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Can genetic propensity for lambing difficulty be predicted by pelvic and body shape dimensions measured by X-ray computed tomography (CT) scanning of ram lambs?

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ABSTRACT

The ability of sheep to lamb unaided is important for both financial and welfare reasons. Current recording of lambing ease is subjective and unreliable for breeding purposes. The aim of this study was to investigate genetic control of measurements that could be taken from routine x-ray computed tomography (CT) scanning of ram lambs, within UK breeding programmes, to predict lambing difficulty of their progeny, or their daughters' progeny. Measurements of 6 CT-derived lambing ease predictor traits (hip width, shoulder width, pelvic area, pelvic height, pelvic width, pelvic angle) were taken from archived CT images from 437 Texel ram lambs from 58 flocks (average age ~20 weeks) scanned over 15 years, as part of the UK national terminal sire breeding programme. Heritabilities, after adjusting for live weight, ranged from 0.16 to 0.65, with the highest estimates for the pelvic traits. Lambing difficulty scores (17705 records over 16 years), recorded on a six-point scale of increasing severity, were available from lambs born within the same flocks. Lambing difficulty was lowly heritable when expressed either as a trait of the lamb ($h^2 = 0.05$) or the ewe ($h^2 = 0.02$) with large common litter effects, low maternal effects and low repeatability in the ewe. Genetic correlations gave some indication that wide hips and shoulders, at a fixed live weight, may be associated with increased lambing difficulty of the lamb ($r_g = 0.28$ and 0.47) and that lower pelvic width and angle (more horizontal) may be associated with increased lambing difficulty of the ewe ($r_g = -0.22$ and -0.39), although standard errors were high. Moderate genetic correlations between body width and pelvic measurements suggest scope to select for optimal combinations of these measurements. Further research in this area could lead to incorporation of robust breeding values for lambing ease into sheep breeding programmes to improve animal welfare.

1. Introduction

It is acknowledged that agriculture must supply more food from less land/resources, and with less environmental impact, to meet Millennium Development goals on world hunger (https://www.un.org/sustainabledevelopment/hunger/). This must involve increased efficiency and sustainability of livestock production, as well as reductions in associated waste. Genetic improvement of terminal sire sheep has been successful in making reductions to waste, by increasing lean meat percentage and reducing carcass fat, which forms a significant proportion of processing waste (Simm et al., 2005). Such improvements in carcass composition have been accelerated by the use of ultrasound scanning and X-ray computed tomography (CT) in terminal sire breeding programmes (Bunger et al., 2011). However, the total quantity of waste from meat production is influenced by all elements of the supply chain, beginning on the farm.

The ability of sheep to lamb unaided is important for both financial and welfare reasons. The estimated mean neonatal lamb mortality rate in the UK is approximately 10 % (Binns et al., 2002) and lambing difficulty is one of the most common causes of mortality. Dystocia has been reported to account for between 9 % to over 50 % of neonatal lamb deaths (Brown et al., 2014; Refshauge et al., 2016). It can affect lamb survival and performance, as well as ewe maternal ability, longevity and efficiency. Maternal pelvic capacity has been indicated as an important factor causing dystocia in ewes (Quinlivan, 1971). Many lambing difficulties are due to the disproportionate size or shape of the lamb and ewe,

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as a result of a large lamb, a small pelvic opening, or both (McSporran and Fielden, 1979a; Kilgour and Haughey, 1993; Jacobson et al., 2020).

In cattle studies, pelvic height, width and area, have been measured via the rectum using a pelvimeter, in order to investigate heritabilities and relationships of these dimensions with calving ease (Morrison et al., 1986; Naazie et al., 1992). However, these measurements are taken on breeding cows and there is some debate over the best time to measure pelvic dimensions in breeding females in relation to pregnancy and birth and stage of pelvic relaxation. Presumably due to the smaller size of sheep than cattle and the invasive nature of the procedure, internal pelvimetry using a similar method has been applied less commonly in sheep. However, examples exist where devices and methodology have been developed specifically for this purpose (van Rooyen et al., 2012). Attempts to predict pelvic dimensions by external measurements have been shown to be impracticable and often of low repeatability (Zhou, 2020) and several publications have demonstrated that internal pelvic dimension could not be accurately predicted by external pelvic measurements (Bassett, 1955; McSporran and Fielden, 1979a), and so dissection, radiography and computer tomography have been recommended for such measurements (Bassett, 1955; Bilbe et al., 2005; Bunger et al., 2011; McSporran and Fielden, 1979a; McSporran and Wyburn, 1979b).

The use of X-ray measured pelvic dimensions showed that an incompatibility in size between the maternal pelvis and the lamb at birth is largely responsible for the need for repeated assistance at birth across parities (McSporran and Fielden, 1979a). Preliminary studies undertaken at Scotland's Rural College (SRUC) used in vivo x-ray computed tomography (CT) to measure various dimensions of the pelvic area of Scottish Blackface ewes and identified some associations with the incidence of dystocia, as well as with maternal behaviour score (Bilbe et al., 2005). The availability of spiral x-ray computed tomography (CT) scanning, allowing 3D imaging, has substantially increased the opportunities to measure pelvic dimensions in these animals and to derive new CT-based selection traits to breed for low dystocia (Bunger et al., 2011). *In vivo* pelvic dimension measurements using 3D CT images have been shown to be highly repeatable and accurate and accounted for variation in lambing assistance in Texel-type ewes after adjustment for lamb birth weight (McLean et al., 2009). Previous CT studies of Scottish Blackface and Texel-type ewes showed differences in the mean pelvic dimensions of daughters from different sires, indicating that genetic variation in pelvic dimensions exists within a breed and genetic selection on these traits may be possible (Bilbe et al., 2005; McLean et al., 2009).

As well as anatomical differences in ewes that affect lambing ease, there may also be anatomical differences in the shape of the lambs that make them more difficult to deliver. Differences have been identified in the abilities of ewes to lamb unassisted and in the incidence of malpresentation of lambs due to breed of the sire, which may be due to differences in shape characteristics (such as shoulder width), as well as birth weights (Speijers et al., 2009, 2010). Lambing difficulties in Scottish Blackface ewes were higher in a line where breeding animals were selected by eye to reflect commercial industry preferences for type, compared to genetic lines selected on a breeding index incorporating ewe and lamb traits (either high index line or the control line selected for average index score), possibly due to visual selection for a particular body shape which also increases lambing difficulties (e.g. big horns, wide shoulders). Ewe sire and lamb sire both had significant effects on lambing difficulty in that study (Lambe et al., 2006). The CT study on Texel-type ewes and their lambing abilities found some indication that lamb shape at the shoulders and head may influence lamb presentation at birth within breed (McLean et al., 2009). Spiral CT scanning allows measurement of dimensions, circumferences, areas and volumes of different body regions in-vivo (Masri, 2013; Navajas et al., 2007), either at the level of the skeleton, or also including soft tissue (muscle and / or fat), so could provide accurate and repeatable measurements of shape traits, which could be related to lambing difficulties.

To help understand the effects of ewe and lamb anatomical dimensions on lambing difficulty, large data sets are required to identify robust CT predictors of lambing difficulty and investigate their genetic control. The ultimate aim is to identify traits that can be measured in sires, during routine CT scanning of ram lambs from the national UK terminal sire breeding programmes (Bunger et al., 2011), and can be incorporated into genetic evaluations to provide tools to breed for reduced lambing difficulties, whilst simultaneously improving growth and carcass traits. The goal is for sires to be selected that will produce progeny of a shape that can be born more easily and daughters that can lamb unassisted. Genetic parameters need to be quantified for CT-measured predictors of lambing difficulties, including their relationships with other important production traits, before selective breeding for "easy-lambing" anatomical traits could be recommended.

Within the UK national breeding programme for terminal sire sheep, estimated breeding values (EBVs) are available for lambing ease for Texel sheep, based on a scoring system describing the level of intervention at lambing. However, to collect these scores requires additional recording at lambing and the need for intervention is subjective, so scoring may differ between breeders. CT scanning of elite rams is now routine in most UK terminal sire breeding programmes (including 2D and 3D CT image collection). Additional information available from CT images has allowed a further set of novel traits to be investigated for the first time, relating to the hip, shoulder and pelvis of Texel animals. The relationship between these traits and dystocia is of particular interest. The extraction of further data from routinely-collected CT images could predict lambing difficulty for minimal extra cost and could help understand the underlying reasons for lambing difficulties.

The aims of this study were, therefore, to use data collected as part of the UK Texel breeding programme to investigate measurements that could be taken from CT scans of ram lambs to predict lambing difficulty of their progeny, or their daughters' progeny, and to determine the genetic control of CT-measured lambing ease/difficulty predictors. Additionally, this study aims to estimate genetic parameters for lambing ease scores recorded on-farm, both as a direct trait of the lamb and as a trait of the ewe, and estimate genetic and phenotypic correlations between the new CT predictor traits and lambing ease scores.

2. Materials and methods

2.1. Animals and data collection

All procedures involving animals were approved by the SRUC Animal Ethics Committee and were performed under UK Home Office license, following the regulations of the Animals (Scientific Procedures) Act 1986.

Data were available for Texel ram lambs that had been CT scanned between 2000 and 2015, as part of the UK national terminal sire breeding programme (Bunger et al., 2011). Lambs were submitted for CT by individual breeders from a total of 58 flocks, with between 1 and 53 lambs per flock across the years. Lambs were CT scanned at an average age of 150 d (range 101 – 207 d) and average live weight of 48 kg (range 42 – 58 kg). All lambs were kept off feed for a minimum of four hours prior to CT scanning.

2.2. CT-measured lambing ease predictor traits

Lambs were scanned using a Siemens Somatom Esprit scanner (current 100 mA; voltage 130 kKV; field of view 450 mm) with slice width set at 8 mm, and a spiral pitch of 2. Lambs were lightly sedated, using Rompun™ (20 mg/mL % weight per volume, Bayer plc; 0.1–0.2 mg xylazine hydrochloride/kg body weight), and secured in a standard position on their backs in a cradle with their forelegs bent and strapped to their chest and their hind legs strapped in an extended position, before being CT scanned. A spiral scan sequence was stored from each lamb capturing images along the length of the body from the neck to the hock. Additional measurements were taken from these existing CT images to derive lambing ease predictor traits, which included two widths measured on the full body topogram image: shoulder width (ShW (mm); Fig. 1a), measured perpendicular to the spine at the widest part of the shoulder though the first thoracic vertebra; and hip width (HW (mm); Fig. 1b), measured perpendicular to the spine, through the knee joint. Three measurements were also taken relating to the pelvic opening, which was visualised by reconstructing the spiral scan sequence of images in 3-dimensions and then manipulating the image plane until the full pelvic opening was shown (Fig. 1c), allowing the measurement of: pelvic opening height (PH (mm); Fig. 1c), measured from the point above the middle of the last lumbar vertebra to the pubic symphysis; pelvic opening width (PW (mm); Fig. 1c), measured from half way along the PH line and crossing it at 90ο; and pelvic opening area (PArea (mm^2); Fig. 1c), measured by manually tracing round the edge of the pelvic opening and calculating the area within. The measurements for PH and PW are similar to conjugate diameter and transverse diameter, respectively, as defined by Fogarty and Thompson (1974) from measurement of dissected carcasses, but use the end-points above, as they can be clearly defined from the corresponding CT images. Finally, pelvic angle (PAng (°); Fig. 1d), was measured as the angle of the pelvis relative to the scanning table, as the lambs lay on their back. Measurements were taken from the scan images using STAR software (Mann et al., 2013). A summary of the data available is given in Table 1.

2.3. Lambing difficulty scores

Lambing ease information was available from animals born on the 58 flocks represented in the initial CT analyses (recorded on both male and female lambs). The scoring criteria used by the flocks was a six-point scale of increasing severity from 1 to 6. Therefore, although the trait is defined as lambing ease in the national breeding programme, an increasing score is associated with increased lambing difficulty, so will be termed lambing difficulty (LD) score here. These scores were then transformed (by adjusting for the average and standard deviation values of each contemporary group and the overall population) before any data analyses took place (Table 2). When lambing difficulty was considered as a direct trait of the lamb (LD), there were 17705 records available, recorded on lambs born between 2006 and 2016. The frequency of the scores awarded (scores 1–6) are given in Table 2 (no animals were given a score 6).

Lambing difficulty was also considered as a trait of the ewe (EweLD) and was therefore associated with repeated measures across the years. Data were available for 7557 individual ewes (using the same 17705 records used previously in the direct LD analyses).

Table 1
Summary of the computed tomography (CT) traits included in the analyses.

Trait	Count	Min	Max	Average	s.d.
Hip Width (HW; mm)	437	314	385	350	10
Shoulder Width (SW; mm)	437	243	344	311	18
Pelvic Area (PArea; mm^2)	390	3121	6378	4400	488
Pelvic Height (PH; mm)	390	54	81	68	5
Pelvic Width (PW; mm)	390	52	81	64	5
Pelvic Angle (PAng;°)	390	5.8	31.5	17.3	3.8

Table 2
Lambing difficulty scoring criteria and number of records per score.

Score	Score definition	Transformed score value	Number of records
1	No assistance	-0.67	10863
2	Slight assistance by hand	0.74	5425
3	Severe assistance	1.76	1143
4	Non-surgical vet assistance	2.32	159
5	Vet assistance, surgery required	2.93	115
6	Elective caesarean	–	0

2.4. Genetic analyses

2.4.1. CT-derived lambing ease predictor traits

Genetic analyses were performed using ASReml v3 (Gilmour et al., 2009) to estimate heritabilities for the CT-derived lambing ease predictor traits. The animal model fitted for each of the CT traits was:

$$\text{CT Trait} = \text{CT live weight} + \text{litter size reared} + \text{dam age} + \text{birth year} + \text{flock}$$

Live weight at CT scanning was fitted as a covariate. Litter size reared was the number of lambs reared together by the same ewe (2 levels; 1 and >2) and dam age was the age of the dam at lambing in years (4 levels; 2 to >5). Each fixed effect was significant for the majority of traits and to remain consistent, the same models were fitted across the different traits. Birth year of the lambs ranged from 2000 to 2015, but did not include any data from 2001 due to the foot and mouth outbreak in the UK. The full Texel pedigree was pruned using the RelaX2 pedigree analysis programme (Stranden and Vuori, 2006) to retain only information required for estimating variance components. The pedigree file used for these analyses, therefore, included sire and dam information for 32,168 animals.

Bivariate genetic analyses were performed using ASReml v3 (Gilmour et al., 2009) to estimate genetic and phenotypic correlations between each pair of traits amongst the CT lambing ease predictor traits. The data and model fitted for each trait was the same as used previously in the univariate analyses.

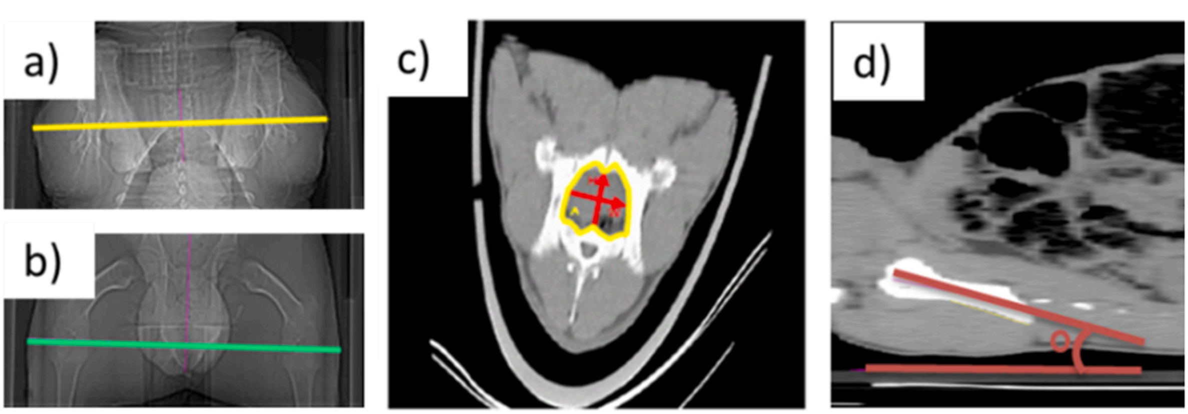

Fig. 1. Positioning of measurements taken on the CT images of shoulder width (a), hip width (b), pelvic width, height and area (c) and pelvic angle (d).

2.4.2. Lambing difficulty scores

Genetic analyses were performed using ASReml v3 (Gilmour et al., 2009) to estimate heritabilities for the lambing difficulty traits. The animal model fitted for the direct LD trait was the current model used in the UK national terminal sire genetic evaluations:

Direct LD = Birth weight + litter size at birth + CG1 + (Birth weight x CG2) + (Birth weight x litter size at birth) + breed at birth + embryo transfer

Where birth weight was fitted as a covariate, litter size at birth was the number of lambs born in the same litter (3 levels: 1–3), breed at birth was also fitted (3 levels: 1–3) and if the lamb was an embryo transfer lamb (2 levels, yes or no). Two different contemporary groups were also included in the model: CG1 (combining flock, year, season and dam age) and CG2 (combining flock, year, season, lamb sex and management group at 8 weeks old). Random effects fitted included a direct genetic effect (animal), a maternal genetic effect and a litter effect. The pedigree file used for these analyses included sire and dam information for 49,948 animals.

The analyses were then repeated, considering lambing difficulty as a trait of the ewe (EweLD), rather than a direct trait of the lamb (LD). An animal model was used, fitting the same fixed effects as the original model and random effects of the ewe (direct genetic animal effect), the sire (of the lamb), permanent environment and litter effects.

2.4.3. Relationships between CT traits and lambing difficulty

Bivariate genetic analyses were performed using ASReml v3 (Gilmour et al., 2009) to estimate genetic and phenotypic correlations between the new CT traits and both lambing difficulty traits – LD and EweLD. The data and models fitted were the same as used previously in the univariate analyses. In order to assess the relationship between body weight and lambing difficulty, additional bivariate analyses were also performed between live weight at the time of CT scanning (CTLWT) and each of the lambing difficult traits (LD and EweLD). The same model was fitted for CTLWT as for the other CT traits, but age at CT scanning (d) replaced CT live weight as the covariate. There were no animals in the EweLD analyses that had both a CT record and a EweLD record, as CT scanning was only performed on male lambs, whereas EweLD was only recorded on females, so the residual covariance in these analyses were set to zero.

3. Results

3.1. Genetic parameters for CT-derived lambing ease predictor traits

The results of the univariate genetic analyses for the CT-derived lambing ease predictor traits are summarised in Table 3. Assuming that heritabilities can be defined as low in magnitude if < 0.2, moderate if 0.2–0.5 and high if > 0.5, the heritabilities estimated ranged from low to high (0.16–0.65), with standard errors ranging from 0.15 to 0.17. The highest heritability estimates were associated with the pelvic traits.

The results of the bivariate genetic analyses between CT lambing ease predictor traits are summarized in Table 4. For reference, magnitude of correlations were defined as high (>0.6), moderate (0.4–0.6), low (0.2–0.4), or negligible (<0.2) (Brown and Turner, 1968). The genetic correlations estimated ranged from − 0.81–0.86, with a number of estimates significantly different to zero (P < 0.05), including high positive correlations of PArea with both PH and PW. The phenotypic correlations associated with these traits were also high and positive, indicating that larger pelvic areas are associated with higher and wider pelvis measurements. Other high genetic correlations included the positive relationship between HW and SW and the negative relationships between SW and PH, although these estimates also had the highest standard errors (0.55–0.56). The highest genetic correlation associated with PAng was with PH.

Table 3
Genetic parameters (genetic variance, V_A; phenotypic variance, V_P; heritability, h^2) for the computed tomography (CT) lambing ease predictor traits.

Trait	V_A	V_P	h^2
Hip width (HW)	10.87	47.12 (3.93)	0.23 (0.17)
Shoulder width (SW)	19.73	127.11 (10.32)	0.16 (0.15)
Pelvic area (PArea)	108493	199250 (18688)	0.54 (0.15)
Pelvic height (PH)	8.11	20.83 (1.93)	0.39 (0.17)
Pelvic width (PW)	12.82	19.63 (1.92)	0.65 (0.16)
Pelvic angle (PAng)	7.34	13.16 (1.27)	0.56 (0.17)

Table 4
Genetic and phenotypic correlations, above and below the diagonal respectively, between the computer tomography (CT) traits (standard errors in parenthesis).

Trait	HW	SW	PArea	PH	PW	PAng
Hip width (HW)		0.83 (0.55)	0.42 (0.30)	0.18 (0.43)	0.55 (0.33)	-0.09 (0.38)
Shoulder width (SW)	0.42 (0.05)		-0.35 (0.39)	-0.81 (0.56)	0.24 (0.31)	0.41 (0.36)
Pelvic area (PArea)	0.15 (0.06)	0.09 (0.06)		0.86 (0.13)	0.75 (0.12)	0.29 (0.25)
Pelvic height (PH)	0.10 (0.06)	0.05 (0.06)	0.73 (0.03)		0.31 (0.30)	0.56 (0.30)
Pelvic width (PW)	0.15 (0.06)	0.10 (0.06)	0.65 (0.04)	0.16 (0.06)		0.30 (0.22)
Pelvic angle (PAng)	0.01 (0.06)	0.02 (0.06)	-0.06 (0.06)	0.01 (0.06)	-0.002 (0.07)	

3.2. Genetic parameters for lambing difficulty

The heritability estimates for both lambing difficulty traits (as a trait of the lamb, LD, or the ewe, EweLD) were low (Table 5). Common litter effects accounted for a large proportion of the variation in both lambing difficulty traits, whereas permanent environment and maternal genetic effects were low. Lambing difficulty of the ewe was also lowly repeatable.

3.3. Relationships between CT traits and lambing difficulty

The genetic correlations estimated between the CT traits and direct LD (Table 6) all had high standard errors (between 0.24 and 0.39) associated with them, which limited their interpretation. However, the general direction of the relationships observed indicate that lambs with wider hips and shoulders may be more likely to be involved in a difficult lambing (low to moderate positive genetic correlations). All other correlations with LD were negligible in magnitude, including the correlations with CTLWT.

Likewise, the standard errors associated with the genetic correlations estimated between the CT traits and LD of the ewe (EweLD; Table 6) imply that these results should be treated as a preliminary indication of these genetic relationships only. However, general trends indicate that

Table 5
Genetic parameters (phenotypic variance, V_P; litter effect, h_l^2; sire effect, h_s^2; permanent environmental effect, pe; maternal genetic effect, h_m^2; repeatability, rep and direct heritability, h_d^2) for lambing difficulty as a trait of the lamb (LD) or the ewe (EweLD).

Trait	V_P	h_l^2	h_s^2	h_m^2	*pe*	*rep*	h_d^2
Lambing Difficulty (LD)	0.53 (0.01)	0.71 (0.01)	–	0.02 (0.01)		–	0.05 (0.01)
Lambing Difficulty of the ewe (EweLD)	0.53 (0.01)	0.70 (0.01)	0.02 (0.01)	–	0.02 (0.01)	0.04 (0.01)	0.02 (0.01)

Table 6
Phenotypic (r_p) and genetic (r_g) correlations estimated between lambing difficulty as a trait of the lamb (LD) or the ewe (EweLD) and each of the CT-derived lambing ease predictor traits or live weight.

	Lambing Difficulty (LD)		Lambing Difficulty of the ewe (EweLD)	
Trait	r_p	r_g	r_p	r_g
Hip width (HW)	-0.02 (0.07)	0.47 (0.39)	-0.01 (0.04)	0.10 (0.45)
Shoulder width (SW)	-0.02 (0.08)	0.28 (0.36)	-0.01 (0.04)	-0.01 (0.42)
Pelvic area (PArea)	-0.06 (0.07)	-0.06 (0.25)	-0.02 (0.05)	-0.13 (0.31)
Pelvic height (PH)	0.01 (0.08)	0.18 (0.28)	0.02 (0.05)	0.15 (0.34)
Pelvic width (PW)	-0.01 (0.08)	-0.16 (0.24)	-0.04 (0.05)	-0.22 (0.28)
Pelvic angle (PAng)	-0.004 (0.07)	0.14 (0.26)	-0.06 (0.05)	-0.39 (0.31)
Live weight (CTLWT)	-0.09 (0.08)	-0.003 (0.37)	0.002 (0.04)	0.02 (0.42)

animals with pelvic openings that are wider or with higher pelvic angle measurements may experience less lambing difficulties (low negative genetic correlations). The other CT-measured traits had negligible correlations with EweLD, as did CTLWT.

4. Discussion

4.1. Genetic parameters

The results from this study suggest that genetic variation exists in traits that can be measured by CT scanning that could have potential associations with lambing ease. In particular, moderate to high heritabilities (~0.4–0.65) were estimated for skeletal traits related to the size and angle of the pelvis, after adjustment for live weight, so phenotypically independent of body size (weight). High heritabilities have been found for pelvic dimensions previously. For example, in earlier work in cattle, pelvic height, width and area, measured via the rectum using a pelvimeter, were found to have heritabilities of 0.5 or over (Morrison et al., 1986; Naazie et al., 1992). However, these measurements were taken on breeding cows and there is some debate over the best time to measure pelvic dimensions in breeding females in relation to pregnancy and birth and stage of pelvic relaxation. Pelvic measurements of cattle, taken at 400 or 600 days of age, were found to be moderately to highly heritable with strong, positive genetic correlations between males and females (Upton and Burke, 1995). Estimates of heritability for dimensions of the pelvic opening in sheep are hard to find, which may be linked to the difficulties in measuring these traits in a repeatable and practical way. Therefore, the estimates presented here are of considerable value in understanding the genetic control of pelvic dimensions in sheep.

Heritabilities have been published for external body dimension traits in meat sheep, such as lengths, widths and heights, measured with rulers, tapes or callipers, as well as for well-defined descriptive scores assessing type traits of meat or dairy sheep, including pelvic slope and rump width. For these traits, heritabilities tend to be low to moderate (Fernando de la Fuente et al., 2011; Janssens and Vandepitte, 2004). The heritabilities estimated here for shoulder and hip widths measured by CT are of a similar magnitude. Considering linear dimensions of crossbred lamb carcasses, measured by video image analysis in the abattoir, moderate heritabilities were estimated for shoulder (h^2 0.23) and hip (h^2 0.39) width measurements (Rius-Vilarrasa et al., 2010), taken in similar anatomical locations as the CT width traits presented here, when adjusted for slaughter age. Subjective scoring of the rump and or pelvis slope, from external visual appraisal, has been undertaken in previous studies and heritabilities estimated (e.g. h^2 0.2, Janssens and Vandepitte, 2004). However, it is not clear how this relates to the pelvic angle measurement taken in the current trial, which isolates the pelvic bone, and measures the angle to the scanning table, which is generally parallel to the spine when the sheep is lying on its back.

The low heritabilities for direct and maternal lambing difficulty agree with other studies (Brien et al., 2010; Li and Brown, 2016; McHugh et al., 2020). The large litter effect is also expected, as a lamb is more likely to be assisted if other lambs in the litter are assisted. When considering only single-born lambs, McHugh et al. (2020) estimated a slightly higher heritability for lambing ease (h^2 0.12), as compared to when lambs of all litter sizes were combined (h^2 0.05). The lambing ease scores used in the current study were recorded on farm by individual breeders. These scores are subjective and depend on many factors that could influence the decision to assist a ewe in lambing. The low repeatability estimated for EweLD, once a common litter effect was accounted for, is of interest and could suggest that culling ewes for dystocia may not be valid. However, the low repeatability may be a consequence of ewes being culled from the flocks (and so the data set) following their first difficult lambing event, so being unable to express genetic propensity for lambing difficulty on numerous occasions. Unfortunately, reliable data were not available on ewe longevity or mortality from these commercial flocks to relate to lambing difficulty data.

4.2. Correlations between pelvic / body dimensions and lambing difficulty

The genetic correlations with lambing difficulty found in the current study were inconclusive, due to large standard errors, but general trends imply that animals with larger hip and shoulder widths, at the same live weight, will have more difficulty being born (positive genetic correlations with LD), but that ewes with larger pelvic angles, and to a lesser extent pelvic widths, at the same live weight, will have less lambing difficulties when they give birth (negative genetic correlations with EweLD). No effect of live weight of ram lambs, at ~150d age on average, on LD of the lamb or ewe was found, suggesting that ease of lambing may be more influenced by genetic control of body or pelvic dimensions than body size (weight) in general. These results should be confirmed with larger data sets to reduce associated standard errors, however, the general directions of these associations seem plausible. The genetic correlations between the body width traits (HW and SW) and the pelvic measurements, suggest some antagonisms (HW positively correlated with PArea and PW; SW positively correlated with PW and PAng; Table 3), but the moderate size of these correlations suggests scope for divergent selection.

Correlations among body and pelvic dimensions and between pelvic dimensions and lambing difficulty in the literature are generally presented at the phenotypic level and tend to be low or inconsistent. In a study of Dorper ewes, low phenotypic correlations were estimated between internal pelvic dimensions, measured by pelvimetry via the rectum, and external body dimensions, including shoulder width, hindquarter width and rump slope (van Rooyen et al., 2012). In the current study, negligible phenotypic correlations were estimated between hip width or pelvic angle and pelvic dimensions, but the corresponding genetic correlations were moderate and positive, albeit with large standard errors. Cloete et al. (1998) found breed differences between SA Mutton Merino and Dormer ewes in the effect of rump score and pelvic dimensions, measured by radiographic pelvimetry, on length of parturition. Significant effects on parturition length of conjugate diameter, pelvic inlet area and rump score were observed in the Merino ewes, but not in the Dormer ewes, and no significant effect of pelvic angle (between the sacrum and conjugate diameter) was observed in either breed. Pelvic slope (as assessed on a nine-point scale from 1 = horizontal to 9 = sloping) tended to be lowly or negatively genetically correlated to most other body dimensions or type traits in a study of Belgian Bleu du Maine, Suffolk and Texel sheep (Janssens and Vandepitte, 2004). In the results presented here, pelvic angle was positively genetically associated with each of the pelvic dimension traits, as well as shoulder width, but not hip width. Pelvic angle was also negatively genetically correlated with lambing difficulty as a trait of the ewe, with similar trends for pelvic area and width, suggesting that ewes that have a less horizontal and larger pelvis may lamb more easily.

Pelvic measurements taken on Australian Angus cows between 300 and 700 days of age were found to be moderately positively correlated with calving ease (r_g 0.21–0.65; Meyer and Graser, 1999), implying that cows with larger pelvic openings calved more easily. However, corresponding direct-maternal genetic correlations were negative (−0.27 to −0.51), suggesting antagonism between pelvic dimensions and calving ease of the next generation (Meyer and Graser, 1999). Unfortunately, the current data set on lambs was not powerful enough to estimate reliable correlations between direct genetic and maternal effects. However, this fits with the results presented here when considering ease of birth either as a direct or maternal trait.

4.3. Practical implementation and implications

Female sheep are not routinely CT scanned as part of UK breeding programmes, although a sub-set of males are scanned each year within the terminal sire breeds. Therefore, identification of heritable lambing ease predictor traits that could be measured on males by CT would be extremely valuable in the context of UK terminal sire breeding programmes. An early study of pelvic measurements in cattle, taken at 400 or 600 days of age, found strong, positive genetic correlations between measurements taken on males and females (Upton and Burke, 1995), suggesting scope to measure these traits in either sex.

Selection for traits to reduce lambing difficulties has been identified as a priority by UK sheep breeders (particularly terminal sire breeders) and research towards this goal would align with strategic research priorities, particularly those related to supporting agriculture and food futures, in the areas of genetics and animal welfare. Further expansion of this work could help improve health and welfare of sheep flocks, by providing a better understanding of the causes of lambing difficulties and suggesting possible options to mitigate these problems, to promote improved welfare and agricultural productivity. Increased knowledge on an important factor affecting lamb survival, ewe longevity and ewe efficiency should also help in the design of efficient future farming systems.

It would be of interest to predict the magnitude of genetic gains in improving lambing ease (and lamb survival) that could be achieved by including these traits in the breeding objective, with relevant CT measurements of body and pelvic dimensions as selection criteria. Lambing ease traits would need to be included in a relevant multi-trait selection index alongside other (potentially correlated) traits related to production, health, welfare and maternal traits, reflecting selection indexes and breeding goals currently in use in the UK. Further work is needed before such an index can be developed, including: more robust estimates of genetic correlations between lambing ease and CT predictor measurements, using a more powerful data set; estimates of genetic correlations with other traits; derivation of appropriate weighting criteria for future breeding goals (potentially driven by desired gains, economic values or environmental impact). The Texel Sheep Society in the UK are currently reviewing selection indices for their breed and these studies can help to inform future developments.

5. Conclusions

Genetic variation has been identified in body and pelvic dimension traits that can be routinely measured in ram lambs by CT scanning. Preliminary genetic correlations with lambing ease were inconclusive, but general trends suggest that selection of breeding animals with narrower hips and shoulders at a fixed live weight, as measured from CT scans, may improve ease of birth of lambs, but that breeding for larger pelvic widths and a less horizontal pelvic angle, at a fixed live weight, may result in ewes that suffer less lambing difficulties. Further analyses on larger data sets are required to confirm these associations. Moderate genetic correlations between these CT measurements suggest scope for selection for optimal combinations of these traits that could potentially impact on lambing ease. Further research in this area could lead to incorporation of robust breeding values for lambing ease into sheep breeding programmes, alongside traditional growth and carcass traits, allowing simultaneous genetic progress in both areas, to provide a sustainable system of high quality food production that also improves animal welfare.

CRediT authorship contribution statement

Ann McLaren: Methodology, Data curation, Writing – original draft, Writing – review & editing, Software, Formal Analysis, Visualization. **Kirsty McLean:** Methodology, Data curation, Software, Validation, Investigation. **John Gordon:** Methodology, Data curation, Software, Validation, Investigation. **Nicola Lambe:** Conceptualization, Funding acquisition, Methodology, Project administration, Supervision, Writing – original draft, Writing – review & editing.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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