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The use of X-ray computer tomography for measuring the muscularity of live sheep

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Abstract

Potential measures of muscularity derived from X-ray computer tomography (CT) were assessed using data for 160 sheep (50 Suffolk males, 50 Suffolk females, 40 Texel males and 20 Charollais males). One-fifth of the lambs within each breed and sex were slaughtered at each of 14, 18 or 22 weeks of age and two-fifths slaughtered at 26 weeks. All lambs were CT scanned prior to slaughter with longitudinal and cross-sectional scans taken at three positions along the body [5th lumbar vertebra (LV5), mid-shaft of the femur (FEM) and ischium (ISC)]. After slaughter, linear measurements of side length (SL) and M. longissimus thoracis et lumborum *(LTL) width (A) and depth (B) (12/13th thoracic vertebra) were taken on the left side of the carcass. The side was dissected and femur length (FL), the weight of three muscles surrounding the femur (M3) and the total muscle weight in the side (TM) were recorded. Five muscularity measures were calculated for the carcass. Two for the LTL muscle (A/SL, B/SL), one for the hind leg* ($\sqrt{\mathrm{M3} / \mathrm{FL}^3}$) *and one for the whole carcass* ($\sqrt{\mathrm{TM} / \mathrm{SL}^3}$)*.*

Correlations between spine length measured on the CT longitudinal scans and side length measured on the carcass were high (> 0·62), while correlations between measurements of LTL width and depth on the carcass with those on the LV5 scan were moderate (> 0·41). CT measures of muscularity were derived using linear measurements taken on CT scans together with a prediction of total muscle weight using CT tissue areas. Correlations between CT measures and dissection measures of LTL and whole carcass muscularity were moderate to high (0·33–0·54). Correlations between the dissection measure and four CT measures of hind leg muscularity were higher (0·48–0·60). These results clearly show that good in vivo *measures of muscularity can be obtained for sheep by using measurements that can be taken on CT scans. This will be a useful tool for selection programmes aiming to improve sheep carcass shape, particularly those already using CT scanning to increase rates of genetic improvement in lean tissue growth.*

Keywords: *computed tomography, live estimation, muscles, sheep.*

Introduction

Muscularity has increasingly been advocated as being preferable to conformation as a measure of the shape of a lamb carcass (Kirton *et al.*, 1983; Purchas *et al.*, 1991; Waldron *et al.*, 1992; Abdullah *et al.*, 1993; Hopkins, 1996; Jones *et al.*, 2002). That is because, unlike conformation, muscularity when defined as 'the thickness of muscle relative to a skeletal dimension' (de Boer *et al.*, 1974) is independent of carcass fatness. Moreover, whereas conformation can only be assessed subjectively, objective measures of muscularity can be obtained using the ratio of a muscle thickness to a bone length or muscle weight to a bone length, as proposed by Purchas *et al.* (1991).

If the shape of the carcass and hence muscularity is considered commercially valuable then it should be considered as a selection goal in breeding schemes for meat breeds of sheep. For this to be done effectively, methods of accurately assessing the muscularity of a live animal will be required. Such methods are not available at present.

The aim should be to develop *in vivo* measures that are closely associated with measures considered most important in describing the muscularity of a carcass. Jones *et al.* (2002) proposed that muscularity measures based on the *M. longissimus thoracis et lumborum* (LTL) muscle and hind leg were the most important since they affect the shape of the most valuable joints (loin and leg). In their study, phenotypic correlations between muscularity measures in the loin and leg were low for Suffolk and Charollais lambs, indicating that measures would be required for both regions to describe muscularity of a carcass in these breeds. However, a single measure of whole carcass muscularity was found to provide a good measure of muscularity throughout the carcass for Texel lambs.

The measures of muscularity for the carcass derived by Jones *et al.* (2002) were based on the ratio of two components. Measures for the loin were based on the ratio of a LTL cross-section dimension to carcass side length. Measures for the whole carcass and hind leg were derived using the approach of Purchas *et al.* (1991), whereby muscularity was calculated as $[\sqrt{(Wt/L_B)}]/L_B$, where Wt is the weight of muscle and L_B is a closely associated skeletal dimension. Whole carcass muscularity was derived using total muscle weight in the half carcass and side length, while hind leg muscularity used the weight of three muscles surrounding the femur and femur length. Similar muscularity measures for the live animal could be derived if reliable measurements of the same components could be obtained.

The most widely used method for *in vivo* measurement of carcass components in sheep is ultrasonic scanning. Although good measurements of the depth of the LTL muscle can be obtained, the image produced is relatively poor and measurements of LTL width and area are less precise (McEwan *et al.*, 1989; Edwards *et al.*, 1989; Hopkins *et al.*, 1993; Binnie *et al.*, 1995). In addition, the technique does not lend itself readily to the measurement of muscle depth in other areas of the body nor for *in vivo* measurement of bone lengths.

Considerable research has been conducted over recent years into the application of more advanced imaging techniques for *in vivo* scanning of medium sized livestock, such as sheep or pigs, with the main focus being their value for predicting composition. Techniques investigated include X-ray computer tomography (CT), magnetic resonance imaging (MRI) and dual-energy X-ray absorptiometry (DEXA) (Standford *et al.*, 1998, review; Sehested, 1984; Young *et al.*, 1987 and 1996, 1999; Mitchell *et al.*, 1998a). The majority of the research has focused on the use of CT and MRI, with DEXA only being used relatively recently for *in vivo* scanning having previously been used for scanning carcasses (Mitchell *et al.*, 1998b; Clarke *et al.*, 1999). Accurate predictions of body composition have been achieved using both CT and MRI. However, the relatively lower cost associated with CT scanning has generally resulted in its emergence as the most preferred method (Standford *et al.*, 1998). CT scanners for scanning livestock are now available in Norway, New Zealand and the UK, with commercial services being provided in the latter two countries (Standal, 1984; Davies and Fennessy, 1996; Young *et al.*, 2001)

Using CT, detailed images of sections through various regions of a sheep's body can be obtained. Excellent predictions of carcass composition have been achieved by using the area of tissues in cross-sectional scans and live weight in prediction equations (Sehested, 1984; Young *et al.*, 1987, 1996 and 1999). In the most recent study Young *et al.* (1999) showed that, by using live weight and tissue areas from three scans, a prediction accuracy (R^2) of 96, 98 and 89% could be achieved for the total weight of muscle, fat and bone, respectively, in the carcass for Suffolk lambs. Muscle weight in different parts of the carcass (i.e. leg/chump) could also be predicted accurately using live weight and muscle area from just one cross-sectional scan ($R^2 > 91\%$).

Given the high quality of images produced, accurate *in vivo* measurements of cross-sectional dimensions on the LTL muscle and of skeletal dimensions may be possible. Such measurements, along with the predictions of muscle weight, could be used to develop *in vivo* measures of muscularity similar to those derived for the carcass post slaughter by Jones *et al.* (2002). The value of CT for measuring such dimensions *in vivo* has not been investigated in previous studies.

The aim of this study was to investigate whether useful, objective measures of muscularity could be derived for live sheep, using data extracted from CT scan images.

Material and methods

Data were collected in 1997 at the Scottish Agricultural College (SAC) on 50 Suffolk male, 50

Suffolk female, 40 Texel male and 20 Charollais male lambs. Suffolk lambs were obtained from the SAC Suffolk flock and consisted of equal numbers within sex from the lean growth selection and control lines. Texel lambs were obtained from the flock at the Institute of Rural Studies (IRS), Aberystwyth and consisted of equal numbers from the lean growth and leg conformation selection lines. Charollais lambs were obtained from two commercial pedigree flocks. Jones *et al.* (2002) provides further details about the origin and management of these lambs.

One fifth of lambs within each breed-sex category were slaughtered at 14, 18 and 22 weeks of age. The remaining two-fifths were slaughtered at 26 weeks of age. All lambs were ultrasound and CT scanned 24 to 72 h prior to slaughter.

Slaughter measurements

Live weights were recorded prior to slaughter. After slaughter carcasses were chilled for 24 h and then weighed. The carcass was then split and side length (SL) was measured as the distance from the anterior end of the symphysis pubis to the anterior dorsal edge of the first thoracic vertebra. The left side of the carcass was frozen and retained for subsequent dissection.

After thawing the depth (B) and width (A) of the LTL muscle were measured on the posterior surface when the side was cut between the last and second to last thoracic vertebrae (Pálsson, 1939). The left side of the carcass was separated into eight joints as described by Cuthbertson *et al.* (1972). Each joint was weighed and then dissected into muscle, bone, fat (subcutaneous and inter-muscular) and waste. Three muscles from the hind leg (*m. semitendinosus, m. semimembranosus* and *m. gluteobiceps*) were individually separated and their weights recorded. The length of the femur (FL) was measured. Jones *et al.* (2002) provides further details of the carcass measurements collected.

Dissection measures of muscularity

Two measures of muscularity were derived for the LTL: the ratio of LTL width to side length (ASL) and the ratio of LTL depth to side length (BSL). One measure of muscularity for the hind leg and one for the whole carcass were derived using the approach of Purchas *et al.* (1991). The hind leg measure was based on the length of the femur and the combined weight of the three dissected muscles (M3FL), while the whole carcass measure was derived using the total weight of muscle in the side and side length (TMSL). Further details of how these measures were calculated are given in Table 2.

Ultrasound scanning

Measurements of LTL depth were taken by ultrasound with a view to comparing results with those obtained using CT. Measurements were taken on the right side of the lambs at the position of the 12/13th thoracic vertebrae using a Vetscan real-time B-mode ultrasonic scanner with a 3·5 mHz transducer, within 24 h of CT scanning. Muscle depth was measured vertically at the deepest point of the muscle. The resolution of measurements taken using this machine was 1 mm.

CT scanning

All lambs were fasted for a minimum of 4 h before scanning to minimize any risk of pneumonia due to inhalation of regurgitated fluid. Fifteen minutes prior to scanning lambs were injected intramuscularly with a mild sedative to minimize the amount of movement during the scanning process [0·1 to 0·2 mg xylazine hydrochloride per kg body weight (ROMPUN 2%, Bayer p. l. c., Animal Health Business Group, Bury St Edmonds, UK)]. Body weights were measured just prior to injection to determine the correct dosage.

Once sedated, lambs were placed on their backs in a semi-cylindrical plastic cradle for scanning. Foam pads and straps were used to restrain the lamb with the hind legs extended and the fore legs held along its chest. Each lamb was scanned following a standard scanning protocol. Firstly, two partly overlapping longitudinal scans of the body were taken (topograms), one covering predominantly the thoracic region (topogram 1) and the other covering the abdomen and thighs (topogram 2). When combined, the scans covered the area from just below the knee joint (caudal to the ischium) to just cranial of the first rib. A series of cross-sectional scans (tomograms) were then taken at specific sites identified and positioned in relation to bony landmarks on the topograms. The time taken to scan each lamb, once they were strapped in the cradle, was approximately 5 min.

A total of seven tomograms were available for each lamb, having been taken as part of a separate trial (see Young *et al.*, 1999). Three of these were selected for use as part of the current study. These were positioned (i) through the 5th lumbar vertebra (LV5), (ii) through the mid-shaft of the femur (FEM), and (iii) through the ischium (ISC). The LV5 scan was chosen to obtain measurements of LTL dimensions since a scan through the 12/13th thoracic vertebrae, where ultrasound and carcass measurements were taken, was not available. An example of the image obtained from the topograms depicting positions of the three tomograms is shown in Figure 1.

Image analysis

Analysis of scan images was undertaken using the Sheep Tomogram Analysis Routines software (STAR, version 0·6), which was developed jointly by Biomathematics and Statistics Scotland (BioSS) and SAC. The software was used to determine the total area of fat, muscle and bone in each image and to measure linear dimensions and areas of individual tissue units on CT scans. The resolution for these measurements is determined by the resolution of images. Since each image is composed of a number of 2 mm × 2 mm pixels, measurement resolution was 2 mm.

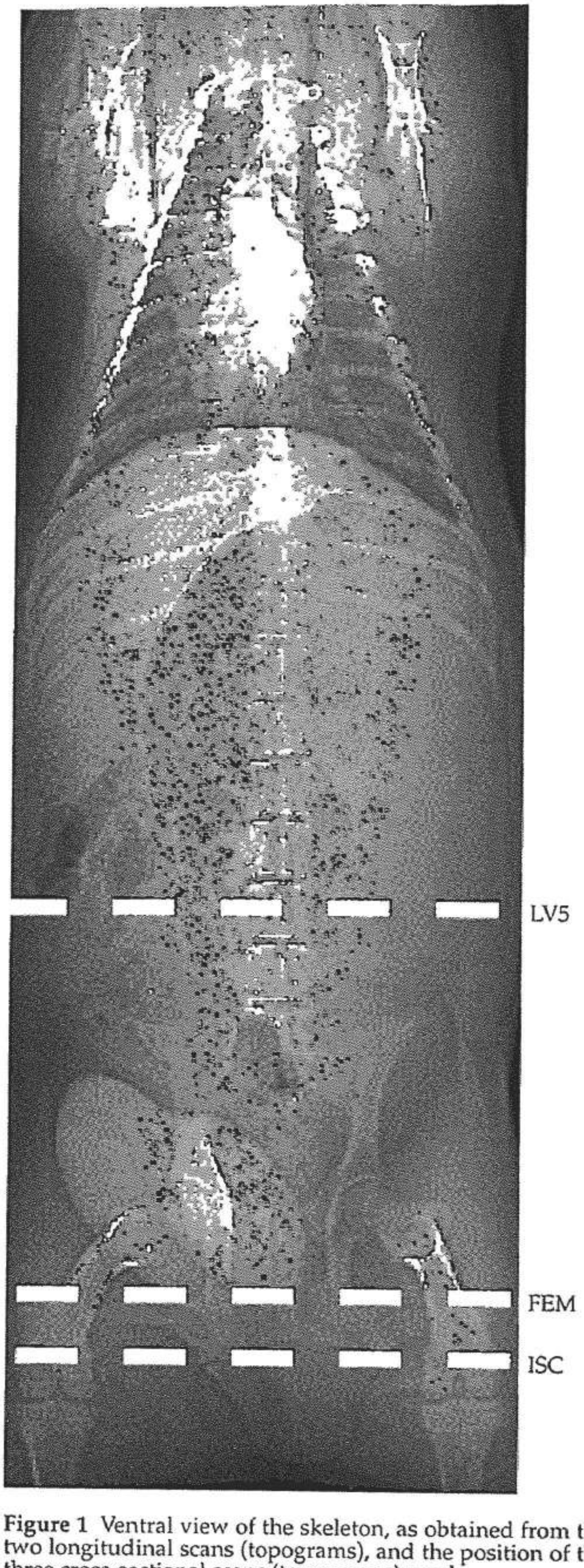

Figure 1 Ventral view of the skeleton, as obtained from the two longitudinal scans (topograms), and the position of the three cross-sectional scans (tomograms) used.

Prediction of total carcass muscle weight

Young *et al.* (1999) showed that the total weight of muscle in the carcass of Suffolk lambs could be predicted accurately ($R^2 = 96\%$) using equations that included live weight and the area of muscle on CT scans from the 8th thoracic vertebra (TV8), LV5 and ISC positions. Similar breed-specific equations, which included the same predictors were also developed for Charollais and Texel sheep (using the data described here), with prediction accuracies (R^2) of 98 and 96% respectively (M. J. Young *et al.*, unpublished). The relevant equation was used to predict the total weight of muscle (TM_{CT}) for each lamb in the current study.

Linear measurements

Spine length. The exact position of the *Symphysis pubis* was not always clear on the topogram 2 scan, but the disc between the pelvis and the last lumbar vertebrae could be seen. The length of the lumbar-thoracic spine was therefore measured in preference to side length. Since the whole spine could not be seen on a single topogram, separate measurements of the thoracic and lumbar sections were taken. The length of the thoracic section of the spine (SPL_{Thor}) was measured on the topogram 1 scan as the distance from the first disc caudal to the last rib to the first disc cranial to the first rib. The length of the lumbar section (SPL_{Lum}) was measured on the topogram 2 scan as the distance from the disc on the cranial side of the pelvis to the first disc caudal to the last rib. The number of vertebrae in each of the measured sections was also recorded. Overall spine length (SPL) was calculated as the sum of the lengths of the two sections. Diagrammatic representation of these measurements is shown in Figure 2.

M. longissimus thoracis et lumborum (LTL) dimensions. Measurements of width and depth of the cross-section through the LTL muscle were taken on both the left and right muscles on the LV5 CT scan using the method described by Pálsson (1939) for measurements on the carcass (see Figure 3). Care was taken to exclude skin and subcutaneous fat when

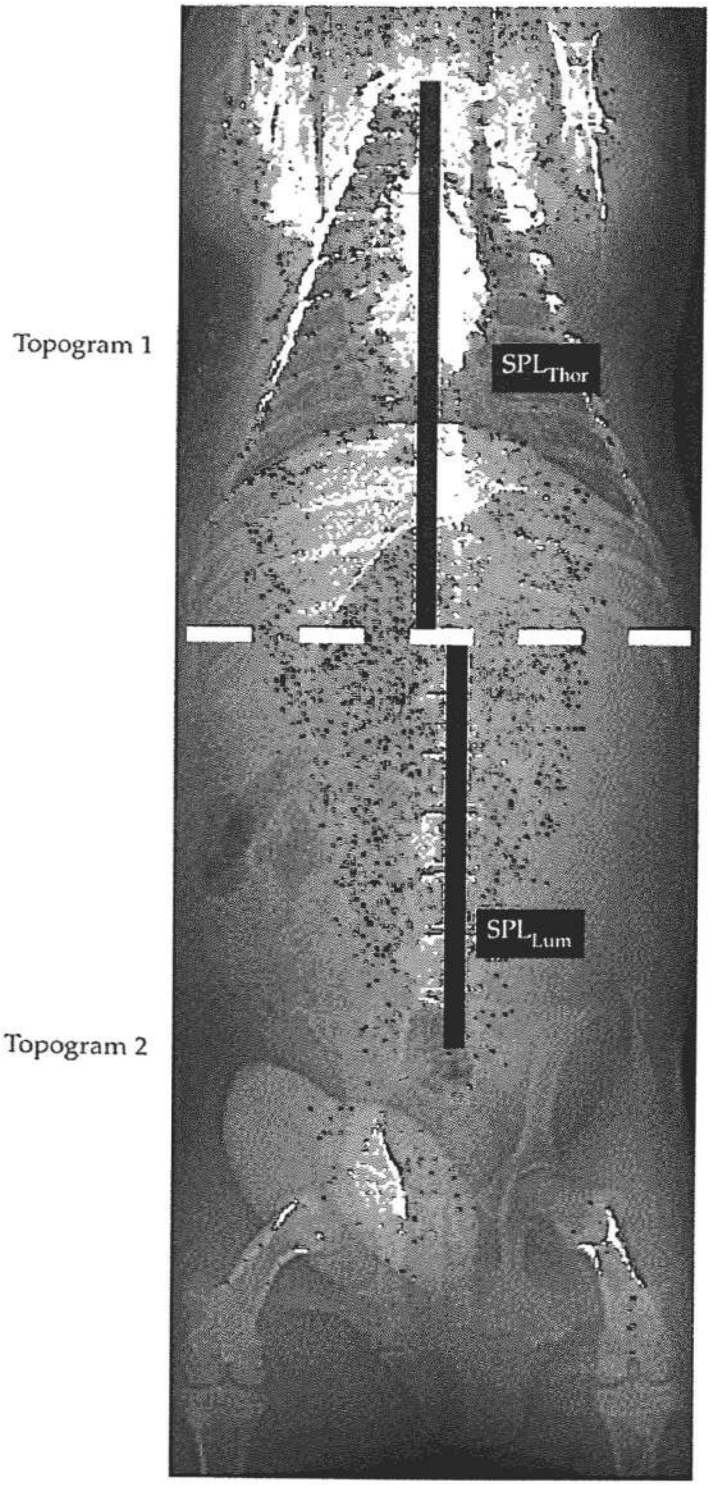

Figure 2 Diagramatic representation of the measurements of length of the thoracic and lumbar regions of the spine taken on the two topogram scans. The broken white line represents where the two topograms have been overlapped to show the complete longitudinal scan of the body.

measuring LTL depth. Means of measurements made on the two sides were used subsequently.

Hind leg. Both femurs could clearly be seen on the topogram 2 scan and the length of each femur was measured as the distance from the central point on the head to the deepest point in the intercondyloid fossa. Coefficients of determination (R^2) for the regression of femur length, measured directly on the dissected carcass, and the mean of the two measurements on the topogram 2 scan were, however, consistently low ($< 5\%$), indicating that these measurements were a poor indicator of actual femur length.

Indirect measures of hind leg muscularity were therefore considered as an alternative approach. Four dimensionless ratios, two on the FEM scan and two on the ISC scan, were derived. These were based on the ratio of two linear measurements taken on the same scan, one of the width and the other of length of the thigh. Measurement positions on the scans were defined in relation to anatomical features that were reliably present and distinguishable on scan images with the aim of achieving highly repeatable measures. Measurements were taken on the right and left thighs in a scan and the mean value used.

Thigh length (L_{FEM} and L_{ISC}) was measured on each scan as the distance from the centre of the ischium bone to the tip of the leg. This measurement passed through the femur. Two width measurements were taken on the FEM scan. The first was defined as a straight line from the furthest point (from the femur) on the *gracilis* muscle to the lateral muscle boundary, crossing the 'length line' at 90°($W1_{FEM}$). The second width measurement was defined as a straight line from the medial to the lateral muscle boundary passing through the fat depot between the *adductor/gracilis* and *semimembranosus* muscles, and crossing the 'length line' at 90°($W2_{FEM}$). Two width measurements were taken on the ISC scan. The first was defined as a straight line from the medial to the lateral muscle boundary, passing through the popliteal fat depot and crossing the 'length line' at 90°(W_{ISC}). The thickness of the popliteal fat depot on this line (P_{ISC}) was also measured and then subtracted from the initial thigh width to obtain a second width measurement, that due only to muscle. Care was taken to exclude any skin and visible subcutaneous fat when width measurements were taken on both scans. Measurements taken on the tomograms are shown in Figure 3.

CT measures of muscularity
Seven CT measures of muscularity were derived : two for the LTL, one for the whole carcass and four for the hind leg. LTL measures were calculated as the ratio of LTL width to spine length ($ASPL_{CT}$) and the ratio of LTL depth to spine length

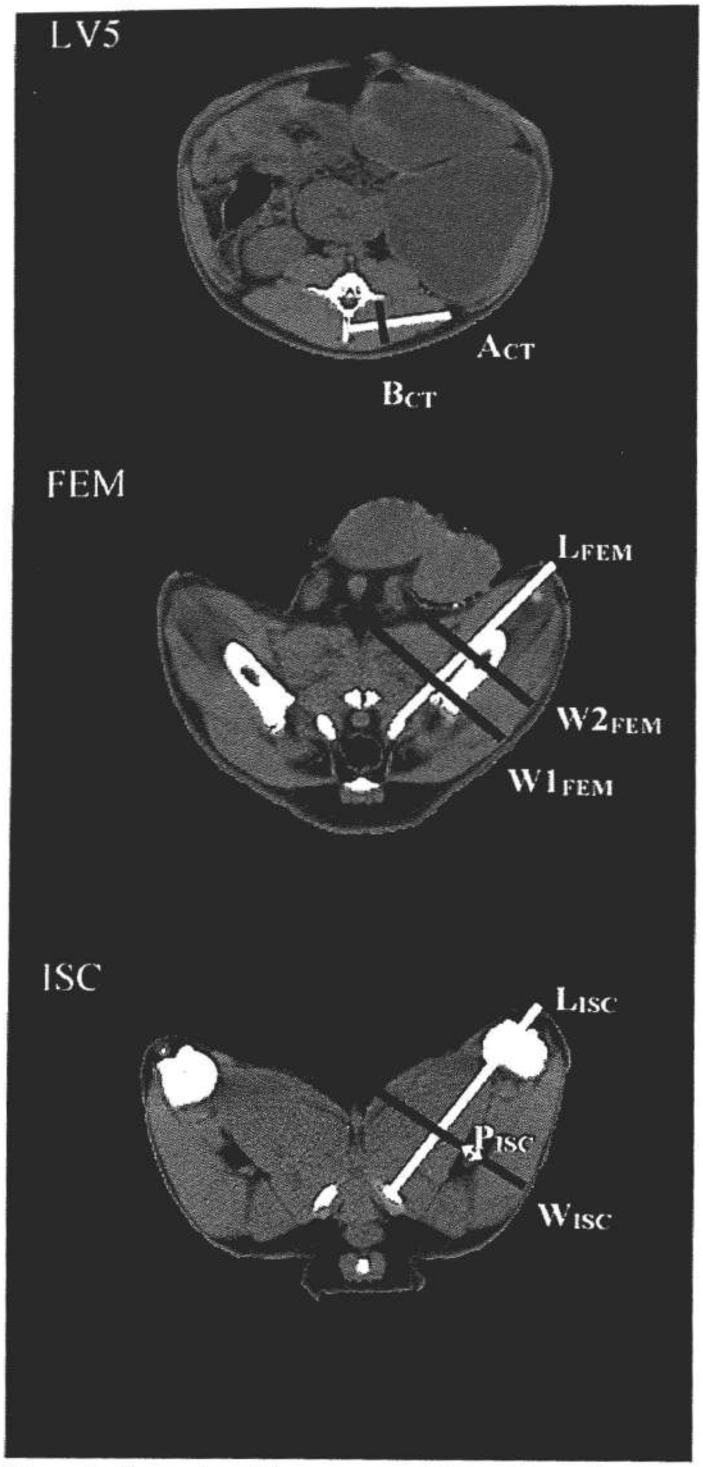

Figure 3 Examples of tomograms obtained from the three positions and diagramatic representation of the measurements taken on each scan.

($BSPL_{CT}$). The whole carcass measure was based on the approach of Purchas *et al.* (1991), and incorporated the predicted carcass muscle weight and spine length ($TMSPL_{CT}$). Further details about the calculations for these measures and the four dimensionless measures for the hind leg ($W1L_{FEM}$, $W2L_{FEM}$, WL_{ISC} and WPL_{ISC}) are given in Table 5.

Statistical analysis
Data for two Suffolk males and three Suffolk females were removed. Their live weights were greater than two standard deviations below the mean for their respective slaughter age groups (within breed-sex) causing the distribution to be highly skewed ($P < 0{\cdot}05$). Data for one Texel lamb were also removed due to poor quality of CT images.

Repeatability of measurements on scans
CT scans for 15 male Suffolk lambs from a single slaughter age group were used to assess the within- and between-operator repeatability for each of the CT linear measurements defined. One operator first repeated the same set of measurements three times at approximately 24-h intervals. Three other operators then measured this same set of CT scans once. Repeatability was assessed as the intra-class correlation between measurement occasions, either within operator or between operators as appropriate. Within and between animal variances were obtained using analysis of variance (ANOVA).

Correlations
Simple and residual correlations (after regressing each variable on live weight) between corresponding measurements taken on the carcass and by CT or ultrasound were initially derived for each breed-sex. Differences between correlation coefficients for each breed-sex category were then tested following a Fisher transformation of these coefficients to z values (Zar, 1996). Comparisons were conducted across all four breed-sexes using a multiple sample test

Table 1 *Within and between operator repeatability (%) for measurements taken on the CT scans*†

Measurement	Within	Between
SPL_{Lum}	99	98
SPL_{Thor}	92	87
SPL‡	86	79
A_{CT}§	99	92
B_{CT}§	95	90
L_{FEM}§	99	99
$W1_{FEM}$§	98	95
$W2_{FEM}$§	91	85
L_{ISC}§	99	99
W_{ISC}§	91	82
P_{ISC}§	97	91

† Diagrammatic representations of each of the measurements are shown in Figures 2 and 3.
‡ Sum of SPL_{Lum} and SPL_{Thor}.
§ Mean of the measurements taken on the left and right side of the image.

(experiment wise error rate of 5%). Correlation coefficients were not different ($P < 0{\cdot}05$) between breed-sex categories for the same pair of variables and therefore a common (pooled) coefficient was calculated across breed-sexes.

Side and spine length

Correlation coefficients between side length (SL) and the individual lengths of the lumbar (SPL_{Lum}) and thoracic regions (SPL_{Thor}), and their sum (SPL), were determined. The correlation of SL with SPL_{Lum} and SPL_{Thor} individually was used to investigate the possibility of using just one of these measurements to represent spine length.

LTL dimensions

Correlations between the CT dimensions and their corresponding carcass dimensions were determined, and between the ultrasound measurement and corresponding carcass LTL depth.

CT and dissection measures of muscularity

Correlations between each of the four dissection measures of muscularity and the equivalent CT measures of muscularity were determined. These included, between ASL and $ASPL_{CT}$; BSL and $BSPL_{CT}$; TMSL and $TMSPL_{CT}$ and between M3FL and each of $W1L_{FEM}$, $W2L_{FEM}$, WL_{ISC} and WPL_{ISC}.

Regression analysis

Although correlation coefficients between the CT and dissection measures of hind leg muscularity were not different between breed-sexes, preliminary investigations suggested that the nature of the relationships differed. These differences were further investigated using regression analysis. Data across breed-sex categories were combined and the effect of breed-sex and the linear regression of hind leg muscularity on a CT scan ratio were fitted. In preliminary investigations, slopes for the regression on each individual ratio were not different between

Table 2 *Means, pooled standard deviation and residual standard deviation for linear measurements taken on the carcass and on the live animal using computer tomography (CT) or ultrasound for Suffolk, Texel and Charollais lambs*

		Mean					
		Suffolk					
	Abbreviation	Males	Females	Texel Males	Charollais Males	s. d. †	Residual s. d. †
No.		48	47	39	20		
Live weight		64·4	54·4	45·93	55·9	12·90	
Side and spine length (cm)							
Carcass, side	SL	65·54	63·30	56·25	63·68	4·42	1·46
CT, spine	SPL	54·02	51·69	45·92	52·39	3·64	1·62
CT, lumbar	SPL_{Lum}	22·87	22·09	19·06	22·16	1·93	1·35
CT, thoracic	SPL_{Thor}	31·15	29·59	26·86	30·23	2·15	1·19
LTL depth (mm)‡							
Carcass§	B	38·40	35·26	38·77	35·85	4·48	3·37
CT, LV5 scan	B_{CT}	39·72	37·36	35·69	34·84	5·18	3·31
Ultrasound§	B_{US}	30·04	28·65	26·17	26·36	3·08	2·65
LTL width (mm)‡							
Carcass§	A	67·08	64·77	67·46	66·40	5·29	4·25
CT, LV5 scan	A_{CT}	80·98	76·34	76·31	78·90	6·19	3·92
Dissection muscularity¶							
LTL	ASL	10·25	10·24	12·00	10·46	0·73	0·70
LTL	BSL	5·91	5·55	6·88	5·64	0·59	0·58
Hind leg	M3FL	4·15	4·10	4·38	3·90	0·25	0·24
Whole carcass	TMSL	5·17	5·00	6·18	5·33	0·24	0·23

† Pooled within breed-sex estimates; residual s. d. is after adjustment for live weight.

‡ LTL = *m. longissimus thoracis et lumborum.*

§ Measurements were taken at the 12/13th thoracic vertebrae.

¶ ASL = (A/SL) × 10; BSL = (B/SL) × 10; TMSL = ($\sqrt{TM / SL^3}$) × 1000; M3FL = ($\sqrt{M3 / FL^3}$) × 10. TM is the total weight of muscle in the left side of the carcass (kg); FL is the length (cm) of the femur; M3 is the combined weight of the *m. semitendinosus, m. semimembranosus and m. gluteobiceps* muscles dissected from the hind leg (g).

breed-sexes (P > 0·05), although intercepts differed (P < 0·05). A single common slope was therefore fitted. Once the regression on any CT scan ratio was fitted the additional affect of live weight was not important (P > 0·05) and therefore was excluded from the model. All statistical analyses were performed using Genstat (1998).

Results

Repeatability of measurements on scans

Within- and between-operator repeatability for each of the key measurements taken on CT scans are shown in Table 1. Generally repeatabilities were high indicating that measurement positions could be clearly identified on each scan with low measurement error. The repeatabilities for overall spine length (SPL), although lower than for both component measurements, were also high.

Summary statistics

Table 2 details simple means, pooled standard deviations and pooled residual standard deviations (after regressing on live weight) within breed-sex for each of the individual carcass, CT and ultrasound measurements, and the dissection measures of muscularity. Pooled estimates of standard deviations and residual standard deviations are presented since within breed-sex estimates were found not to be different when tested using a Bartlett's test (P > 0·05). Within breed-sex means for CT muscularity on the hind leg are not shown, but these ranged from 0·85 to 0·81 for $\mathrm{W1L_{FEM}}$, 0·67 to 0·64 for $\mathrm{W2L_{FEM}}$, and 0·65 to 0·59 for $\mathrm{WPL_{ISC}}$, with Texels consistently having the highest means and Charollais lambs the lowest. Means for $\mathrm{WL_{ISC}}$ ranged from 0·74 to 0·70, and were lowest for Charollais, but in contrast to the other measures, means for both Suffolk sexes tended to be higher than that for Texels. Although not tested this is likely to be the result of a tendency for Suffolks to have a greater thickness of popliteal fat in the hind leg in comparison with the Texels. Pooled standard deviations and residual standard deviations for each of the four measures in the hind leg were in the range of 0·04 to 0·06.

Although mean live weights differed between breed-sexes, a number of general trends were apparent. CT-measured spine length (SPL) was consistently 0·82 of side length measured on the carcass (SL). Similarly, for the CT measurements the thoracic region of the spine accounted for around 0·58 of the total spine length across breed-sexes. The relative differences between the ultrasound and CT measurement of LTL depth were also fairly consistent, the former being 0·73 to 0·77 of that measured using CT at the more caudal position along the spine. This was not unexpected given that the LTL muscle becomes deeper moving from the last rib towards the pelvis (Davies *et al.*, 1987).

Table 3 *Pooled simple and residual correlation coefficients (across breed-sex) between measurements on the carcass and corresponding or similar measurements taken using CT or ultrasound* †

Side and spine length	SL	SPL	$\mathrm{SPL_{Lum}}$
SL	-		
SPL	0·92 (0·62)	-	
$\mathrm{SPL_{Lum}}$	0·76 (0·40)	0·86 (0·71)	-
$\mathrm{SPL_{Thor}}$	0·86 (0·48)	0·90 (0·66)	0·54 (–0·09)
LTL depth	**B**	**$\mathrm{B_{CT}}$**	
B	-		
$\mathrm{B_{CT}}$	0·70 (0·45)	-	
$\mathrm{B_{US}}$	0·59 (0·42)	0·66 (0·50)	
LTL width	**A**		
A	-		
$\mathrm{A_{CT}}$	0·64 (0·41)		

† Residual correlations (after regressions on live weight) are shown in parentheses. Correlation coefficients differ from zero (P < 0·05), except for the residual correlation between $\mathrm{SPL_{Lum}}$ and $\mathrm{SPL_{Thor}}$. Abbreviations are defined in Table 2.

Table 4 *Proportion of lambs within each breed-sex with each thoracic and lumbar vertebrae number combination*

No. of vertebrae		Suffolk males	Suffolk females	Charollais	Texel
Thor.	Lumb.	(no. = 48)	(no. = 47)	(no. = 20)	(no. = 39)
12	6	0	0	0	0·03
12	7	0·02	0	0	0·10
13	6	0·17	0·23	0·30	0·69
13	7	0·75	0·74	0·55	0·15
14	6	0·06	0·02	0·15	0·03

Correlations

Side and spine length. The correlation between side length measured on the carcass and the combined length of the thoracic and lumbar regions of the spine was high (Table 3). However, the correlations between side length and the length of the individual regions was lower, indicating that the length of both regions needs to be measured to ensure a reliable gauge of side length in the carcass.

The lower correlation between side length and its two components was expected given that the correlation between the individual regions themselves was low (residual correlation –0·09). This low correlation was in part because of variation in the number of vertebrae found in the two regions between lambs within each of the breed-sex categories (Table 4). When the correlation was estimated within groups of lambs with the same number of lumbar and of thoracic vertebrae, the correlation between the length of full spine and the individual regions was higher.

Table 5 *Pooled simple and residual correlation coefficients (across breed-sex) between corresponding dissection and CT measures of muscularity*†

	Carcass	CT	Corr.‡
LTL	ASL	$ASPL_{CT}$	0·32 (0·33)
	BSL	$BSPL_{CT}$	0·44 (0·45)
Whole carcass	TMSL	$TMSPL_{CT}$	0·55 (0·54)
Hind leg	M3FL	$W1L_{FEM}$	0·49 (0·48)
	M3FL	$W2L_{FEM}$	0·64 (0·60)
	M3FL	WL_{ISC}	0·69 (0·60)
	M3FL	WPL_{ISC}	0·63 (0·57)

† $ASPL_{CT} = (A_{CT}/SPL)*10$; $BSPL_{CT} = (B_{CT}/SPL)*10$; $TMSPL_{CT} = (\sqrt{TM_{CT}/SPL^3})*1000$; $W1L_{FEM} = W1_{FEM}/L_{FEM}$; $W2L_{FEM} = W2_{FEM}/L_{FEM}$; $WL_{ISC} = W_{ISC}/L_{ISC}$ and $WPL_{ISC} = (W_{ISC} - P_{ISC})/L_{ISC}$. TM_{CT} is the predicted carcass muscle weight (kg). Abbreviations for other components and the carcass measures of muscularity are defined in Figure 3 and Table 2.

‡ Residual correlations (after regressions on live weight) are shown in parentheses. All correlation coefficients differ from zero ($P < 0·05$).

Although numbers of vertebra in both regions of the spine varied within each breed-sex, it is worth noting that the Texels tended to have fewer vertebrae than the other breed-sexes (Table 4). Whilst 13 thoracic vertebrae was most common in all breed-sexes the incidence of 12 thoracic vertebrae was higher in Texel lambs. Similarly in the lumbar region, six rather than seven vertebrae occurred more often in Texel lambs.

LTL dimensions. CT measurements of LTL depth and width were moderately correlated with equivalent measurement on the carcass (residual correlation > 0·41, see Table 3). The CT measure of LTL depth was more strongly related to the equivalent carcass measurement than was the ultrasound measurement although the difference between the residual correlations was small.

CT and dissection measures of muscularity

Correlations between dissection muscularity and CT muscularity are shown in Table 5. Accounting for differences in live weight had very little effect on correlations with both simple and residual estimates being similar for the same pair of measures. All estimates were moderate to high in magnitude, residual correlations ranging from 0·33, for muscle width to skeletal length, to 0·60 for hind leg muscularity. Of the four CT measures of muscularity for the hind leg, three ($W2L_{FEM}$, WL_{ISC} and WPL_{ISC}) had similar high residual correlations with the dissection measure (0·57–0·60). This suggests that any of these three measures would provide a good prediction of the dissection measure. The residual correlation with the remaining $W1L_{FEM}$ measure, although still high, was lower in comparison (0·48), suggesting that it was less reliable than the other three measures.

Table 6 *Intercepts (α) for each breed-sex and common slope (β) for the regression of dissection hind leg muscularity on each of four CT measures of muscularity in the hind leg*

		α					
Y †‡	X †	Suffolk male	Suffolk female	Texel	Charollais	β	R^2
M3FL	$W1L_{FEM}$	1·947 (0·324)^b	1·864 (0·327)^{bc}	2·196 (0·327)^a	1·765 (0·315)^c	2·635 (0·385)	48·0
M3FL	$W2L_{FEM}$	1·561 (0·252)^b	1·464 (0·255)^c	1·736 (0·257)^a	1·378 (0·247)^c	3·967 (0·383)	57·1
M3FL	WL_{ISC}	1·983 (0·186)^b	1·930 (0·186)^b	2·272 (0·182)^a	1·828 (0·180)^c	2·942 (0·250)	61·6
M3FL	WPL_{ISC}	2·485 (0·170)^b	2·484 (0·165)^b	2·692 (0·173)^a	2·363 (0·160)^c	2·593 (0·261)	55·3

^{a,b,c,d} Within rows, intercepts with different superscripts differ ($P < 0·05$).

† Y is the response (dependent) variable and X is the independent variable. Other abbreviations are defined in Tables 2 and 5.

‡ Raw standard deviation for M3FL across breed-sexes is 0·29.

Regression analysis

Intercepts for the regression of hind leg muscularity on each of the CT measures differed between breeds ($P < 0{\cdot}05$; Table 6). However, the intercepts were not different between the male and female Suffolk's, with the exception of $W2L_{FEM}$. The estimates were consistently highest for Texel lambs followed by Suffolk and then Charollais lambs. This indicates that if any of these CT measures were to be used to compare across breeds, breed specific equations to predict hind leg muscularity would need to be developed. Using a single equation across breed-sex categories would result in under prediction of hind leg muscularity for the Texels and over-prediction for the Charollais.

Discussion

Side and spine length

In the past, skeletal dimensions could be approximated on the live animal only by using external measurements on the body measured with a tape measure, ruler or calliper. Even when clear measurement protocols have been developed, measurement positions are often obscured by subcutaneous fat or wool (where lambs are not sheared) and this can lead to high measurement errors. This is the case for measurements of body length (e.g. anterior point of shoulder to posterior extremity of the pin bone), which is similar to the spine length used here (Taneja, 1955; Tallis *et al.*, 1964).

These problems were not encountered with the CT measurement of spine length since measurement position could be clearly delineated on each topogram. Measurement errors would therefore be expected to be less. Although the external measurement of body length has been used in numerous sheep studies as a measure of skeletal size, the correlation with side length measured on the carcass has not been estimated (Taneja, 1955; Tallis *et al.*, 1964; Weiner and Hayter, 1974; Wolf *et al.*, 2001). Therefore direct comparisons with the results presented here was not possible. Nevertheless, Taneja (1955) and Tallis *et al.* (1964) reported the repeatability of measurements of body length taken on the same animal by a single operator as 0·61 and 0·49 respectively. Taneja (1955) reported the repeatability between two measurements taken at the same catching and thus is similar to the within-operator scenario reported in this study. However, Tallis *et al.* (1964) calculated the repeatability across four measurements, two at each of two catching events. Between-scanning repeatability of CT measurements of spine length was not estimated in this study, but this has been estimated in a small separate trial at SAC (no. = 15; H. Jones and M. J. Young, unpublished). The repeatability was found to be 0·75, despite repeated measurements being taken at 3-weekly intervals. This supports the expectation of higher accuracy for the CT measurements.

LTL dimensions

The images produced using CT were much clearer than those produced using ultrasound. Nevertheless, the partial correlation with the carcass measurements of LTL depth was only marginally higher for the CT as opposed to the ultrasound measurement and both estimates were similar to those reported for ultrasound in previous sheep studies (McEwan *et al.*, 1989; Ward *et al.*, 1992; Hopkins *et al.*, 1993). This suggests that there was little benefit in using CT over ultrasound for measuring LTL depth. A number of factors may account for this finding. The position of the CT scan used was different from that for the carcass and ultrasound measurements (5th lumbar *versus* 12/13th thoracic), and the resolution of the measurements on CT scans was lower in comparison to that for ultrasound (2 *v.* 1 mm). Furthermore, operators of ultrasound scanners can adjust the position or orientation of the scanner head to account for the animal's posture, whereas such corrections cannot be made using CT. Some increase in the correlation between the CT and carcass LTL depth may be achieved by the measures being taken at the same anatomical position, but the increase is unlikely to be large. In preliminary analyses, correlations with measurements taken on a scan at the LV2 position, which is closer to the position on the carcass, were very similar to those obtained with measurements on the LV5 scan.

The partial correlation between the carcass and CT measurement of LTL width was substantially higher than previous estimates for ultrasound, which are typically less than 0·10 (McEwan *et al.*, 1989; Hopkins *et al.*, 1993; Binnie *et al.*, 1995). Thus CT scanning is better than ultrasound for measuring this dimension. Ultrasound is considered to be less effective for measuring LTL width than depth because the reflective characteristics and hence image definition of the lateral boundary of the muscle is poor (McEwan *et al.*, 1989). X-ray CT images, in contrast, are based on the absorption of X-rays, which differs between tissues; all tissue boundaries are therefore clearly delineated allowing equally good measurements of both LTL width and depth (Young *et al.*, 1996). LTL area can also be measured with CT. However, LTL area was not measured on the carcasses in this study and so a direct comparison of *in vivo* and dissection LTL area could not be made.

In previous studies, correlations between *in vivo* measurements and the corresponding dissection measurement have been interpreted as a measure of the accuracy of the *in vivo* measuring technique (i.e. Houghton and Turlington, 1992). However, these correlations are likely to be an underestimate of the 'true' accuracy of the technique in most studies, and particularly in this study. That the shape of the LTL muscle can change post slaughter as a consequence of the carcass being hung, chilled and split is widely accepted (Fortin and Shrestha, 1986; Binnie *et al.*, 1995). Some increase in area and depth likely result due to the effects of cold shortening of the muscle prior to the onset of *rigor mortis*. This is particularly true where carcasses have been hung by the Achilles tendon as opposed to the pelvis, as was done in the current study, since the skeletal restraints on the LTL muscle are reduced (Lawrie, 1991; Houghton and Turlington, 1992). The degree of cold shortening has been shown to vary with time delay before chilling, chilling conditions, body size and, in particular, fatness (Smith *et al.*, 1976). The lambs used in this study were slaughtered at four different ages and varied in fatness and body size both within and between breed-sex categories (Jones *et al.*, 2002). Although reducing the amount of variation present, the regression on live weight used in the analysis would not be expected to fully account for variation in both fatness and body size between lambs. In addition to this, the carcass measurements of LTL dimensions were taken on the thawed carcass. Once thawed the muscle is fairly pliable and can be distorted with handling such that measurement errors on the carcass are likely to be higher than if measured on the chilled or frozen carcass as done in other studies (McEwan *et al.*, 1989; Binnie *et al.*, 1995).

CT and dissection measures of muscularity

LTL and whole carcass. Since each of the carcass and CT muscularity measures derived were dimensionless, the small size of the difference between the simple and residual correlations for these measures was not surprising. For the LTL and whole carcass measures the magnitude of the correlations generally reflected how well the individual components were predicted by the CT measurements. The upper limit for the estimates was likely determined by the correlation between the CT spine length and side length on the carcass (0·62), and hence all estimates were lower than this. That the highest correlation was between the whole carcass measures was also to be expected given that total muscle weight was predicted with near perfect accuracy for lambs of each breed from CT information using the prediction equations available ($R^2 = 96$-98%).

Hind leg. In contrast to spine length the relationship between femur length measured on the topogram and actual measurement on the dissected carcass was poor. The orientation of the spine relative to the plane of the topogram is relatively constant. In contrast, the angle of the hind leg can vary in the X, Y and Z planes but the topogram only displays an X-Y image. Hence we cannot account for variation in leg angle relative to the Z-dimension from just one topogram. Some improvement may be achieved by modifying the way in which the lamb's hind legs are restrained in the scanning cradle but this is unlikely to be sufficient to allow good measurements of femur length to be obtained.

This study used the ratio of two perpendicular measurements on a CT scan to characterize hind leg muscularity. It was assumed that as the angle between the plane of the CT scan and the femur changed both the length and the width of the thigh would change to a similar extent such that changes in their ratio would be small. Whether this assumption is correct remains to be tested.

CT muscularity was a good predictor of dissection muscularity in the hind leg. The ischium scan is one of the three tomograms used in the prediction of composition in terminal sire breeds of sheep (Young *et al.*, 1999). From a practical perspective, a measure of hind leg muscularity on this scan would therefore be preferred, so that additional scans are not required.

The correlation of carcass hind leg muscularity with the WL_{ISC} measure was marginally higher than with WPL_{ISC}. This is likely the result of measurement errors being higher for WPL_{ISC} compared to WL_{ISC}, through the additional measurement of popliteal fat thickness, which was often small and approached the resolution of the image (2 mm). Nevertheless, ignoring the thickness of the popliteal fat depot, may be undesirable if doing so results in a positive association between the measure of leg muscularity and carcass fatness. A further investigation of the relationship between WPL_{ISC} and WL_{ISC} with fatness would be required for this to be established.

Use of CT in selection programmes

In comparison to ultrasound methods, the cost of X-ray CT scanning is high. Cost effective use of the technology is therefore only likely to be achieved as part of a two-stage selection programme, where a subset of lambs are put forward for CT scanning following initial scanning of the larger population using more practical and less costly methods, such as weighing and ultrasound scanning (Jopson *et al.*, 1995 and 1997). Recent work in the UK involving the terminal sire breeds considered in this study indicate that economic returns, net of the costs of CT scanning, will be highest in breeding schemes that CT scan the best 10-20% of rams, as judged by ultrasound scanning on farm (R. M. Lewis *et al.*, unpublished).

If CT scanning was used as part of a two-stage selection programme to obtain accurate predictions of lean and fat weights, the additional cost of obtaining the *in vivo* measures of muscularity would be low. This is because no additional scanning would be required, as the linear dimensions used in this study to derive the *in vivo* measures were taken on the same scans that are used to predict lean and fat weight.

Conclusions

This study has shown that good *in vivo* measurements of the width and depth of the LTL muscle and of the length of the spine can be obtained from CT scans. By using these measurements and total muscle weight (also predicted using CT), measures of muscularity for the whole body and the LTL can be obtained for live sheep. Furthermore, good *in vivo* measures of hind leg muscularity are also possible using CT scanning.

If *in vivo* muscularity measures are to be included in selection programmes for sheep, estimates of genetic and phenotypic parameters for such measures and the correlations between them and other important traits are required. Obtaining these estimates should be the main focus of future work in this area.

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