

Prediction of lean meat proportion of lamb carcasses

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SUMMARY

The objectives of this study were to identify a reduced pertinent set of variables from an original set of 18 carcass measurements and the development of linear regression models to predict lean meat yield of lamb carcasses. Forty-six male lambs, 26 of Churro Galego Bragançano Portuguese local breed and 20 of Suffolk breed were used. Lambs were slaughtered and carcasses were weighed approximately 30 min after slaughter in order to obtain hot carcass weight (HCW). After cooling at 4°C for 24-h a set of 17 carcass measurements were recorded. The data interrelationships were analysed following the common factor analysis procedure. HCW was lowly correlated with leg length ($r = 0.17$) and moderately correlated with measurements that characterize carcass lengths and perimeters ($r = -0.39$ to 0.56). Four common factors (factor I = HCW; factor II = breast bone thickness; factor III = subcutaneous fat thickness; and factor IV = carcass conformation) were retained, accounting for 81.9% of the variation in the 18 original variables. This study shows that common factors analysis can be used to condense the information given by large sets of variables, by selecting a reduced number of variables, which avoids collinearity problems and simplifies the development of carcass composition estimation models.

Key words: lambs, carcass, tissue, measurements, common factors

INTRODUCTION

Since Pálsson (1939) pioneering studies with carcass and tissues measurements, many studies were conducted to develop models in order to predict carcasses composition through the use of carcass weight, carcass dimensions (Wood et al., 1980; Stanford et al., 1997; Wolf et al., 2006), subcutaneous fat thickness (Wood and MacFie, 1980; Jones et al., 1992; Teixeira et al., 2006; Wolf et al., 2006), *longissimus* muscle depth (Jones et al., 1992; Delfa et al., 1996; Teixeira et al., 2006; Wolf et al., 2006) and total tissues thickness measurements (Kirton et al., 1984; Delfa et al., 1996), as independent variables. Most models were developed by multiple linear regression procedures where collinearity among the independent variables was not evaluated. However, collinearity problems among the independent variables should be expected, as these are both genetically and phenotypically correlated (Simm and Dingwall, 1989), and it is known that models based on

multicollinear variables can limit inferences and the accuracy of predictions (Chatterjee et al., 2000). In fact, the use of collinear variables as independent variables does not improve the models precision, and creates instability in the regression coefficients estimation (Shahin and Hassan, 2000). When a large set of potential independent variables is available, the first step in the data analysis should be their description and interpretation in order to evaluate if a subset of these variables can be used to replace the entire original set. The common factor analysis has been used as a tool to understand what the data are measuring and to detect multicollinearity problems in data on buffalos (Shahin et al., 1993), rabbits (Shahin and Hassan, 2000) and ducks (Shahin, 1999). The objectives of this study were to identify a reduced number of variables from a large set of variables of HCW, carcass dimension, and tissues measurements, to be used as independent variables in order to avoid collinearity and simplify the development of multiple linear regression models to predict lean meat yield of lamb carcasses.

MATERIAL AND METHODS

Animals

Forty-six male lambs of the Churra Galega Bragançana (CGB; n = 26) and Suffolk (SUF; n = 20) breed, selected in order to cover the usual carcass weight range of lambs slaughtered in Portugal. The lambs were randomly selected from the experimental flock of the Escola Superior Agrária de Bragança. Lambs were raised with the mothers in natural suckling until slaughter, and had access to pasture, natural meadow hay, and to commercial concentrate mixture and mineral-vitamin supplementation.

Slaughter procedure and carcass measurements

Lambs were slaughtered after 24-h fast in the experimental slaughterhouse at the Escola Superior Agrária de Bragança, and carcasses were weighted proximately 30 min after slaughter in order to obtain the HCW according to Fisher & Boer (1994). After chilling at 4°C for 24-h, carcasses were suspended on a gamble with 21-cm distance between legs. The following carcass measurements were taken: 1) carcass length (K, mm) measured from the base of the tail to the base of the neck (Pálsson, 1939); 2) leg length (F, mm), representing the smallest distance from the perineum to the interior face of the tarsal-metatarsal articular surface (Pálsson, 1939); 3) buttocks width (G, mm) measured using the calliper at the level of the proximal edge of the patellae (Fisher and Boer, 1994); 4) thorax circumference (U, mm) measured using a tape held horizontally around the thorax at the level of the caudal portion of the scapula; and, 5) buttock circumference (CB, mm) was measured using a tape held horizontally around the buttocks at the level of the caudal insertion (Fisher and Boer, 1994).

Carcass quartering and joints dissection

Carcasses were halved through the centre of the vertebral column, and the kidney knob and channel fat (KKCF) was removed and weighed. During carcasses quartering, the *longissimus* muscle (LM) depth and subcutaneous fat thickness were taken with a calliper on maximum depth of the LM depth between the 12th and 13th ribs (B12 and C12, respectively), 1st and 2nd lumbar vertebrae (B1 and C1, respectively), and 3rd and 4th lumbar vertebrae (B3 and C3, respectively). Additionally LM area (cm²) between the 12th and 13th ribs (LEA12), 1st and 2nd lumbar vertebrae (LEA1), and 3rd and 4th lumbar vertebrae (LEA3) was traced on acetate sheet and LM area was measured using a digital planimeter (model KP-90; Koizumi Placom, Niigata, Japan). Lastly, total breast bone thickness (mm) was taken with a sharpened steel rule at the middle of the 2nd (BT2), 3rd (BT3) and 4th (BT4) sternebrae. Each joint was then dissected into muscle, subcutaneous fat, intermuscular fat, bone, and remainder (major blood vessels, ligaments, tendons, and thick connective tissue sheets associated with muscles). The carcass lean meat yield was evaluated as the dissected muscle weight (kg) and muscle proportion (g kg⁻¹).

Statistical analysis

Data were analyzed using the SAS (2001) software. Summary statistics were computed by the MEANS procedure, and PROC FACTOR procedure was used to perform a principal components common factor analysis and the factors retained were those with eigenvalue higher than one (Krzanowski, 1990). Models to predict lean meat weight (kg) and proportion (g kg⁻¹) were developed using the PROC REG procedures, by stepwise regression with a 5% significance level for independent variables to enter and to be removed from the models. Model 1 was developed using as independent variables the entire set of original variables (OV). Model 2 was developed using the retained common factors (CF). Models fitting quality was evaluated via the coefficient of determination R² and the root mean square error (RMSE; Montgomery, 1997). The models may be written as follows:

$$\text{Model 1: } y_{ijk} = \beta_0 + \sum_{i=1}^{18} \sum_{j=1}^{18} \beta_{ij} OV_{ij} + e_{ijk}$$

$$\text{Model 2: } y_{ijk} = \beta_0 + \sum_{i=1}^4 \sum_{j=1}^4 \beta_{ij} CF_{ij} + e_{ijk}$$

Where:

y_{ijk} = lean meat proportion; β_0 = intercept; β_{ij} = regression coefficient; OV = original variables; CF = common factors extracted from the reduced set of variables.

The normality of the residuals was evaluated using the Shapiro-Wilk test. The residuals were subjected to analysis of variance in order to evaluate if the models were breed biased.

RESULTS AND DISCUSSION

General results

Table 1 shows the mean, CV, minimum and maximum for the HCW, carcass dimension, tissues thickness, and area measurements. The HCW had a CV around 17%, and the carcass dimension measurements (F, K, G, U and CB) had the lowest CV (from 5.7 to 8.1%). In buffalos, Shahin et al. (1993) reported CV of 5% in the carcass dimension measurements that reflect bone lengths, and 14% in measurements that reflect the development of muscle and fat tissues (carcass widths). Similar results have been presented by Anous (1986) in a study with several sheep breeds explored in France. Subcutaneous fat thickness measurements (C12, C1 and C3) had the highest CV (> 44.5%) of all the measurements recorded. These results are in agreement with the high variability observed in the carcass fat tissues (Teixeira et al., 1996; Teixeira et al., 2005). Afonso and Thompson (1996) also observed that subcutaneous fat area measurements, obtained by computer tomography, grow faster than BW. Breast bone thickness (BT2, BT3, and BT4) measurements had CV values greater than that observed for HCW, but lower than that observed in subcutaneous fat thickness measurements. These measurements have a magnitude higher (from 5.9 to 13.6 times) than the subcutaneous fat thickness measurements; therefore, breast bone thickness measurements would present smaller errors, especially in light carcasses that have little subcutaneous fat. The CV observed for LM depth (B12, B1, and B3) and area (LEA12, LEA1, and LEA3) and lean weight (varying from 12.1 to 19.3%) were similar to that observed for HCW.

Table 1. Mean, CV, minimum and maximum for hot carcass weight (HCW), carcass dimensions and tissue measurements

	Mean	CV	Minimum	Maximum
HCW, kg	12.2	16.7	8.0	15.0
Carcass measurements, mm				
F - Leg length	272.9	7.7	230.0	310.0
K - Carcass length	723.9	8.1	613.0	820.0
G - Buttocks width	208.9	6.0	183.0	230.0
U - Thorax circumference	618.5	5.7	550.0	675.0
CB - Buttocks circumference	545.5	5.9	474.0	605.0
Subcutaneous fat thickness, mm				
C12 - 12 th /13 th rib	1.3	44.5	0.4	2.5
C1 - 1 st /2 nd lumbar vertebrae	1.2	57.1	0.4	3.2
C3 - 3 rd /4 th lumbar vertebrae	2.1	64.0	0.3	5.4
Breast bone tissue thickness, mm				
BT2 - 2 nd sternebrae	16.4	20.8	7.8	24.3

BT3 - 3 rd sternebrae	14.7	23.7	8.0	23.6
BT4 - 4 th sternebrae	12.9	25.8	5.7	20.7
LM depth, mm				
B12 - 12 th /13 th rib	24.9	15.7	17.3	32.7
B1 - 1 st /2 nd lumbar vertebrae	26.6	15.4	19.8	35.0
B3 - 3 rd /4 th lumbar vertebrae	24.0	12.1	17.5	32.6
LEA area, cm ²				
LEA12 - 12 th /13 th rib	10.5	19.3	6.4	14.6
LEA1 - 1 st /2 nd lumbar vertebrae	10.7	18.1	6.7	14.9
LEA3 - 3 rd /4 th lumbar vertebrae	10.4	15.9	6.7	14.2
Lean meat weight, kg	6.9	17.8	4.4	9.0
Lean meat proportion, g kg ⁻¹	638.6	4.6	595.5	694.9

Variables interrelationships

Linear correlations among HCW, carcass dimensions, and tissue measurements are shown in Table 2. The HCW had high and positive correlations coefficients ($r > 0.74$) with the measurements that characterize carcass widths (G) and perimeters (U and CB). However, HCW was lowly correlated with leg length (F; $r = 0.17$), and moderately correlated with carcass length (K; $r = 0.56$). It was interesting to note the very low correlation ($r = 0.04$) between carcass length (K) and buttocks width (G). These results show that the increase in carcass length (F and K measurements) is less dependent on the increase in HCW than on the carcass width (G) and perimeter (U and CB) measurements. Results of the current study are in agreement with those of Bocard et al. (1964), who stated that, in early ages, body weight is more related to the growth of the body width dimensions (tissue accretion) than to bone elongation. Subcutaneous fat thickness measurements were lowly correlated with HCW ($r = 0.03$ to 0.14), and highly correlated ($r = 0.67$ to 0.75) among themselves. In a study using lambs from several breeds, Safari et al. (2001) also reported that HCW and subcutaneous fat thickness measurements were lowly correlated which reflected the diversity in the degree of maturity in lambs from different breeds slaughtered at equal carcass weight. At equal carcass weight, lambs with large differences in the mature body weight, as the two breeds used in this study, will present differences in the development of the adipose tissue (Taylor et al., 1989; Rodrigues et al., 2006). Breast bone thickness measurements were highly and positively correlated among themselves ($r > 0.81$), and moderately correlated with HCW ($r = 0.49$ to 0.57). Similarly, subcutaneous fat thickness and breast bone thickness measurements had low to high positive correlations. Collinearity can be evaluated by analysing the linear correlations between all pairs of variables. Clearly, these results suggest collinearity problems between HCW and carcass width (G) and perimeter (U and CB) measurements, which are in agreement with the findings in sheep (Bocard et al., 1964) and buffalo (Shahin et al., 1993). However, the interpretation of the 166 linear correlations is a problematic work and does not provide a complete picture of all data interrelationships.

Table 2. Correlations among hot carcass weight (HCW), carcass dimensions, and tissues measurements

Variables ^b	HCW	F	K	G	U	CB	B12	B1	B3	LEA12	LEA1	LEA3	C12	C1	C3	BT2	BT3
F	0.17																
K	0.56	0.79															
G	0.74	-0.39	0.04														
U	0.91	0.42	0.70	0.55													
CB	0.91	0.09	0.46	0.73	0.80												
B12	0.52	-0.21	-0.04	0.50	0.38	0.54											
B1	0.62	-0.27	0.10	0.71	0.49	0.57	0.64										
B3	0.51	-0.18	0.14	0.53	0.41	0.52	0.60	0.66									
LEA12	0.59	-0.43	-0.10	0.69	0.34	0.60	0.67	0.61	0.55								
LEA1	0.75	-0.16	0.23	0.65	0.59	0.75	0.57	0.65	0.58	0.75							
LEA3	0.59	-0.03	0.17	0.49	0.42	0.61	0.26	0.43	0.37	0.49	0.56						
C12	0.12	0.32	0.29	-0.13	0.18	0.24	-0.31	-0.27	-0.23	-0.10	-0.05	0.26					
C1	0.03	0.21	0.05	-0.11	-0.00	0.11	-0.25	-0.35	-0.17	0.02	-0.14	0.27	0.75				
C3	0.14	0.47	0.35	-0.21	0.21	0.20	-0.06	-0.27	-0.13	-0.07	-0.10	0.10	0.67	0.68			
BT2	0.57	0.41	0.61	0.12	0.55	0.46	0.19	0.18	0.19	0.30	0.33	0.39	0.39	0.38	0.54		
BT3	0.46	0.46	0.58	0.02	0.46	0.29	0.11	0.13	0.13	0.19	0.22	0.31	0.29	0.37	0.51	0.90	
BT4	0.49	0.49	0.57	0.11	0.51	0.40	0.19	0.10	0.10	0.24	0.21	0.21	0.30	0.44	0.55	0.81	0.89

^aCoefficient of linear correlation for null hypothesis $|r| = 0$, $P < 0.05$ if $|r| > 0.374$;

^bLook Table 1 for variables definitions.

Table 3. Factor pattern, after varimax rotation, communalities, unique factor, eigen values, variance explained and description of the four common factors retained by the mineigen criterion through the factor analysis on the original variables

Variables ^a	Rotated common factors				Communalities	Unique factor
	I	II	III	IV		
HCW	0.84	0.25	0.08	0.43	0.947	0.053
F	-0.30	0.38	0.13	0.80	0.883	0.117
K	0.13	0.39	0.05	0.87	0.924	0.076
G	0.88	-0.13	-0.02	-0.02	0.798	0.202
U	0.64	0.24	0.05	0.66	0.902	0.098
CB	0.86	0.12	0.22	0.34	0.911	0.089
B12	0.68	0.26	-0.36	-0.18	0.686	0.314
B1	0.80	0.04	-0.34	0.03	0.759	0.241
B3	0.69	0.13	-0.27	-0.04	0.574	0.426
LEA12	0.82	0.22	-0.02	-0.37	0.861	0.139
LEA1	0.86	0.09	-0.05	0.08	0.761	0.239
LEA3	0.67	0.06	0.40	0.05	0.618	0.382
C12	-0.05	0.14	0.89	0.20	0.862	0.138
C1	-0.09	0.34	0.86	-0.13	0.885	0.115
C3	-0.12	0.55	0.62	0.16	0.725	0.275
BT2	0.28	0.81	0.25	0.27	0.867	0.133
BT3	0.14	0.90	0.15	0.24	0.902	0.098
BT4	0.17	0.87	0.19	0.25	0.882	0.118
Eigen Values	7.16	4.63	1.78	1.18	-	-
Variation, %	35.14	17.98	14.47	14.32	-	-

^aLook Table 1 for variables definitions.

Common factor analysis

Common factors pattern (after varimax rotation), communalities, unique factor, eigen values, variance explained, and description of the four common factors retained by the mineigen criterion through the common factor analysis on the original variables are displayed in Table 3. The contribution of the original variables to each factor can be evaluated by its loading (variable-factor correlation) on each one of the extracted common factors. Common factor analysis was able to identify four common factors which accounted for 81.9% of the variation on the 18 original variables.

Factor I was characterized by high, positive loadings in the HCW ($r = 0.84$), carcass dimension measurements ($r = 0.64$ to 0.88), and LM depth and area measurements ($r = 0.67$ to 0.86). This factor accounted for 35.1% of the variation in the 18 original variables and was identified as HCW. Factor II accounted for an additional 18% variation in the original variables, and showed high and positive loadings ($r = 0.81$ to 0.90) in breast bone thickness measurements, and was identified as breast bone thickness. Factor III was identified as subcutaneous fat thickness. Lastly, factor IV accounted for 14.3% of the variability in the 18 original variables. It was identified as carcass length

due to its high and positive loadings on carcass ($r = 0.87$) and leg ($r = 0.80$) length measurements.

Communality indicates how much of the variation in the original variables was captured in the factors retained (Krzanowski, 1990). Mathematically, they are the sum of the squared loadings for the retained factors. The four extracted common factors explained 57.4 to 94.7% of variation among the variables. Communalities were particularly high for HCW (0.95) and for carcass dimensions measurements (from 0.80 to 0.93). Subcutaneous fat thickness and breast bone thickness measurements had communalities ranging from 0.73 to 0.90, whereas the lowest communalities were observed for LM area and depth measurements, with variations among anatomical locations. Higher communalities on carcass dimension measurements were also observed in buffalos (Shahin et al., 1993), indicating that variability in carcass dimension measurements can be accounted for by their interrelationships.

Variables with high loadings on the same factor are redundant, since they do not add any information to each other when used as independent variables in multiple linear regression models. Moreover, the inclusion of collinear variables as independent variables in multiple linear regression models can give rise to collinearity problems. Clearly, results from common factors analysis identify four sets of collinear variables: 1) the set formed by HCW, carcass dimension (G, U, CB) and LM area (LEA12, LEA1, and LEA3), and depth (B12, B1, and B3) measurements; 2) the set of breast bone thickness (BT2, BT3, and BT4) measurements; 3) the set of subcutaneous fat thickness (C12, C1, and C3) measurements; and 4) the set formed by carcass length (K) and leg length (F) measurements.

Prediction of lean meat

Multiple regression equations for predicting carcasses lean meat weight (kg) and proportion (g kg^{-1}) using the entire set of original variables (Model 1) are presented in Table 4. HCW accounted for 94.3% of the lean meat weight with a RMSE of 0.412 kg. The model admitted also the LEA1, and accounted for 95.4% of the variance with a RMSE of 0.371 kg. Some collinearity problems between HCW and LEA12 were observed since the VIF were higher than 1 (2.28). In opposition, HCW only explained 1.2% of the variation in lean meat proportion with a RMSE of 29.4 g kg^{-1} (data not shown). For lean meat proportion, C3 was the first independent variable admitted in to the model, and the BT3 was also admitted. These two variables accounted for 41.3% of the lean meat proportion variation, with a RMSE of 26.9 g kg^{-1} . The residuals showed mean zero, were homocedastic, followed a normal distribution ($P > 0.05$), and were breed unbiased ($P < 0.05$) for prediction of lean meat weight and lean meat proportion. However, a trend to the underestimation in Churro Galego Bragançano and to the overestimation in Suffolk lambs was observed (Table 4).

Table 4. Multiple regression equations for predicting carcasses lean meat weight (kg) and proportion (g kg⁻¹), bias and deviation of Model 1

Step	Variable ^a	Lean meat weight, kg		Lean meat proportion, g kg ⁻¹	
		Parameter	VIF	Parameter	VIF
1	Intercept	-0.25 ± 0.269NS		665.0 ± 6.64***	
		0.58 ± 0.022***		-	
	HCW				
	C3			-12.5 ± 2.66***	
	R ²	0.943		0.334	
	RMSE	0.412		27.8	
	2	Intercept	-0.45 ± 0.253NS		698.8 ± 15.35***
0.51 ± 0.030***			2.3		
HCW					
LEA1		0.10 ± 0.031**	2.3		
C3				-8.0 ± 3.14*	1.5
BT3				-2.9 ± 1.21*	1.5
R ²		0.954		0.413	
RMSE		0.371		26.9	

	Bias	Deviation	Bias	Deviation
Model	0.00±0.041	0.23±0.022	0.0±3.54	19.6 ±1.98
CGB	-0.03±0.055	0.22±0.030	-4.2±4.66	18.7±2.66
SUF	0.04±0.062	0.24±0.034	5.5±5.31	20.9±3.03

^aLook Table 1 for variables definitions;
VIF = variance inflation factor

Multiple regression equations for predicting carcasses lean meat weight (kg) and proportion (g kg⁻¹) using the retained common factors (Model 2) are shown in Table 5. Factor I was the first admitted in the model and accounted for 74.5% of the variability of carcass lean weight. This result is as expected since HCW presents a high loading (0.84) on this Factor. The model also admitted the factors II and IV, and the fitting quality was improved as can be observed by the improvement in the variance explained by 19.6 percentage units and by the reduction on the RMSE of 49%. For the prediction of lean meat proportion, the Factor II was the first entering in the model and accounted for 29.5% of the observed variation with a RMSE of 2.8%. Factor III was also admitted in the model improving model fitting quality, as observed by the increase of 7.3 percentage units in the R², and by the 2.5% reduction in the RMSE. In spite of the low coefficient of determination (36.8%), the RMSE was low (2.75%). The residuals showed mean zero, were homocedastic, followed a normal distribution (P > 0.05), and were breed unbiased (P < 0.05) for prediction of lean meat

weight and lean meat proportion. However, a trend to the underestimation in CGB and to the overestimation in Suffolk lambs can be observed (Table 5).

Several authors observed that multiple regression models developed to predict lean meat weights are dominated by live weight (Sehested, 1986; Teixeira et al., 2006) or carcass weight (Wood and MacFie, 1980; Delfa et al., 1996) as in this study for Model 1. Nevertheless, HCW was not admitted as independent variable for the prediction of lean meat proportion, and subcutaneous fat and breast bone measurements dominate the models. The smaller R^2 observed in models to predict the lean meat proportion are due to the smaller variation (Fortin and Sherestha, 1986; Silva, 2001) observed in lean meat proportion (CV = 4.6%) when compared to variation observed in lean meat weight (CV = 17.8%). These results confirm those of Garret et al. (1992) considering that carcass weight present small contribution to the explanation of carcasses lean meat proportion. The reduction in lean meat proportion due to increase of carcasses fatness is well documented (Simm, 1987; Jones et al., 1996), and fat tissue depths are good indicators for carcass degree of fatness, being good predictors of carcass lean meat proportion as shown by these results.

It is important to notice that carcass dimensions measurements were not admitted in Model 1, for the prediction of both lean meat weight and lean meat proportion. These results confirm the lack of relationship between carcasses conformation and composition (Kempster et al., 1986; Laville et al., 2002), being measurements that reflect skeleton dimension rather than carcass muscle and fat indicators (Laville et al., 2002). Despite the lower fitting quality, it is worthwhile to point that Model 2 showed greater stability on the estimation of the regression coefficients, since the introduction of new factors did not induce great changes in the regression coefficients of the factor already present in the model. The lower standard errors of the regression coefficients need also to be taken into account.

CONCLUSIONS

Common factor analysis is an efficient technique to understand the interrelationships among variables in large data sets, and to identify problems of collinearity. The results presented in this work show that the models to predict lean meat of lamb carcasses can be based on simple models using as independent variables the HCW, subcutaneous fat and breast bone tissues thickness. If a large set of variables is available, the transformation by common factors analysis can be an efficient procedure to avoid collinearity among predictors and to develop more stable models.

REFERENCES

- Afonso, J. and Thompson, J. M. (1996). Fat distribution in sheep selected for/against backfat depth, during growth on ad libitum feeding. *Livestock Production Science*, 46, 97–106.
- Anous, M. R. (1986). Interrelations entre les principaux composants anatomiques, conformation et longueur des os du gigot des ovins. *Annales de Zootechnie*, 32, 185–200.
- Boccard, R., Dumont, B. L. and Peyron, C. (1964). Etude de la production de la viande chez les ovins. VIII - Relations entre les dimensions de la carcasse d'agneau. *Annales de Zootechnie*, 13, 367–378.
- Chatterjee, S., Hadi, A. S. and Price, B. (2000). *Regression analysis by example*. John Willey & Sons, Inc., New York.
- Delfa, R., Gonzalez, C., & Teixeira, A. (1996). Use of cold carcass weight and fat depth measurements to predict carcass composition of rasa aragonesa lambs. *Small Ruminant Research*, 20, 267–274.
- Fisher, A. V. and Boer, H. (1994). The EAAP standard method of sheep carcass assessment. carcass measurements and dissection procedures. Report of the EAAP working group on carcass evaluation, in cooperation with the CIHEAM Instituto Agronomico Mediterraneo of Zaragoza and the CEC Directorate General for Agriculture in Brussels. *Livestock Production Science*, 38, 149–159.
- Fortin, A. and Sherestha, J. N. B. (1986). In vivo estimation of carcass meat by ultrasound in ram lambs slaughtered at an live weight of 37 kg. *Animal Production*, 43, 469–475.
- Garret, R. P., Savell, J. W., Edwards, J. W. and Tatum, J. D. (1992). Evaluation of the hennessy grading probe to predict yields of lamb carcasses fabricated to multiple end points. *Journal of Animal Science*, 70, 1146–1152.
- Jones, S. D. M., Jeremiah, L. E., Tong, A. K. W., Robertson, W. M. and Gibson, L. L. (1992). Estimation of lamb carcass composition using an electronic probe, a visual scoring system and carcass measurements. *Canadian Journal of Animal Science*, 72, 237–244.
- Jones, S. D. M., Robertson, W. M., Price, M. A. and Coupland, T. (1996). Prediction of saleable meat yield in lamb carcasses. *Canadian Journal of Animal Science*, 76, 49–53.
- Kempster, S. J., Jones, D. W. and Wolf, B. T. (1986). A comparison of alternative methods for predicting the carcass composition of crossbred lambs of different breeds and crosses. *Meat Science*, 18, 89–110.
- Kirton, A. H., Woods, E. G. and Duganzich, D. M. (1984). Predicting the fatness of lamb carcasses from carcass wall thickness measured by ruler or by total depth indicator probe. *Livestock Production Science*, 11, 185–194.
- Krzanowski, W. J. (1990). *Principles of multivariate analysis. A user's perspective*. Oxford science publications, Oxford.

- Laville, E., Bouix, J., Sayd, T., Eychenne, F., Marcq, F., Leroy, P. L., Elsen, J. M., & Bibe, B. (2002). La conformation bouchère des agneaux. Étude et la variabilité génétique entre races. *INRA Productions Animales*, 15, 53–66.
- Montgomery, D. C. (1997). *Design and analysis of experiments*. John Wiley & Sons, New York, fourth edition.
- Pálsson, A. (1939). Meat qualities in the sheep with special reference to Scottish a breeds and crosses. *Journal of Agricultural Science (Camb.)*, 29, 544–626.
- Rodrigues, S., Cadavez, V., & Teixeira, A. (2006). Breed and maturity effects on Churra Galega Bragançana and Suffolk lamb carcass characteristics: Killing out proportion and composition. *Meat Science*, 72, 288–293.
- Safari, E. D., Hopkins, D. L., & Fogarty, N. M. (2001). Diverse lamb genotypes. 4. Predicting the yield of saleable meat and high value trimmed cuts from carcass measurements. *Meat Science*, 58, 207–214.
- SAS (2001). *SAS/STAT user's guide*. SAS Institute, Inc., Cary, NC.
- Sehested, E. (1986). In-vivo prediction of lamb carcass composition by computer tomography. Master's thesis, Agricultural University of Norway.
- Shahin, K. A. (1999). Sources of shared variability in muscle and fat weight distribution in Pekin ducklings. *Annales de Zootechnie*, 48, 59–66.
- Shahin, K. A. and Hassan, N. S. (2000). Sources of shared variability among body shape characters at marketing age in New Zealand white and Egyptian rabbit breeds. *Annales de Zootechnie*, 49, 435–455.
- Shahin, K. A., Soliman, A. M., & Moukhtar, A. E. (1993). Sources of shared variability for the Egyptian buffalo body shape (conformation). *Livestock Production Science*, 36, 323–334.
- Silva, S. J. C. R. (2001). *Composição das carcaças e dos depósitos internos de gordura de ovelhas de raça Churra da Terra Quente*. PhD thesis, Universidade de Trás-os-Montes e Alto Douro, Vila Real, Portugal.
- Simm, G. (1987). Carcass evaluation in sheep breeding programmes. In: *New techniques in sheep production*. pp. 125–144. Butterworths, London.
- Simm, G. and Dingwall, W. S. (1989). Selection indices for lean meat production in sheep. *Livestock Production Science*, 21, 223–233.
- Stanford, K. , Woloschuk, C. M., McClelland, L. A., Jones, S. D. M. and Price, M. A. (1997). Comparison of objective external carcass measurements and subjective conformation scores for prediction of lamb carcass quality. *Canadian Journal of Animal Science*, 72, 217–223.
- Taylor, S. C. S., Murray, J. I., & Thonney, M. L. (1989). Breed and sex differences among equally mature sheep and goats. 4. Carcass muscle, fat and bone. *Animal Production*, 49, 385–409.
- Teixeira, A., Delfa, R. and Treacher, T. (1996). Carcass composition and body fats depots of Galego Bragançano and crossbred lambs by Suffolk and Merino Precoce sire breeds. *Animal Science*, 63, 389–394.
- Teixeira, A. , Batista, S. , Delfa, R. and Cadavez, V. (2005). Lamb meat quality of two breeds with protected origin designation. Influence of breed, sex and live weight. *Meat Science*, 71, 530–536.

- Teixeira, A., Matos, S., Rodrigues, S., Delfa, R. and Cadavez, V. (2006) In vivo estimation of lamb carcass composition by real-time ultrasonography. *Meat Science*, 74, 289–295.
- Wolf, B. T., Jones, D. A. and Owen, M. G. (2006). In vivo prediction of carcass composition and muscularity in purebred Texel lambs. *Meat Science*, 74, 416–423.
- Wood, J. D. and MacFie, H. J. H.(1980). The significance of breed in the prediction of lamb carcass lamb carcass composition from fat thickness measurements. *Animal Production*, 31, 315–319.
- Wood, J. D., MacFie, H. J. H., Pomeroy, R. W. and Twinn, D. J. (1980). Carcass composition in four sheep breeds: The importance of type of breed and stage of maturity. *Animal Production*, 30, 135–152.