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Relationships between growth-related traits with carcass and meat quality traits in Spanish Assaf suckling lambs

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HIGHLIGHTS

- Suckling lamb carcass and meat are highly valued in mediterranean Europe markets.
- Birth weight (BW) and daily gain can be used as selection criteria for breeding.
- BW reduced leg fatness and increased forequarter proportion and meat quality.
- Low average daily gain of suckling lambs resulted in poor carcass quality.

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ABSTRACT

Suckling lamb meat is a relevant product in Mediterranean European dairy sheep farms, and the dairy breed Spanish Assaf is widely extended through the Iberian Peninsula. Knowledge of the influence of birth body weight (bBW) and growth rate on suckling lamb carcass and meat quality is scarce, but useful for breeding optimisation and product homogeneity. In turn, these growth-related traits of lambs might be affected by dietary restrictions of their dams. In this study, 34 male Assaf suckling lambs born from two groups of ewes that had been fed diets with different protein levels when they were prepubertal female lambs (17 lambs per group) were analysed. After birth, the suckling lambs were fed ad libitum on milk replacer until their sacrifice (10–12.5 kg live body weight). The quality traits evaluated in carcasses and meat were carcass compactness, fatness and jointing, meat composition, colour, texture and oxidative stability, and fatty acid profile. The dam group did not show significant effects on lamb growth characteristics or carcass and meat quality traits. The bBW factor showed a negative effect on leg subcutaneous fatness and a positive effect on the forequarter and shoulder percentages of the carcass. The bBW also resulted in increased moisture, lipid oxidation stability, and n-3 FA content (lowering the n-6/n-3 ratio) in the meat. Suckling lambs showing very low average daily gain (ADG) tended to present low carcass quality, i.e., higher bone percentage in the loin and low percentages of muscle or fat compared to those showing high ADG. Further studies are needed to confirm and explain the mechanisms of the significant effects reported here for bBW and ADG on the affected quality traits.

1. Introduction

Suckling lamb meat is typically produced on sheep farms in the European Mediterranean region (Sañudo et al., 1998). For the last three decades, Spanish Assaf (Ugarte et al., 2001), a semi-fat-tailed high-performance-level breed that originated in Israel from the cross between the fat-tailed Awassi and the Friesian East breeds, has been amongst the most abundant breeds in Spanish dairy farms. In these farms lambs are mainly reared under intensive systems, and suckling lamb meat production represents the second source of income (Milán

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et al., 2014). According to Milán et al. (2011) and De la Fuente et al. (2006), the annual crop of Assaf lambs per dam is 1.35, and the means for weight at birth, growth rate, and weight at slaughter averaged 5.3 kg, 0.26 kg/day and 10.5 kg, respectively, with the age at slaughtering between 18 and 30 days. A series of carcass and meat quality traits of Assaf suckling lambs have been previously described by several authors (Caro et al., 2018; Mateo et al., 2018; Rodríguez et al., 2008).

Birth body weight (bBW) and ADG, which are influenced by genetic factors and farming systems, are relevant growth-related traits in suckling lamb production. Low bBW has been associated with lower lamb survival during the first days of life, linked to a lower ability to maintain body temperature (Dwyer and Morgan, 2006; Telef et al., 2009). Low bBW has also been related to less efficient feed conversion, and lower growth rates in fattening lambs (Acciaro et al., 2020; Csizmar et al., 2013; Peeters et al., 1995), suggesting that bBW is connected to the time and the needed food intake to achieve the fattening lamb foreseen slaughter age. Furthermore, growth performance is a productive trait with economic relevance in lamb production. Average daily gain (ADG) is an indicator of growth performance considered as an indirect selection criterion for breeding (Cammack et al., 2005; Eskandarinasab et al., 2010). Birth body weight and ADG might be affected by differences in the feeding backgrounds of the dams. Different studies reported that dietary restrictions in replacement prepubertal female lambs can affect their growth, ruminant energy metabolism and age at puberty (Boulanouar et al., 1995; Villenueve et al., 2010). This, in turn, might exert a latter effect on the growth-related traits in offspring lambs.

Birth body weight and ADGcould affect the quality traits of lamb carcass and meat. However, to the best of our knowledge, little research has been carried out in relation to suckling lamb production systems to study the potential association of bBW and ADG with lamb carcass and lamb meat quality traits. The research works reported by Acciaro et al. (2020) and Andrés et al. (2020) are amongst the scarce studies found on the connection between bBW and lamb quality, but both focused on fattening lambs, not suckling lambs.

A better understanding of the bBW and ADG effects on the suckling lamb meat produced would contribute to improve lamb breeding practises, by allowing the achievement of more homogeneous and potentially higher quality products (Acciaro et al., 2020). Moreover, knowledge of the effects of prepubertal dam protein restriction on suckling lamb carcass and meat quality would be useful in optimising the cost of the dams' diet from a meat production perspective in dairy sheep farms. Considering the limited knowledge of the effect of the mentioned factors on traits of interest in suckling lamb production, the present study aimed to investigate the influence of a dietary restriction performed in prepubertal female Assaf lambs and bBW and growth rate of their offspring on carcass traits, meat quality and fat composition of Assaf suckling lambs.

2. Materials and methods

2.1. Animals

A total of 34 male suckling lambs born in the same lambing season (January and February 2020) and reared at the Instituto de Ganadería de Montaña (IGM) farm (León, Spain) were included in this study. The suckling lambs came from two groups of dams from a previous nutritional protein restriction experiment. The dams had been acquired from one flock located in the northwest region of Castilla y León (Spain) when they were two-month female lambs. After that, they were reared at the facilities of the Instituto de Ganadería de Montaña (IGM) in Grulleros (León, Spain). The female lambs were fed a standard diet for replacement-ewe lambs, providing 16% crude protein, until they were 3 months old. Then, female lambs were divided into two groups of similar average body weight (BW): Control (C, $n = 20$, average BW = 29.1 kg) and nutritional protein restriction (NPR, $n = 20$; average BW = 28.3 kg) groups. Hence, the C lambs received for 64 days a standard diet, whereas the NPR lambs received for the same time the same diet but without soybean meal, which meant a 44% reduction in protein intake (details on the ingredients and chemical composition of the diets provided during the dietary restriction experiment of the dams are given in Table S1). The diet of the NPR group was designed to mimic a feed restriction challenge taking place in a commercial flock due to a trade market problem and a shortage of concentrate inputs, and so, both groups had access to barley straw ad libitum. After this challenge, all the prepubertal ewes were managed in a single group and fed with the same diet until lambing according to standard commercial practices based on the animals' needs across the different physiological stages. The ewes were artificially inseminated at 10 months of age.

After birth, the new-born lambs were weighed and kept with their dams for 4 to 8 h to suck the colostrum. From the 34 male lambs studied in this work, 17 belonged to the C dam group and the other 17 lambs belonged to the NPR dam group. These lambs were randomly selected from each group by birth rank (single or twin), so 14 were single-born lambs (7 from C and 7 from NPR groups), and 20 were twins (10 from C and 10 from NPR groups). Then, the lambs were held in lamb pens and fed with milk replacer (Ovilac 60; Calfvet®) ad libitum until slaughter and weighed 24 h before slaughter. Lambs were slaughtered one day per week once they reached a body weight into the range between 10 and 12.5 kg and at a maximum age of 35 days, which are the limits established for a regional suckling lamb quality label (ITACYL, 2019). The management, transport, and sacrifice of the animals were in accordance with Spanish and EU legislation [Spanish Laws 32/2007, 6/2013 and RD 37/2014; Council Regulation (EC) 199/2009].

2.2. Plan of the experiment

The experiment consisted of determining and registering a number of selected production pre-mortem traits in the lambs included in the study, namely bBW, litter size, and growth rate (estimated as ADG). Moreover, after the slaughter of the studied suckling lambs, carcass compactness, fatness and jointing; meat composition, colour, texture and oxidative stability; and fatty acid profile were determined. The effects of dam group (C vs NPR), bBW, litter size (single or twin), and ADG on the carcass and meat quality traits were individually investigated.

2.3. Determination of carcass and meat quality and fatty acid composition

At 24 h post-mortem, lamb carcasses were split into two halves at the slaughterhouse, and the right halves were weighed, transported to the lab, and used for quality analysis. The half-carcass internal length (L), pelvic limb (leg) length (F), and chest depth (Th) were determined and the ratio half carcass weight/L (g/cm) as carcass compactness index was calculated (Miguélez et al., 2006), and each half carcass was divided into forequarter and hindquarter at the level of the 5th rib, which were separately weighed. Afterwards, the thymus, kidney, perirenal fat, testicles, epiploic fat, and tail were removed, and the perirenal fat and each half carcass thus prepared were weighed. The half carcasses were then jointed according to Colomer-Rocher et al. (1988) and Campo et al. (2016). Five suckling lamb carcass commercial cuts, namely loin (composed of the shoulder-ribs and loin plus rack), leg, shoulder, breast (including the breast and flank) and neck were ths obtained. The cuts were weighed and leg weight/F (expressed as g/cm) was calculated to obtain the leg compactness (Velasco et al., 2000).

In order to assess the effects of the lamb-growth related variables on the carcass main-tissue composition, the leg and the loin, were selected as sample cuts to be dissected (Barton and Kirton, 1958). Only a part of the whole loin was used to facilitate the dissection process, while intending to achieve a reasonable representativeness of the whole loin. Thus, two 3-vertebrae loin portions, one from the lumbar and the other from thoracic (rib) region (supplementary Figure S1), were subsampled by cutting the loin transversally from the 1st to the 3rd lumbar vertebrae

Table 1
Premortem characteristics of all male Assaf suckling lambs used ($n = 34$) and the lambs separated by dam group, C ($n = 17$) and NPR ($n = 17$), and litter size, singles ($n = 14$) and twins ($n = 20$).

	All M±SD	Range	C M±SD	NPR M±SD	p-level	Singles M±SD	Twins M±SD	p-level
bBW (kg)	4.58±1.02	2.9–6.6	4.65±1.07	4.51±1.00	0.692	5.19±1.10	4.16±0.72	0.020
ADG (kg/day)	0.28±0.05	0.18–0.37	0.28±0.04	0.27±0.05	0.394	0.27±0.05	0.28±0.05	0.404
sAge (day)	24.9 ± 5.5	16–35	23.71±4.87	26.00±5.51	0.208	23.2 ± 5.6	26.00±4.8	0.130
sBW (kg)	11.2 ± 0.8	10.0–12.5	11.21±0.74	11.22±0.84	0.979	11.16±0.71	11.25±0.82	0.761
BWG (kg)	6.6 ± 0.9	4.8–8.1	6.56±0.89	6.71±0.95	0.641	6.0 ± 0.9	7.1 ± 0.6	<0.001

C: Ewes fed a standard diet from the three months of age to lambing; NPR: Dams fed a protein restricted diet from three to five months of age and then a standard diet until lambing.
M±SD: Mean±standard deviation.

and from the 8th to the 10th thoracic vertebrae. The mean weight of the lumbar portions obtained was 117 g and that of the thoracic portions 85 g, with the mean weight of the whole loin being 693 g. Before the dissection of the two loin portions, one hour after the lumbar portion was cut, meat colour was measured in duplicate on both cut surfaces of the longissimus lumborum (LL) muscle, using a CM-700d spectrophotometer (Konica Minolta Sensing Inc., Osaka, Japan) operating with a D65 illuminant in SCI mode, an 11-mm aperture for illumination, an 8-mm aperture for measurement, and a 10° visual angle. Dissection of the leg and the loin portions was carried out following the procedure described by Fisher and De Boer (1994) to obtain, and then weigh, the following tissues: lean, fat (subcutaneous, intermuscular and pelvic), bone and the mix of other tissues (or remainders; tendons, lymph nodes, large nerves etc.). Each tissue weight was converted into percentage of the sum of tissue weights.

Afterwards, the longissimus thoracis (LT) muscle section was obtained from the loin at the level of the 3rd to the 8th thoracic vertebrae. The meat pH was determined, at 24 h post-mortem with a puncture electrode (CRISON GLP22, Alella, Barcelona, Spain) by puncturing the electrode in the centre of both the above-mentioned LT muscle section and the adductor muscle in the leg. The LT muscle section was frozen until analysis; then it was thawed and homogenised, and aliquots were sampled to determine moisture and intramuscular fat content in duplicated samples (Association of Official Analytical Chemists; AOAC, 1999). Analyses were also performed in duplicate to determine the fatty acid (FA) profile of intramuscular fat. The protocol described by Manso et al. (2011), with some modifications (the split ratio was 10:1, and the internal standard was not used), was applied to a 1 g muscle aliquot (after lyophilisation).

The LL muscle section obtained from the last 3rd–4th lumbar vertebrae was used to measure cooking losses and Warner–Bratzler shear force (WBSF) following the reference guidelines proposed by Honikel (1998). Once obtained, the muscle portion was weighed, vacuum packaged, and cooked in a water bath at 80 °C for 30 min (reaching a core temperature of 78 °C), removed from the packaging, and weighed again to calculate the losses due to cooking. Then, three 1 cm × 1 cm × 2 cm prisms were obtained with the help of a scalpel to measure the WBSF using a TA-XT2i analyser (Godalming, Surrey, UK) with a 30 kg cell load operating at 1 mm/s test speed with the blade cutting perpendicular to the muscle fibres.

Finally, the LT section between the 8th and the 13th ribs was used for the measurement in duplicate of thiobarbituric acid reactive substances (TBARS; Nam and Ahn, 2003). Before analysis, the muscle section was vacuum packaged and cooked (80 °C, 30 min) and then cut into two similar portions. One the portions was submitted to TBARS analysis without storage (day 0), and the other was overwrapped with an oxygen-permeable cling film (580 ml/m 2 /h) and stored under refrigeration for 48 h before another TBARS analysis (day 2).

2.4. Statistical analysis

The statistical analysis was carried out using SPSS version 26 software (SPSS Inc., IBM Corp.; Armonk, NY). Pearson correlations were calculated between the lamb growth factors, i.e. bBW, ADG, body weight gain from birth to slaughter (BWG), slaughter body weight (sBW), and days of life (sAge). Pearson correlations were also calculated within pairs variables regarding carcass, meat, or fat quality traits (product quality traits).

The effects of the dam group and litter size (single or twin) on the premortem traits and the carcass and meat quality traits were carried out either by one-way analysis of variance (ANOVA) or covariance (ANCOVA). One-way ANOVA was used for those traits not significantly correlated with sBW (as previously assessed with Pearson correlation), and ANCOVA, with the sBW as a covariate, for those traits significantly correlated ($p < 0.05$) with sBW. The rationale of this two-step procedure was to prevent the eventual confounding effect of sBW because it was within a given range (10.0 to 12.5 kg) and thus was only partially controlled.

For the effects of bBW and ADG on product quality traits both a continuous and a discontinuous effect approach were conducted. The continuous effect was evaluated using the Pearson correlation analysis between bBW or ADG and each of the considered carcass and meat quality traits. The correlation was simple for those variables not significantly correlated with sBW, and was partially controlled by sBW for the significantly correlated variables ($p < 0.05$).

The discontinuous effect approach was carried out using ANOVA or ANCOVA. The lamb cases were grouped into five categories of 6 or 7 lambs on the basis of lamb bBW or ADG: very low, VL ($n = 7$); low, L ($n = 6$); medium, M ($n = 7$); high, H ($n = 7$); and very high, VH ($n = 7$). The ranges (minimum – maximum), and average ± standard deviation values for the bBW (kg) groups stablished were the following: VL, 2.9 – 3.6, 3.23 ± 0.27; L, 3.7 – 4.2, 3.92 ± 0.19; M, 4.3 – 4.7, 4.52 ± 0.15; H, 4.8 – 5.5, 5.10 ± 0.32; and VH, 5.6 – 6.6, 6.04 ± 0.36. Those values for the ADG groups (g/d) were as follows: VL, 0.18 – 0.22, 0.20 ± 0.017; L, 0.23 – 0.26, 0.25 ± 0.011; M, 0.27 – 0.28, 0. 28 ± 0.007; H, 0.29 – 0.31, 0.30 ± 0.012; and VH, 0.32 – 0.37, 0.34 ± 0.017. ANOVA was used for those variables not correlated with sBW (Pearson correlation $p > 0.05$) and ANCOVA for the variables correlated with sBW (Pearson correlation $p < 0.05$). If the ANOVA or ANCOVA were significant ($p < 0.05$), the least square difference test (LSD) was used to detect differences between pairs of means.

3. Results and discussion

3.1. Relationships between lamb production (premortem) traits

The mean values of the lamb production traits obtained for the complete group of male suckling lambs and for the subgroups generated by both the dam group and litter size are provided in Table 1. No effect of dam group on suckling-lamb growth-related characteristics were found. This agrees with Villenueve et al. (2010) who found no compromise on bBW by prepubertal moderate restriction of feeding in their dams. These authors stated that a lack of effect is expected provided the time after the restriction period would allow a full

Table 2
Pearson correlation coefficients between premortem characteristics of the Assaf suckling lambs considering the whole sample of lambs, or separately by dam group (C and NPR) and litter size (singles and twins).

	ADG	sAge	sBW	BWG
All the sample ($n = 34$)				
Birth body weight (bBW)	0.382*	−0.762***	0.515**	−0.678***
Average daily gain (ADG)	1	−0.748***	0.713***	0.184
Age at slaughtering (sAge)		1	−0.425*	0.488**
Slaughtering body weight (sBW)			1	0.281
Body weight gain (BWG)				1
C dam group ($n = 17$)				
Birth body weight (bBW)	0.347	−0.790**	0.569*	−0.729**
Average daily gain (ADG)	1	−0.669**	0.669**	0.140
Age at slaughtering (sAge)		1	−0.385	0.529*
Slaughtering body weight (sBW)			1	0.149
Body weight gain (BWG)				1
NPR dam group ($n = 17$)				
Birth body weight (bBW)	0.410	−0.752**	0.472	−0.626**
Average daily gain (ADG)	1	−0.793**	0.760**	0.244
Age at slaughtering (sAge)		1	−0.478	0.363
Slaughtering body weight (sBW)			1	0.391
Body weight gain (BWG)				1
Single-born lambs ($n = 14$)				
Birth body weight (bBW)	0.520	−0.866**	0.553*	−0.763**
Average daily gain (ADG)	1	−0.736**	0.825**	0.019
Age at slaughtering (sAge)		1	−0.501	0.644*
Slaughtering body weight (sBW)			1	0.116
Body weight gain (BWG)				1
Double-born lambs ($n = 20$)				
Birth body weight (bBW)	0.563*	−0.628**	0.744**	−0.170
Average daily gain (ADG)	1	−0.906**	0.651**	0.247
Age at slaughtering (sAge)		1	−0.436	0.532*
Slaughtering body weight (sBW)			1	0.651**
Body weight gain (BWG)				1

C: Ewes fed a standard diet from the three months of age to lambing; NPR: Ewes fed a protein restricted diet from three to five months of age and then a standard diet until lambing.
* : $p < 0.05$.
** : $p < 0.01$.
*** : $p < 0.001$.

compensatory growth, which was the situation observed in the dams of the studied lambs here.

Comparing our results with those reported by De la Fuente et al. (2006) for Assaf lambs, the male mean bBW was 0.7 kg lower in the present study, although the means for ADG and age at slaughtering (sAge) were comparable. The dam group, defined based on the prepubertal dietary protein restriction, showed no significant effect on any of the premortem variables analysed. The litter size (single or twin) had a significant effect on bBW and BWG. Twin lambs tend to be born lighter than single lambs (Dwyer and Morgan, 2006). Consequently, twins would have to gain more weight to reach the targeted slaughter weight (10.0 – 12.5 kg). Litter size did not significantly affect ADG. This is in contrast to the results reported by Acciaro et al. (2020) and Csizmar et al. (2013), who found that twin lambs have a lower ADG than single lambs. Differences amongst studies could be attributed to differences in the type of feeding and slaughter age since, in previous studies, lambs were fed on maternal milk until weaning and reared 50–60 days. Thus, in contrast to that previously found for fattening lambs, litter size did not affect the ADG of milk replacer-reared suckling lambs slaughtered before weaning.

The Pearson correlation coefficients (r) between each pair of the studied quantitative lamb production variables (ADG, sAge, sBW, and BWG) are shown in Table 2. This table has been divided into the following sections: the sample set of male lambs ($n = 34$), the males from each lamb group based on the prepubertal nutritional treatment, and the males from the single- and twin-born subgroups of lambs. Regarding the whole sample, bBW and ADG (growth rate) were significantly correlated ($r = 0.382$; $p < 0.05$). Other studies have also reported a positive relationship between bBW and ADG in fattening lambs (Andrés et al., 2020; Dwyer and Morgan, 2006; Peeters et al., 1995), which might be associated with a lower daily intake for lambs with lower bBW. However, in this study, with suckling lambs, the correlation was weak. Furthermore, the correlation between bBG and ADG became insignificant when a partial correlation was made by controlling for sBW ($r < 0.2$; not shown in Tables). Some other pairs of variables were more strongly correlated with each other ($p < 0.01$). Thus, as expected, bBW was inversely correlated to sAge (days of life) and BWG. Similarly, sAge (days) was directly correlated with BWG.

It can also be seen in Table 2 that lambs showing lower ADG were slaughtered at a higher age or a lower weight (lower bBW), and lambs born with higher bBW tended to present higher sBW (and vice versa). Hence, sAge was inversely correlated with sBW. These observations were expected considering the experimental restriction of a once-per-week slaughtering frequency and the age and weight limits imposed in the experiment. Thus, when the poor performance lambs approximated the allowed maximum of 35 days of age, they had to be slaughtered while tendering towards the lower values of the range allowed for sBW. In contrast, the heavier lambs at birth, or those growing faster, had to be slaughtered younger to avoid their body weights being over the limit of 12 kg, and thus tended to be towards the upper values of the range allowed for slaughter weight.

The above-mentioned results for the complete sample set of male lambs were very similar to those observed for each of the two groups, defined based on the prepubertal nutritional challenge of the lamb's dams. They were also comparable to the results for single and twin lambs separately, except that for the twin lambs, bBW was not correlated to body weight increase, which, in turn, was correlated to sBW. This could be related to a lower and more uniform bBW in twins compared to singles and, thus, to a higher weight increase needed to achieve the targeted body weight.

3.2. Effects of dam group and slaughter body weight on carcass and meat quality

No significant effect was found for the dam group, based on the nutritional protein restriction of the prepubertal female lambs, on carcass and meat quality (Supplementary Tables S5–S7). The lack of effect of the dam group on both lamb production characteristics and product quality traits permitted the study of the effects of bBW and ADG in the complete sample sets, regardless of the dam group. The means ± standard deviations (SD) and the value ranges for all quality traits analysed in the complete set of lambs included in the study are presented in the Supplementary Material (Tables S2–S4).

The Pearson correlation coefficients (*r*) between these variables and sBW were also included in S2–S4 Supplementary Tables. In suckling light lambs, despite their short sBW weight ranges, increased sBW tends to increase carcass compactness (Santos et al., 2007). In agreement, results in this study showed a significant correlation between sBW and the variables related to carcass compactness, namely carcass length, Th, and carcass and leg compactness ($r > 0.65$). The sBW variation also affected carcass tissue proportions, finding decreased leg bone percentages with increased lamb slaughter weights ($r = –0.38$). The negative effect of sBW on carcass or leg bone percentage has been also reported in suckling lambs from other breeds (Velasco et al., 2000; Díaz et al., 2003), and has been related to bone having an allometric coefficient lower than 1. For all variables affected by sBW, as mentioned previously, statistical analysis was performed including sBW as a control

Table 3
Significant effect of birth body weight on suckling lamb carcass and meat quality assessed and the fatty acid (FA) profiles (% of FA of total FA) of intramuscular fat by both ANCOVA/ANOVA and Pearson correlation coefficients (r, between birth body weight and quality traits).

	VL ($n = 7$)	L ($n = 6$)	M ($n = 7$)	H ($n = 7$)	VH ($n = 7$)	MSE	p-level	r
Conformation								
Leg weight/length (g/cm)[&]	33.73	33.62	33.35	32.53	32.32	1.313	0.289	−0.360*
Carcass regional composition (%)								
Forequarter	40.13	40.67	40.86	41.53	41.80	1.493	0.256	0.338*
Hindquarter	59.87	59.33	59.14	58.47	58.20	1.493	0.256	−0.338*
Shoulder	19.11	18.80	19.27	19.24	19.94	0.774	0.130	0.415*
Leg tissue composition (%)								
Bone[&]	30.64[d]	30.43[cd]	31.01[bc]	31.31[ab]	32.30[a]	1.339	0.004	0.623***
Muscle	55.59	57.10	57.21	56.96	57.57	1.560	0.185	0.430*
Subcutaneous fat	6.83[a]	5.53[bc]	5.00[c]	5.36[c]	3.91[d]	1.112	0.001	−0.607**
Total fat	12.86[a]	11.63[ab]	10.81[bc]	11.01[bc]	9.40[c]	1.737	0.016	−0.580**
Meat composition (%)								
Moisture	75.58	76.04	76.32	76.46	76.71	0.870	0.177	0.347*
Technological traits								
TBARS, day 2	8.37[a]	7.28[ab]	8.16[ab]	6.62[ab]	6.32[b]	1.232	0.016	−0.473*
FA, intramuscular fat[#]								
n-3 FA	1.74	1.81	1.86	2.05	2.18	0.383	0.210	0.495**
n-6 FA/n-3 FA	15.15[a]	14.34[ab]	13.91[ab]	13.64[b]	12.00[c]	1.207	0.001	−0.727***
Odd chain FA	0.306[b]	0.342[ab]	0.346[ab]	0.340[ab]	0.381[a]	0.032	0.015	0.492**

VL, L, M, H, VH: lamb groups formed by birth body weight, very low, low, medium, high, and very high, respectively.
MSE: Mean squared error.
TBARS, day 2: Thiobarbituric acid reactive substances in cooked meat after 2 days of refrigerated aerobic storage, expressed as mg of malondialdehyde/kg meat.
[abcd] : Means in the same row showing different letters are significantly different ($p < 0.05$).
[#] SFA: Saturated FA; PUFA: Polyunsaturated FA.
[&] Correlated to slaughter body weight, thus the estimated means, MSE, and p-level were obtained by ANCOVA, and r was controlled by slaughter body weight.
[*] : $p < 0.05$.
[**] : $p < 0.01$.
[***] : $p < 0.001$.

variable or covariate in the correspondent model.

3.3. Birth body weight effects on carcass, meat and fat quality

The significant effects of bBW on the carcass, meat, and fat quality traits detected by either ANOVA/ANCOVA (discontinuous approach) or Pearson correlation (continuous approach) are summarised in Table 3. The total, non-significant, and significant effects are shown in Supplementary Material (Tables S8–S10).

The lambs with a higher bBW tended to show lower leg compactness than those with a lower bBW. Higher bBW was also associated with legs with higher bone and muscle and lower fat percentages, with the bone and fat percentages of the leg being significantly affected in the ANOVA/ANCOVA and showing high Pearson correlation coefficients. Moreover, bBW correlated positively with forequarter (negatively with hindquarter) and shoulder percentages in the half carcass weight. Thus, a high bBW implies higher development of the carcass forequarter and lower fatness in the legs. As a semi-fat-tail breed, Assaf suckling lambs have a characteristic tendency to deposit reserve fat in the tail and surrounding regions of the leg (Mateo et al., 2018), and according to our results, this deposition might depend inversely on bBW.

Meat characteristics were affected by bBW on the LT muscle moisture percentage, as we found a positive significant correlation between these traits ($r = 0.347$; $p < 0.05$), while intramuscular fat was not affected by bBW. When cooked, the meat from lambs with higher bBW showed more stability to lipid oxidation, with the meat from VL group showing significantly higher amounts of TBARS than the VH group. Increased meat oxidative stability is the result of a more favourable balance of anti- and pro-oxidant intrinsic compounds (Domínguez et al., 2019), such as antioxidant vitamins and enzymes, on the one hand, and polyunsaturated fatty acids, or free iron.

Intramuscular fat contains important amounts of structural lipids, i.e. cell membrane phospholipids, which are rich in PUFA, and the proportion of PUFA in the intramuscular fat tends to reduced levels as the percentage of intramuscular fat increases (Wood et al., 2008). This effect would be especially noticeable in suckling lamb meat, because it contains low level of intramuscular fat. In the case of the Assaf suckling lambs analysed here, this was reflected by the significantly negative Pearson coefficient estimated between the intramuscular fat and PUFA ($r = -0.368$; $p < 0.05$).

Our study shows that bBW did not significantly affect the PUFA content in intramuscular fat. However, bBW increased the n-3 percentages and decreased the n-6/n-3 ratio, from a value of 15 in the VL group to 12 in the VH group, thus making the FA profile of lambs with higher bBW healthier (Cheng et al., 2015). The bBW also increased the percentage of odd-chain FA in intramuscular fat. The presence of these FAs in the intramuscular fat would have been derived from the lamb prenatal-growth phase because they are neither present in the milk replacers given to the lambs (Osorio et al., 2009) nor can they be synthesised in the rumen or lamb tissues after birth (Battacone et al., 2019).

Table 4
Significant effect of litter size on the quality traits of suckling lamb carcasses and meat.

	Singles ($n = 14$)	Twins ($n = 20$)	MSE	p-level
Leg tissue composition (%)				
Bone[&]	32.12	30.49	1.439	0.003
Subcutaneous fat	4.65	5.79	1.322	0.019
Total fat	10.25	11.74	1.881	0.029
Rib-region loin tissue composition (%)				
Subcutaneous fat	9.86	12.18	2.474	0.012
Total fat	12.94	15.27	3.233	0.049
FA, intramuscular fat[#]				
n-6 FA/n-3 FA				

MSE: Mean squared error.
[&] Correlated to slaughter body weight, thus the estimated means, MSE, and p-level were obtained by ANCOVA.
[#] n6/n3 ratio calculated from the FA percentages in perirenal fat.

Table 5
Significant effect of growth rate (average daily gain) on suckling lamb carcass and meat quality assessed by both ANCOVA/ANOVA and Pearson correlation coefficients (r; between growth rate and quality traits).

	VL ($n = 7$)	L ($n = 6$)	M ($n = 7$)	H ($n = 7$)	VH ($n = 7$)	MSE	p-level	r
Conformation								
Chest depth (cm)[&]	18.74[b]	19.19[ab]	18.82[ab]	19.12[ab]	19.55[a]	0.390	0.027	0.319
Lumbar-region loin tissue composition (%)								
Bone	27.89	25.11	26.35	24.99	25.20	3.476	0.490	−0.413*
Subcutaneous fat	8.02	8.18	9.78	10.98	10.67	2.357	0.082	0.393*
Rib-region loin main tissue composition (%)								
Bone	41.96[a]	37.30[b]	36.36[b]	38.82[b]	37.10[b]	2.800	0.007	−0.413*
Muscle	36.81[b]	41.82[a]	41.53[a]	40.08[a]	41.18[a]	3.020	0.029	0.367*
Meat quality								
Cooking loss (%)	20.14	20.46	20.71	21.93	22.59	2.207	0.227	0.406*

VL, L, M, H, VH: lamb groups formed by birth body weight, very low, low, medium, high, and very high, respectively.
MSE: Mean squared error.
**: $p < 0.01$.
[&] Correlated to slaughter body weight, thus the estimated means, MSE, and p-level were obtained by ANCOVA and r was controlled by slaughter body weight.
[ab] : Means in the same row showing different letters are significantly different ($p < 0.05$).
[*] : $p < 0.05$.

The effect of bBW on odd-chain FA suggests that the higher the bBW, the larger the proportion of the muscle lipid fatty acids originating from the prenatal-growth phase, with this resulting in higher odd-chain FA percentages. This can be at least partially explained because lambs with higher bBW need to gain less weight (BWG) to reach sBW.

The effects of bBW and litter size could be confounded by each other since twin lambs tend to be lighter at birth. The number of twin lambs belonging to each bBW category was not uniform: VL, 6 out of 7; L, 4 out of 6; M, 6 out of 7; H, 4 out of 7; and VH, 0 out of 7 (not shown in the tables). Table 4 shows the significant effects of litter size, and the complete results are in Supplementary Tables S5–S7. Bone and fat percentages of the leg and n-6/n-3 ratio, which were relevantly and significantly affected by bBW, were also significantly affected by litter size. In contrast, no significant effect of litter size was found for the other variables found to be affected by bBW. Furthermore, litter size, in contrast to bBW, significantly affected the fat percentages of the rib-region loin, showing twins to have higher fatness than single-born lambs.

3.4. Average daily gain effects on carcass, meat and fat quality

The significant effects of ADG on carcass, meat, and fat quality are shown in Table 5 (Tables S11–S13 contain the results for all studied variables). As for carcass quality, the highest impact was located in the rib region of the carcass. Significant differences were found in Th between the VL and VH groups (greater in VH). Moreover, bone and muscle percentages in the rib-region loin portion were higher and lower in VL-ADG than in the rest of the groups. The correlation of ADG with bone and with muscle percentages in the rib-region of the loin was also significant: negative for bone and positive for muscle. In the lumbar region of the loin, the bone percentage was also negatively correlated to ADG, but it was the subcutaneous fat and not the muscle tissue that was correlated to ADG ($r = 0.367$; $p < 0.05$). A high percentage of muscle and low of bone in the loin anatomical region are relevant for the quality of suckling lamb since loin has the highest commercial value amongst the carcass commercial cuts. Thus, suckling lamb carcasses from the VL group could be considered lower in quality.

Regarding meat quality, cooking loss was directly correlated with ADG. The value of this quality trait is affected by a number of factors, such as pH decline, proteolysis, intracellular architecture, and rigour intensity (Huff-Lonergan and Lonergan, 2005), which makes it difficult to suggest mechanisms for the observed effects.

4. Conclusions

The present study has shown, first, that a protein dietary restriction performed in Assaf replacement ewes at the prepubertal age did affect neither the bBW nor the growth performance of their offspring suckling lambs reared with milk replacer. This dietary restriction also did not affect the suckling lamb carcass and meat quality. Moreover, in the Assaf suckling lambs studied, bBW and ADG, which showed a low inconsistent relationship between each other, each affected different carcass or meat quality traits. Assaf lambs with higher bBWs showed increased forequarter percentage and decreased subcutaneous-fat percentage of in the leg, which does not clearly mean improved (or impaired) carcass quality. However, higher bBW appears to improve meat quality by increasing lipid oxidation stability and n-3 FA levels. As for ADG, lambs showing very low values, i.e. lower than 0.22 kg/day, resulted in low-quality carcasses, with increased bone percentage and reduced muscle or fat content in the loin.

Authorship contribution

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Declaration of Competing Interest

The authors declare that there is no conflict of interest.

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Supplementary materials

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