07 and from 165.1 to 175.3, respectively.

Slaughter procedures, carcass measurements and chemical analyses

Animals in both studies were subjected to similar slaughter procedures. They had a fasting period of 16 h before slaughter to measure the SBW. At slaughter, the animals were first stunned with a non-penetrating dart gun following by severing the jugular vein and carotid artery. Blood and organs were collected and weighed. The digestive tract was weighed and then emptied and flushed with water. The empty BW (**EBW**) was calculated as the difference between SBW and the weight of the contents of the digestive tract, bladder and biliary vesicle. The carcass was immediately stored in a cold room at 4 °C. After 24 h of refrigeration, the following measurements were made on the carcass, according to Yáñez et al. (2004) recommendations: leg length (LegL, cm): the distance between the greater trochanter of the femur and the edge of the tarsus-metatarsal joint; thoracic circumference (ThorC, cm): the perimeter based on the lower part of the chest and withers, passing the Tailor's measurement tape behind the shoulder; hind circumference (HindC, cm): the perimeter around the croup, based on the greater trochanters of the femurs; hind width (HindW, cm): the distance between the greater trochanters of the femurs; thoracic width (ThorW, cm): the maximum chest width, using the middle rib portion as a base; thoracic depth (ThorD, cm): the distance between the chest and the withers and chest width (ChestW, cm): the distance between the lateral faces of the scapulohumeral joints. The cooled carcass was weighed and divided in half longitudinally with a band saw (CAF Máquinas, Rio Claro-SP, Brazil).

In the left half-carcass, the 9–11th rib section was removed, through the cross section from the 9th to 11th rib at the point corresponding to 61.5% of the distance between the sectioned vertebra and the beginning of the cartilage of the 12th rib (Hankins and Howe, 1946). The fore leg was also removed: cut under the scapula, separated from the chest by muscle insertion; and hind leg: separated from the lumbosacral joint, using the protocol followed by Fernandes et al. (2008). To determine the body composition of the animals, half of the empty body was weighed, ground, sampled and frozen at −20 °C for further chemical analysis. Half of the empty body comprised the right half-carcass, all organs, viscera, legs, head, skin and blood. Body parts were processed as follows: each cut was frozen at −20 °C and then ground and homogenized. Samples were collected and frozen at −20 °C until chemical analysis. Finally, the empty body, carcass and body parts were analyzed for moisture (Association of Official Analytical Chemists [**AOAC**], 1990, method 934.01), protein (AOAC, 1990, method 920.87), fat (AOAC, 1990, method 920.85) and ash (AOAC, 1990, method 924.05).

Table 1
Summary statistics of the variables used to build the equations for predicting the empty body and carcass chemical composition of hair sheep.

Item	Mean	SD	Minimum	Maximum
Feedlot				
Shrunk BW (SBW), kg	29.34	4.95	15.10	40.20
BW, kg	32.86	3.52	23.60	42.50
Empty BW (EBW), kg	23.66	4.66	10.04	33.39
Carcass weight, kg	12.57	2.65	4.59	18.01
Carcass measurements, cm				
Leg length (LegL)	41.33	3.89	19.00	48.00
Thoracic circumference (ThorC)	66.06	4.17	52.10	72.80
Hind circumference (HindC)	53.66	5.32	37.00	73.50
Hind width (HindW)	15.26	1.88	11.60	24.20
Thoracic width (ThorW)	18.52	2.74	12.10	28.50
Thoracic depth (ThorD)	25.26	2.20	19.20	30.70
Chest width (ChestW)	15.08	1.86	9.80	25.20
Chemical composition, %				
Empty body				
Water	63.32	5.19	53.54	75.47
Ash	4.37	0.75	2.72	7.20
Fat	14.59	4.73	3.33	24.73
Protein	17.73	1.97	13.88	22.98
Carcass				
Water	65.56	4.50	56.75	88.96
Ash	4.41	1.52	2.26	16.79
Fat	10.97	4.58	1.01	20.48
Protein	19.26	2.67	8.78	24.76
9th–11th rib section				
Water	52.71	6.46	35.29	67.61
Ash	6.26	1.53	3.31	12.26
Fat	19.56	5.93	4.49	32.13
Protein	21.87	3.36	16.42	30.91
Fore leg				
Water	65.46	5.95	49.86	79.51
Ash	4.92	2.06	1.74	19.01
Fat	12.82	3.00	3.50	20.32
Protein	17.99	2.39	13.18	22.59
Hind leg				
Water	65.66	5.39	53.30	79.27
Ash	4.47	1.24	1.51	8.67
Fat	11.65	3.65	1.77	19.90
Protein	18.32	2.46	12.97	24.75

Statistical analysis

Statistical analyses were performed using SAS (SAS Institute Inc., Cary, NC, 2017; version 9.4). Descriptive statistics were obtained with PROC MEANS. Backward elimination multiple regression analysis (Hair et al., 2013) was conducted to develop equations for predicting water, ash, fat and protein contents in the body (i.e., expressed as a percentage of the total EBW) and carcass (i.e., expressed as a percentage of the total carcass weight) using the PROC MIXED. The prediction variables tested included the chemical composition (i.e., water, ash, fat and CP, expressed as a percentage) of the body parts (i.e., fore leg, hind leg and 9-11th rib section), carcass measurements (i.e., LegL, ThorC, HindC, HindW, ThorW, ThorD and ChestW) and SBW. An additional multiple regression analysis was developed to build prediction equations for body and carcass chemical composition only considering carcass measurements as potential regressors. In all statistical analyses, a predictor variable was included in the model when significant ($P \leq 0.10$). A meta-analytic approach for developing the models was used, including the study and residual error as random effects. Outliers and influence values were removed when studentized residuals were $> | 3.0 |$ and Cook's distances were > 0.1, respectively. Besides, the regressors included in the equations were tested for multicollinearity using the variance inflation factor (**VIF**).

The corrected Akaike's information criterion (**AIC$_c$**) was used to select the most reliable mathematical models, in which a smaller value represents a better goodness-of-fit of the equation. Adequacy of the models (i.e., precision and accuracy) was evaluated calculating the R^2 and the RMSE (Tedeschi, 2006). The precision was assessed by the evaluation of the R^2 of the linear regression of Y (i.e. observed) on X (i.e. predicted) (Fonseca et al., 2016). The accuracy was evaluated as the square root of the error variance of the model (i.e., RMSE; Oldick et al., 1999). Models with high and low precision were assumed when $R^2 \geq 0.50$ and $R^2 \leq 0.30$, respectively. Smaller RMSE showed a better accuracy of the model.

Predictive performance of the models was assessed using a leave-one-out cross-validation. Briefly, from the complete data set, one animal was selected and model parameters were estimated with data of the remaining $n - 1$ animals. The values of the empty body and carcass chemical composition were predicted for the selected animal by this regression function. Predicted and observed values were compared using the Model Evaluation System (MES v.3.2.2, http://nutritionmodels.com/mes.html) to measure the precision and accuracy of the models (Tedeschi et al., 2006) by assessing the RMSE of prediction (**RMSEP**) and the concordance correlation coefficient (**CCC**).

Results

Using the chemical composition of body parts (i.e., fore leg, hind leg and 9–11th rib section), carcass measurements (i.e., LegL, ThorC, HindC, HindW, ThorW, ThorD and ChestW) and SBW as independent variables, we fitted equations for predicting the empty body (Table 2) and carcass (Table 3) chemical composition of castrated male hair sheep. Regressors included in the equations showed no collinearity confirmed by VIF values that ranged from 1.00 to 3.48 and were lower than 10, as suggested by Schabenberger and Pierce (2002).

Body composition

The majority of equations showed good accuracy, but precision varied across predictions of the chemical composition components (i.e., water, fat, ash or protein). In general, the use of the chemical composition of all body parts tested provided reliable equations for estimating body composition. However, we mentioned below the equations with the best goodness-of-fit for predicting empty body composition. The multiple regression analysis showed that the most suitable equation for predicting the water contents (EB_{water}; Eq. [9]; $AIC_c = 405.6$; RMSE = 2.05%; Table 2) in the empty body of castrated male sheep included the water content in the 9–11th rib section (HH_{water}), ThorC and ChestW as significant variables ($P < 0.01$). This model showed high precision ($R^2 = 0.812$) for predicting EB_{water}. The best equation for predicting the ash contents in the empty body (EB_{ash}; Eq. [6]; $AIC_c = 141.7$; RMSE = 0.51%; Table 2) included the ash contents in the hind leg (HL_{ash}) and ChestW as significant predictor variables ($P < 0.05$). This equation showed low precision ($R^2 = 0.247$).

The best prediction equation for the fat contents in the empty body (EB_{fat}; Eq. [7]; $AIC_c = 395.1$; RMSE = 2.21%; Table 2) included the fat contents in the hind leg (HL_{fat}), ThorC and ChestW as significant predictor variables ($P < 0.01$). This equation showed high precision ($R^2 = 0.727$). Finally, the best equation for predicting the protein contents in the body ($EB_{protein}$; Eq. [4]; $AIC_c = 260.4$; RMSE = 0.89%; Table 2) used the protein contents in the fore leg ($FL_{protein}$), ThorW and SBW as significant predictor variables ($P < 0.01$). This equation showed high precision ($R^2 = 0.804$). Predictive performances (i.e., accuracy and precision) reasonably good were observed for EB_{water}, EB_{fat} and $EB_{protein}$ models (i.e., low RMSEP and CCC values close to 1), irrespective of body part considered (Table 2). Conversely, EB_{ash} prediction models showed high accuracy but low precision (i.e., both low RMSEP and CCC; Table 2).

Carcass composition

Using the same statistical approach for predicting the body chemical composition, we developed equations for estimating the carcass chemical composition in hair sheep (Table 3). The use of the chemical composition of hind leg and fore leg provided equations with reasonable precision and accuracy for estimating all chemical components in the carcass. Conversely, the 9–11th rib section was only able to predict water and fat components in the carcass. Therefore, we mentioned below the equations with the best goodness-of-fit for predicting carcass composition.

The statistical analysis revealed that the most reliable equation for predicting the water contents in the carcass (C_{water}; Eq. [17]; $AIC_c = 460.9$; RMSE = 2.7%), included the water contents in the hind leg (HL_{water}), HindW and ThorD as significant variables ($P < 0.10$). This equation showed moderate precision ($R^2 = 0.375$) for predicting C_{water}. In addition, the most adequate equation for predicting the ash contents in the carcass (C_{ash}; Eq. [14]; $AIC_c = 219.4$; RMSE = 0.72%) included the ash contents in the fore leg (FL_{ash}) as significant predictor ($P < 0.01$). However, this equation showed low precision ($R^2 = 0.247$).

The best equation for estimating the fat contents in the carcass (C_{fat}; Eq. [19]; $AIC_c = 451.8$; RMSE = 2.67%) included the HL_{fat}, ThorD and SBW as significant predictor variables ($P < 0.10$). This equation showed a high precision ($R^2 = 0.650$) for predicting C_{fat}. Finally, the most suitable equation for predicting the protein contents in the carcass ($C_{protein}$; Eq. [16]; $AIC_c = 387.7$; RMSE = 1.56%) included the $FL_{protein}$ as a significant predictor ($P < 0.01$) and this showed a high precision ($R^2 = 0.640$). After predictive performance evaluation of the carcass chemical composition models, in general, the precision and accuracy were reasonably good for all chemical components, except for C_{water} and C_{ash} predictions whose CCC was less than or equal to 0.5 irrespective of the body part used (Table 3).

Use of carcass measurements as predictors of the empty body and carcass chemical composition

In an independent multiple regression analysis, we built equations for estimating the body and carcass chemical composition of castrated male sheep, only testing carcass measurements as potential predictors (Table 4). Regarding body chemical composition, the equation built for predicting EB_{water} (Eq. [23]; $AIC_c = 435.5$; RMSE = 2.36%) included the ThorC as a significant variable ($P < 0.05$).

Table 2
Regression equations to predict the empty body composition[1] of hair sheep using the body part[2] composition,[3] carcass measurements[4] and shrunk BW (SBW) as regressors.

Variables	No.	Equations[5]	VIFs 1	VIFs 2	VIFs 3	VIFs 4	n	Statistics AIC_c	R^2	RMSE	Cross-validation RMSEP	CCC
Fore leg (FL), %												
Water	[1]	$EB_{water} = 52.592\ (8.318^{*}) + 0.557\ (\pm 0.0802^{***}) \times FL_{water} - 0.322\ (\pm 0.0749^{***}) \times ThorC - 0.307\ (\pm 0.143^{**}) \times HindW$	1.39	1.58	1.53		96	431.7	0.801	2.138	2.206	0.876
Ash	[2]	$EB_{ash} = 4.113\ (\pm 0.688^{*}) + 0.138\ (\pm 0.0562^{**}) \times FL_{ash} + 0.124\ (\pm 0.0356^{***}) \times HindW - 0.0443\ (\pm 0.0225^{*}) \times ThorW - 0.0544\ (\pm 0.0146^{***}) \times SBW$	1.12	1.39	1.09	1.33	87	163.6	0.321	0.534	0.569	0.396
Fat	[3]	$EB_{fat} = 0.922\ (\pm 0.103^{***}) \times FL_{fat} - 0.124\ (\pm 0.071^{*}) \times ThorC + 0.220 (\pm 0.086^{**}) \times HindC$	1.74	3.48	2.95		93	449.4	0.682	2.443	2.513	0.780
Protein	[4]	$EB_{protein} = 17.008\ (\pm 2.172^{*}) + 0.306\ (\pm 0.0869^{***}) \times FL_{protein} - 0.140\ (\pm 0.041^{***}) \times ThorW - 0.0784\ (\pm 0.0223^{***}) \times SBW$	1.01	1.06	1.06		92	260.4	0.804	0.887	0.910	0.879
Hind leg (HL), %												
Water	[5]	$EB_{water} = 67.268\ (\pm 8.176^{*}) + 0.367\ (\pm 0.0717^{***}) \times HL_{water} - 0.330\ (\pm 0.0783^{***}) \times ThorC - 0.438\ (\pm 0.188^{**}) \times ChestW$	1.21	1.38	1.32		93	423.4	0.789	2.185	2.236	0.869
Ash	[6]	$EB_{ash} = 4.255\ (\pm 0.545^{*}) + 0.220\ (\pm 0.0443^{***}) \times HL_{ash} - 0.0700\ (\pm 0.0347^{**}) \times ChestW$	1.01	1.01			87	141.7	0.247	0.509	0.516	0.356
Fat	[7]	$EB_{fat} = -25.982\ (\pm 4.470^{*}) + 0.5086\ (\pm 0.104^{***}) \times HL_{fat} + 0.353\ (\pm 0.0857^{***}) \times ThorC + 0.774\ (\pm 0.197^{***}) \times ChestW$	1.79	2.09	1.35		87	395.1	0.727	2.211	2.278	0.822
Protein	[8]	$EB_{protein} = 19.532\ (\pm 2.094^{*}) + 0.190\ (\pm 0.0815^{**}) \times HL_{protein} - 0.187\ (\pm 0.0415^{***}) \times ThorW - 0.0660\ (\pm 0.0230^{***}) \times SBW$	1.03	1.08	1.07		94	274.8	0.788	0.931	0.955	0.868
9th to 11th rib section (HH), %												
Water	[9]	$EB_{water} = 80.151\ (\pm 6.385^{**}) + 0.229\ (\pm 0.0398^{***}) \times HH_{water} - 0.318\ (\pm 0.0729^{***}) \times ThorC - 0.561\ (\pm 0.184^{***}) \times ChestW$	1.29	1.64	1.31		91	405.6	0.812	2.049	2.116	0.883
Ash	[10]	$EB_{ash} = 5.350\ (\pm 0.841^{*}) - 0.0236\ (\pm 0.0138^{*}) \times HindC + 0.111\ (\pm 0.0378^{***}) \times HindW - 0.103\ (\pm 0.0461^{**}) \times ChestW$	1.26	1.19	1.15		91	180.7	0.212	0.575	0.587	0.276
Fat	[11]	$EB_{fat} = 0.525\ (\pm 0.0442^{***}) \times HH_{fat} + 0.331\ (\pm 0.0606^{***}) \times ChestW$	1.25	1.25			89	409.4	0.740	2.242	2.298	0.823
Protein	[12]	$EB_{protein} = 22.926\ (\pm 1.930^{*}) - 0.182\ (\pm 0.0417^{***}) \times ThorW - 0.0666\ (\pm 0.0234^{***}) \times SBW$	1.06	1.06			93	272.1	0.781	0.938	0.958	0.866

VIFs = variance inflation factors; AIC_c = corrected Akaike's information criterion; RMSEP = RMSE of prediction; CCC = Concordance correlation coefficient.
[1] Empty body composition: EB_{water} = empty body water (%); EB_{ash} = empty body ash (%); EB_{fat} = empty body fat (%); $EB_{protein}$ = empty body protein (%).
[2] Body parts: FL = Fore leg; HL = Hind leg; HH = 9th to 11th rib section.
[3] FL_{water} = water content in the FL (%); FL_{ash} = ash content in the FL (%); FL_{fat} = fat content in the FL (%); $FL_{protein}$ = protein content in the FL (%); HL_{water} = water content in the HL (%); HL_{ash} = ash content in the HL (%); HL_{fat} = fat content in the HL (%); $HL_{protein}$ = protein content in the HL (%); HH_{water} = water content in the HH (%); HH_{fat} = fat content in the HH (%).
[4] Carcass measurements: ThorC = thoracic circumference (cm); HindC = hind circumference (cm); HindW = hind width (cm); ThorW = thoracic width (cm); ChestW = chest width (cm).
[5] Values within parentheses are Standard Error of the parameter estimate; $^{*}P < 0.10$, $^{**}P < 0.05$, and $^{***}P < 0.01$. Intercepts that were not different from 0 were removed from the final equation.

This model showed high precision ($R^2 = 0.739$). Conversely, the equation fitted for EB_{ash} (Eq. [24]; $AIC_c = 204.6$; RMSE = 0.64%) showed a low precision ($R^2 = 0.248$). This included HindW, ThorW and ChestW as significant variables ($P < 0.05$). In addition, the equation developed for EB_{fat} (Eq. [25]; $AIC_c = 460.4$; RMSE = 2.71%) included ThorC and HindC as significant variables ($P < 0.05$) and this showed good precision ($R^2 = 0.560$). Similarly, the equation built for $EB_{protein}$ (Eq. [26]; $AIC_c = 280.7$; RMSE = 0.95%) showed a high

Table 3
Regression equations to predict the carcass composition[1] of hair sheep using the body part[2] composition,[3] carcass measurements[4] and shrunk BW (SBW) as regressors.

Variables	No.	Equations[5]	VIFs 1	VIFs 2	VIFs 3	n	Statistics AIC_c	R^2	RMSE	Cross-validation RMSEP	CCC
Fore leg (FL), %											
Water	[13]	$C_{water} = 0.484\ (0.109^{***}).\ FL_{water} - 0.281\ (0.0755^{***}) \times SBW$	1.35	1.35		99	482.8	0.497	2.596	2.606	0.500
Ash	[14]	$C_{ash} = 3.048\ (0.296^{*}) + 0.256\ (0.0589^{***}) \times FL_{ash}$				96	219.4	0.247	0.721	0.761	0.310
Fat	[15]	$C_{fat} = -0.173\ (0.103^{*}) \times ThorW + 0.279\ (0.122^{**}) \times ThorD + 0.261\ (0.0837^{***}) \times SBW$	1.03	1.14	1.18	91	468.2	0.621	2.853	2.905	0.742
Protein	[16]	$C_{protein} = 1.079\ (0.0101^{***}) \times FL_{protein}$				101	387.7	0.640	1.561	1.625	0.782
Hind leg (HL), %											
Water	[17]	$C_{water} = 52.994\ (8.415^{*}) + 0.389\ (0.0816^{***}) \times HL_{water} - 0.293\ (0.163^{*}) \times HindW - 0.365\ (0.140^{**}) \times ThorD$	1.06	1.02	1.04	93	460.9	0.375	2.714	2.767	0.495
Ash	[18]	$C_{ash} = 2.732\ (0.320^{*}) + 0.330\ (0.0696^{***}) \times HL_{ash}$				98	225.7	0.195	0.731	0.748	0.280
Fat	[19]	$C_{fat} = 0.225\ (0.105^{**}) \times HL_{fat} + 0.200\ (0.117^{*}) \times ThorD + 0.145\ (0.0860^{*}) \times SBW$	1.43	1.19	1.47	90	451.8	0.650	2.672	2.740	0.762
Protein	[20]	$C_{protein} = 1.064\ (0.00858^{***}) \times HL_{protein}$				101	389.0	0.638	1.574	1.628	0.781
9th to 11th rib section (HH), %											
Water	[21]	$C_{water} = 75.091\ (5.476^{**}) + 0.107\ (0.0522^{**}) \times HH_{water} - 0.317\ (0.150^{**}) \times ThorD - 0.267\ (0.0824^{***}) \times SBW$	1.17	1.21	1.24	93	469.3	0.303	2.855	2.957	0.394
Fat	[22]	$C_{fat} = 0.178\ (0.0676^{***}) \times HH_{fat} + 0.313\ (0.107^{***}) \times ThorD$	1.16	1.16		93	502.9	0.498	3.298	3.368	0.632

VIFs = variance inflation factors; AIC_c = corrected Akaike's information criterion; RMSEP = RMSE of prediction; CCC = Concordance correlation coefficient.
[1] Carcass composition: C_{water} = carcass water (%); C_{ash} = carcass ash (%); C_{fat} = carcass fat (%); $C_{protein}$ = carcass protein (%).
[2] Body parts: FL = Fore leg; HL = Hind leg; HH = 9th to 11th rib section.
[3] FL_{water} = water content in the FL (%); FL_{ash} = ash content in the FL (%); $FL_{protein}$ = protein content in the FL (%); HL_{water} = water content in the HL (%); HL_{ash} = ash content in the HL (%); HL_{fat} = fat content in the HL (%); $HL_{protein}$ = protein content in the HL (%); HH_{water} = water content in the HH (%); HH_{fat} = fat content in the HH (%).
[4] Carcass measurements: HindW = hind width (cm); ThorW = thoracic width (cm); ThorD = thoracic depth (cm).
[5] Values within parentheses are Standard Error of the parameter estimate; $^{*}P < 0.10$, $^{**}P < 0.05$, and $^{***}P < 0.01$. Intercepts that were not different from 0 were removed from the final equation. Multivariate regression analysis did not produce significant equations for predicting C_{ash} and $C_{protein}$ using the chemical composition of HH, CM, and SBW as regressors.

Table 4
Regression equations to predict empty body[1] and carcass[2] composition of hair sheep using carcass measurements[3] as regressors.

Variable	No.	Equations[4]	VIFs			n	Statistics			Cross-validation	
			1	2	3		AIC$_c$	R^2	RMSE	RMSEP	CCC
Empty body, %											
Water	[23]	$EB_{water} = 100.16(5.396^{**}) - 0.567(0.0653^{***}) \times ThorC$				93	435.5	0.739	2.3593	2.394	0.840
Ash	[24]	$EB_{ash} = 5.767(0.879^{*}) + 0.101(0.0406^{**}) \times HindW - 0.0543(0.0267^{**}) \times ThorW - 0.134 (0.0500^{***}) \times ChestW$	1.08	1.09	1.15	94	204.6	0.248	0.6405	0.650	0.341
Fat	[25]	$EB_{fat} = -31.894(4.966^{*}) + 0.430(0.122^{***}) \times ThorC + 0.203(0.0957^{**}) \times HindC + 0.521 (0.211^{**}) \times ChestW$	3.04	2.86	1.22	93	460.4	0.560	2.7121	2.794	0.718
Protein	[26]	$EB_{protein} = 25.755(2.165^{**}) - 0.0527 (0.0200^{***}) \times HindC - 0.182(0.0426^{***}) \times ThorW - 0.132 (0.0739^{*}) \times ChestW$	1.12	1.09	1.17	94	280.7	0.790	0.9542	0.976	0.870
Carcass, %											
Water	[27]	$C_{water} = 75.141 (3.546^{**}) - 0.698(0.234^{***}) \times HindW$				92	478.7	0.090	3.2379	3.315	0.102
Fat	[28]	$C_{fat} = -0.308(0.127^{**}) \times ThorW + 0.405(0.113^{***}) \times ThorD + 0.492(0.188^{***}) \times ChestW$	1.21	1.00	1.21	94	498.7	0.543	3.1381	3.191	0.674

VIFs = variance inflation factors; AIC$_c$ = corrected Akaike's information criterion; RMSEP = RMSE of prediction; CCC = Concordance correlation coefficient.
$^{*}P < 0.10$.
$^{**}P < 0.05$, and $^{***}P < 0.01$ (. Intercepts that were not different from 0 were removed from the final equation. Multivariate regression analysis did not produce significant equations for predicting C_{ash} and $C_{protein}$ using the chemical composition of carcass measurements as regressors.
[1] Empty body composition: EB_{water} = empty body water (%); EB_{ash} = empty body ash (%); EB_{fat} = empty body fat (%); $EB_{protein}$ = empty body protein (%).
[2] Carcass composition: C_{water} = carcass water (%); C_{fat} = carcass fat (%).
[3] Carcass measurements: ThorC = thoracic circumference (cm); HindC = hind circumference (cm); HindW = hind width (cm); ThorW = thoracic width (cm); ThorD = thoracic depth (cm); ChestW = chest width (cm).
[4] Values within parentheses are SE of the parameter estimate.

precision ($R^2 = 0.790$). This included the HindC, ThorW and ChestW as significant variables ($P < 0.10$).

Statistical analysis revealed a non-significant association between carcass measurements and C_{ash} as well as between carcass measurements and $C_{protein}$ contents (i.e., multivariate regression analysis did not detect carcass measurement significant predictors). Hence, we did not build equations for these carcass chemical contents only using carcass measurements as predictors. Conversely, we built equations for C_{water} and C_{fat} (Table 4). The equation built for C_{water} (Eq. [27]; AIC$_c$ = 478.7; RMSE = 3.24%) included HindW as a predictor variable ($P < 0.01$), and this showed very low precision ($R^2 = 0.090$). Conversely, the model built for C_{fat} (Eq. [28]; AIC$_c$ = 498.7; RMSE = 3.14%) showed good precision ($R^2 = 0.543$). This included ThorW, ThorD and ChestW as predictor variables ($P < 0.01$).

Predictive performance evaluation revealed that empty body chemical composition models produced predictions with good accuracy and precision (i.e., low RMSEP and CCC close to 1), except for EB_{ash}, whose prediction model showed low precision (CCC = 0.341; Table 4). Regarding carcass chemical composition models, the predictive performance evaluation showed that the model for C_{fat} produced predictions with reasonable accuracy and precision (RMSEP = 3.19; CCC = 0.674), while the models for C_{water} produced predictions with reasonable accuracy (RMSEP = 3.31) but low precision (CCC = 0.102; Table 4).

Discussion

We observed that the combination of the chemical composition of body parts, carcass measurements and SBW in a multiple regression equation may produce reliable predictions for the body and carcass chemical composition in castrated male hair sheep ranging from 24 to 43 kg BW. The development of prediction equations for calculating the chemical composition of live animals has a significant value to determine maturity and nutrient requirements in small ruminant production systems (Almeida et al., 2016; Teixeira et al., 2017). As we know, the current equations to determine the body chemical composition of small ruminants only include the chemical composition of body parts and BW (Fernandes et al., 2008) as regressors, without considering the potential use of carcass measurements. However, combining the chemical composition of body parts with carcass measurements and SBW may increase the precision and accuracy of body composition predictions, considering that as the animal grows, its body composition (Almeida et al., 2016) and body parts sizes (Castilhos et al., 2018) change.

All body parts (fore leg, hind leg and 9–11th rib section) in association with carcass measurements and SBW yielded equations with reasonable precision and accuracy for estimating the body composition (%) of water, ash, fat and protein. Hence, irrespective of body parts used, reliable predictions of body chemical composition may be produced. However, after selecting the most suitable equations under AIC$_c$ criterion, we observed a positive relationship between HH_{water} and EB_{water}, while there was a negative association between ThorC and EB_{water}, as well as between ChestW and EB_{water} (Eq. [9]). Conversely, HL_{fat}, ThorC and ChestW were positively associated with EB_{fat} (Eq. [7]). These results make biological sense, considering that there is a negative association between body water and fat (Souza et al., 2017), and body fat deposition in tissues increases with the increasing of the age and growth rate of the animal (Almeida et al., 2016; Castilhos et al., 2018). Also, these are in accordance with Fernandes et al. (2008) who showed in goats, that HH_{water} and HL_{fat} are precisely predictors of EB_{water} and EB_{fat}, respectively.

With the advancing of the age, the animal grows and the deposition of body protein and minerals reaches a plateau (Moulton, 1923). This agrees with our results because we found a positive association between $FL_{protein}$ and $EB_{protein}$, whereas both ThorW and SBW were negatively associated with $EB_{protein}$ (Eq. [4]). Similarly, with fact that HL_{ash} and EB_{ash} were positively associated, while ChestW and EB_{ash} were negatively associated (Eq. [6]).

In addition, we observed that irrespective of the body part used, prediction equations for $EB_{protein}$ showed a noticeable precision and accuracy, even superior to proposed by other studies with small ruminants and that used data set with a shorter number of observations (Fernandes et al., 2008). This may be because we gathered data from two studies and we used a mixed model approach to determine the best prediction equations (St-Pierre, 2001). Also, because of body protein is a chemical component with low variation compared to other body major constituents (Marcondes et al., 2015; Almeida et al., 2016).

It was noteworthy that in contrast to other chemical body constituents (water, fat and protein), all the equations developed for predicting the EB_{ash} showed low R^2, accounting up to 32% of the EB_{ash} variation. This agrees with several studies that suggest that EB_{ash} is the body chemical component with the largest variation (Lanna et al., 1995; Fernandes et al., 2008; Marcondes et al., 2015; Almeida et al., 2016). It is known that approximately 80 to 85% of the body's mineral material is located in the bones (Suttle, 2010). Therefore, EB_{ash} is directly related to the growth rate of skeletal tissues (Almeida et al., 2016). However, skeletal growth may be affected by several factors such as sex steroids, identified as activators of bone cell replication and differentiation (McCarthy et al., 2000).

Predictive performance analysis revealed that the combination of body parts, carcass measurements and SBW produced prediction models for the EB_{water}, EB_{fat} and $EB_{protein}$ of castrated male hair sheep with good precision (i.e., CCC close to 1) and accuracy (i.e., low RMSEP). Conversely, irrespective of body part used, EB_{ash} prediction showed low precision (i.e., CCC < 0.40) and good accuracy (i.e., RMSEP < 0.60). This is in accordance with the typical high natural variability of the mineral body content in ruminants (Marcondes et al., 2015; Almeida et al., 2016).

Nowadays, there is an increasing consumer demand for more information on carcass composition to support their decision-making while shopping meat (Moro et al., 2020). Particularly in the sheepmeat industry, labelling carcasses with nutrient composition information is challenging. Hence, the development of novel methods for estimating carcass composition is desirable. The 9–11th rib section has been widely used for predicting carcass chemical composition in ruminants (Hankins and Howe, 1946; Lanna et al., 1995; Fernandes et al., 2008; Marcondes et al., 2012). Similarly, carcass measurements have been shown as suitable predictors of carcass composition in cattle (De Paula et al., 2013; Fonseca et al., 2016; Castilhos et al., 2018). However, to date, equations involving the chemical composition of 9–11th rib section, carcass measurements and SBW as predictors have not been developed. We found that the chemical composition of 9–11th rib section, carcass measurements and SBW was unable for predicting C_{ash} and $C_{protein}$. However, we adjusted equations with reasonable precision and accuracy to predict C_{water} and C_{fat} using these variables.

After the evaluation of Eq. [21], we found a positive relationship between HH_{water} and C_{water}. Conversely, there was a negative relationship between ThorD and C_{water}, as well as between SBW and C_{water}. This makes biological sense, considering that the C_{water} decreases with the increase of SBW and age (Marcondes et al., 2015). Also, these results are in line with findings reported by Fernandes et al. (2008), who showed that the HH_{water} is an accurate predictor for C_{water} in goats.

The aforementioned findings suggest that HH_{water} in association with ThorD and SBW is good predictors of C_{water}. However, after model evaluation, we found that C_{water} can be better predicted (i.e., lower AIC_c and RMSE, and greater R^2) by Eq. [17] than for Eq. [21]. The Eq. [17] revealed that HL_{water} has a positive relationship with C_{water}. Conversely, both HindW and ThorD had a negative relationship with C_{water}. Hence, HL_{water} in association with carcass measurements produces better estimations of C_{water} than those derived from HH_{water}, carcass measurements and SBW as predictors.

As stated in Eq. [22], both HH_{fat} and ThorD had a significant and positive relationship with C_{fat}, predicting it with reasonable precision and accuracy. However, after model evaluation, we found that Eq. [19] showed the lowest AIC_c and also it was more precise and accurate than Eq. [22] for predicting C_{fat}. The estimators of Eq. [19] revealed that HL_{fat}, ThorD and SBW were positively associated with C_{fat}; however, the contribution size of each predictor was different. Thus, when comparing two animals with the same SBW and different ThorD, the animal with the greatest ThorD will have the highest C_{fat}. Information regarding the multivariate relationship between C_{fat}, the chemical composition of body parts, carcass measurements and SBW is valuable for the meat industry, considering that C_{fat} is an important indicator of the feed efficiency in finishing ruminants (Castilhos et al., 2018).

Using the FL_{ash} and $FL_{protein}$ as predictors, it was possible to build equations for estimating the C_{ash} (Eq. [14]) and $C_{protein}$ (Eq. [16]), respectively, with good accuracy. However, the precision of C_{ash} was low, while the one for $C_{protein}$ was high. The slopes of Eq. [14] and (Eq. [16]) were positive, suggesting a positive relationship between FL_{ash} and C_{ash}, as well as between $FL_{protein}$ and $C_{protein}$. Similarly, HL_{ash} and $HL_{protein}$ were significant predictors of C_{ash} (Eq. [18]) and $C_{protein}$ (Eq. [20]), respectively. These results agree with that reported by Fernandes et al. (2008), who showed a significant association between HL_{ash} and C_{ash} with moderate precision ($R^2 = 0.55$) in goats. However, Fernandes et al. (2008) did not report any association between FL_{ash} and C_{ash}, between $FL_{protein}$ and $C_{protein}$ or between $HL_{protein}$ and $C_{protein}$. Hence, our data suggested that in contrast to goats, FL_{ash} and $FL_{protein}$ are suitable predictors for estimating C_{ash} and $C_{protein}$, respectively, in hair sheep. This may be due to mineral and protein dynamics in the body differ between sheep and goats (Wilkens et al., 2014; Härter et al., 2016). Predictive performance analysis revealed that the models obtained to predict C_{fat} and $C_{protein}$ were much more precise and accurate than those built to predict C_{water} and C_{ash}. This suggests that the developed models herein could be useful as a decision tool for determining the ideal slaughter time to reach optimal fat and protein carcass levels, seeking to cater to consumer demands.

Non-invasive methods have been preferred for determining the body and carcass chemical composition due to practicality (Castilhos et al., 2018; Moro et al., 2020). Similarly, carcass measurements have been shown as satisfactory predictors of major chemical components of body and carcass in cattle (Fonseca et al., 2016). However, no methods have yet been proposed to predict major chemical components in the body and carcass of hair sheep only using carcass measurements as predictors.

We showed that carcass measurements can predict EB_{water} (Eq. [23]; $R^2 = 0.739$), EB_{fat} (Eq. [25]; $R^2 = 0.560$) and $EB_{protein}$ (Eq. [26]; $R^2 = 0.790$) with good precision. However, they predicted EB_{ash} (Eq. [24]; $R^2 = 0.248$) with low precision. This agrees with the fact that body ash shows a larger variation than those found for other body constituents (Marcondes et al., 2015). Regarding carcass composition, our data revealed that carcass measurements were not significant predictors for C_{ash} and $C_{protein}$ in castrated male hair sheep. Also, they showed very low precision for predicting C_{water} (Eq. [27]; $R^2 = 0.090$). In contrast, carcass measurements were reasonable predictors of C_{fat} (Eq. [28]; $R^2 = 0.543$). This makes biological sense, considering that the fat percentage in the body is an appropriate variable to describe growth tissue and maturity in small ruminants in contrast to body ash, which showed a lack of significance for predicting animal growth (Almeida et al., 2016).

Predictive performance analysis of the models obtained to calculate the empty body and carcass chemical composition only using carcass measurements as regressors revealed that EB_{water}, EB_{fat}, $EB_{protein}$ and C_{fat} can be predicted with good precision (i.e., CCC > 0.7) and accuracy (i.e., RMSEP < 3.1) using this novel approach. This suggests that the models proposed herein may be used as a useful, rapid and non-invasive option for EB_{water}, EB_{fat}, $EB_{protein}$ and C_{fat} determination in castrated male hair sheep from 24 to 43 kg BW.

In conclusion, the hypothesis of the present study is accepted because we verified that the chemical composition of body parts in association with carcass measurements and SBW may produce reliable prediction equations for the body and carcass chemical composition in castrated male hair sheep. The precision, accuracy and goodness-of-fit of the equations developed drive the selection of hind leg and fore leg as the best body parts. However, from an economic standpoint, the commercial value of body parts may also support the decision-making by prioritizing the body parts with the lowest cost, in which, hind leg may be the best option. Our data also showed that the carcass measurements are significant predictors of water, ash, fat and protein in the body. Nonetheless, carcass measurements without considering the chemical composition of body parts can predict fat content in the carcass with good precision. This information may be useful for reducing economic expenses in nutrition requirement studies, and carcass evaluation programmes due to the determination of carcass measurements is quick, easy, and cheap. A limitation of this study is that empty body, carcass and body part chemical compositions in the models were not related to animals' maturity due to lack of a current definition of mature weight in castrated male Santa Ines sheep. This condition suggests that findings and equations reported herein only can be applied to body composition studies or carcass evaluations of castrated male Santa Ines sheep from 24 to 43 kg BW. Hence, further studies in a wider range of breeds and sexes, as well as considering the degree of maturity of the animals could give us a better understanding of the multivariate relationship among the body and carcass chemical composition, chemical composition of body parts, carcass measurements and SBW in hair sheep.

Ethics approval

All experiments used in this study followed the humane animal care and handling procedures of the university's Animal Care Committee of the Universidade Federal Rural da Amazônia, under protocols: 04/2013 and 03/2014.

Data and model availability statement

None of the data were deposited in an official repository.

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Declaration of interest

None.

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