The Sheep Project (1): determining skeletal growth, timing of epiphyseal fusion and morphometric variation in unimproved Shetland sheep of known age, sex, castration status and nutrition

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ABSTRACT

The Sheep Project was designed to investigate the effects of castration, breeding age and nutritional plane on bone growth, epiphyseal fusion, tooth eruption and tooth wear in sheep. The project investigates a population of 356 unimproved Shetland sheep skeletons evenly distributed between females bred at different ages, males and castrates, raised on either high or low nutritional planes. This first instalment focuses on two aspects of our larger study, namely bone growth and epiphyseal fusion as affected by sex, castration and nutrition. Nutrition, sex and castration are shown to influence bone growth in ways that are often element-dependant and not consistent through time. We demonstrate that metric variability (variance) is strongest in males, with little difference between females and castrates, and that, in our sample, nutrition has little influence on variance in any sex cohort. Of importance to the development of models of past animal management this study demonstrates that the standard epiphyseal fusion ranges used by zooarchaeologists are too narrow in most instances and do not account for the large variation between sexes or the lesser variation between planes of nutrition. We recommend methods for recognizing castration and the presence of more than one sheep breed, or type, within the zooarchaeological record.

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1. Introduction and background

The Sheep Project was developed to create a large modern research collection of domestic sheep (*Ovis aries*) skeletons of known life history to better understand sheep management in the past. The project's key areas of interest are the effects of sex, castration, nutrition, and breeding age on skeletal growth, epiphyseal fusion, and tooth eruption and wear (Baker, 2004; Baker et al., 2005; Dingwall et al., 1996; Payne, 2002). To this end, English Heritage, in collaboration with the Scottish Agricultural College (SAC), raised, slaughtered and processed 356 unimproved Shetland sheep and subsequently recorded data from their skeletons. This is the largest study of known age, sex, and nutritional plane sheep skeletons of a single breed for archaeological purposes to date.

Considerable research has been undertaken on maturation and growth of the sheep skeleton. In advance of the current project, Moran and O'Connor (1994) summarised much of the key literature concluding that a study was required to investigate variation within a single sex group and between sexes within a single controlled population, including the effects of extrinsic factors such as castration and nutrition. They also advocated that the precision of current ageing methods needed to be improved in order to facilitate the elucidation of complicated husbandry regimes, including seasonality. Since then a number of researchers have published results from biometrical and age studies of the sheep skeleton and overviews of methods used in zooarchaeology (Davis, 1996, 2000; Greenfield, 2006; Greenfield and Arnold, 2008; Jones, 2006; Millard, 2006; Twiss, 2008; Zeder, 2006) as well as summaries of our current understanding of the physiological process(es) of bone fusion (Nilsson and Baron, 2004, 2005; Parfitt, 2002). This study follows on from a pilot study of the same material (Baker, 2004),

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limited to castrates and males, as well as these earlier studies. Here we focus on two aspects of our larger study, namely bone growth and epiphyseal fusion as effected by sex, castration and nutrition. Within this study the terms males, females and castrates are used to refer to entire males, or rams, ewes and wethers respectively. These three groups are considered separate sexes unless otherwise specified.

1.1. Epiphyseal fusion: order and age

Most sources agree on the sequence of epiphyseal fusion in sheep (and goat) with few exceptions (see Davis, 2000; Moran and O'Connor, 1994; Zeder, 2006). Factors such as breed/type, domestication status, sex (including castration) (Davis, 2000), or geography (topography and environment) (Zeder, 2006) have little influence over the order in which various epiphyses fuse. Timing of fusion, however, appears to be variable not only between breeds but also between cohorts of a single population (e.g. males, females, castrates) and within cohorts (Davis, 2000) and is a result of various genetic, endocrine and environmental factors, including nutrition, acting on the cartilaginous growth plate between the epiphysis and diaphysis (Nilsson et al., 2005).

1.2. Biometry and fusion

It is a commonly held belief by zooarchaeologists that bones cease longitudinal growth as a result of epiphyseal fusion (though see exceptionally Moran and O'Connor, 1994). The reality is that cessation of longitudinal growth is a precursor to epiphyseal fusion and bones may reach their maximum length some considerable time before epiphyseal fusion occurs; this is particularly true in rodents which do not undergo epiphyseal fusion when reaching sexual maturity (Kennedy et al., 1999). Clinical studies indicate that the key precursor to epiphyseal fusion is growth plate senescence (Marino et al., 2008; Nilsson and Baron, 2004, 2005; Parfitt, 2002) and accompanied cessation of longitudinal growth. Growth in other dimensions (breadth, depth) may cease before fusion or increase following fusion (Davis, 1996, 2000; Payne and Bull, 1988); in rare cases there is negative growth (shrinkage) post-fusion (Davis, 1996, 2000).

1.3. Effects of sex and castration

There are clear indications, from studies of sheep and goats (Davis, 2000; Field et al., 1990; Ho et al., 1989; Moran and O'Connor, 1994), as well as other species (fallow deer: Carden and Hayden, 2006; white-tailed deer: Purdue, 1983; humans: Krogman, 1962; Schwartz, 1995; Stewart, 1979), that fusion occurs earlier in females than in males, although some variation exists. Noddle (1974) records a slight delay (1 month) in male goats compared to females for the distal humerus and proximal phalanges, both early fusing epiphyses. Hatting's (1983) data suggests that some sheep epiphyses fuse earlier in females than in males but other epiphyses follow the reverse pattern, and that this difference is not restricted to early or late fusing epiphyses. The data in Moran and O'Connor (1994) suggest that sheep epiphyseal fusion generally begins earlier in females than in males except for the latest fusing epiphyses in which the timing of the onset of fusion is similar, though completion may be slightly later in females compared to males. Zeder (2006) notes no differences in timing of fusion between male and female sheep. Castrates show a clear pattern of delayed epiphyseal fusion relative to both males and females, irrespective of breed (Davis, 2000; Hatting, 1983; Tschirvinsky, 1909, in Moran and O'Connor, 1994; Noddle, 1974 for goats). The scale of epiphyseal fusion delay is highly variable in sheep, ranging from a few months to 1.5 years in the later fusing epiphyses, and depends partly on the age at

which the animals were castrated (Hatting, 1983; Moran and O'Connor, 1994). There is little agreement amongst the published sources on the influence that timing of castration has on epiphyseal fusion though it has been noted that early castration will lead to around a year's delay in late fusing elements (Davis, 2000).

1.4. Effects of nutrition

In sheep husbandry deliberate varying of nutrition may have several objectives, for example 'flushing' to increase female fertility and poor pasturing to produce finer wool (Fraser, 1951). Husbandry may also lead to more inadvertent nutritional variation, such as seasonal and/or geographical (during transhumance) availability of fodder A number of studies have been undertaken on the effect of different planes of nutrition on development of bones and teeth, almost exclusively within the realm of agricultural science and meat industries (see summary in Moran and O'Connor, 1994). Malnutrition, low planes of nutrition or specific nutritional deficiencies in sheep may lead to a delay in tooth eruption and bone development however the effect of nutritional plane on the skeleton is not straightforward, and levels and timing of malnutrition, sex, and skeletal element, amongst other factors play a part. Zooarchaeological evidence also exists which suggests that poorer nutrition results in small sheep and goats (Davis, 1996; Noddle, 1974). Davis (1996) notes that the bones of Shetland females qualified in life as in poor condition were smaller than those described as average and good. In other species, the effects of poor nutrition are also shown to result in smaller body size. In reindeer, Skogland (1989), summarised in Weinstock (2006) noted that when females are under nutritional stress, their somatic growth is arrested in order to continue their reproductive role.

2. Methods

2.1. Breed choice, flock management, live recording, slaughter, and skeleton preparation

In collaboration with the Scottish Agricultural College (SAC), Penicuik, Scotland, sheep were raised from a first generation of animals bred from females of the unimproved Shetland type raised in the Voe area of Shetland, and males of the pure Shetland breed bought at Lerwick Auction Market, also on Shetland (Dingwall et al., 1996). Sheep of the Shetland breed were chosen for this project because they are relatively unimproved and are closer in type to pre-British Agricultural Revolution (17th—19th century AD) animals than modern English breeds (Payne, 2002).

Only singleton lambs from females were allocated to the experiment eliminating the potential for small body size bias resulting naturally from multiple births. From birth, the project animals were raised on two adjacent fields of different pasture quality, at an altitude of 200 m. The high plane pasture consisted of well-drained rotational grassland while the low plane field consisted of poorly drained native grassland. The nature of the grazing is described in Dingwall et al. (1996). Both groups received additional hay during snow cover but no concentrate feeding was provided. The unimproved and improved nutritional groups are defined as low plane and high plane respectively in this study. Half of the ram lambs were left entire and the other half castrated when a few days old using a rubber ring applied by elastrator (Dingwall et al., 1996). Equal numbers of females were left unbred, bred at 18 months and 30 months.

The 356 sheep were slaughtered from 1999 to 2001 in nine slaughter groups (age cohorts) and 12 treatment groups (nutrition and sex). The maximum sample size for each group is eight animals (Table 1). The sheep were slaughtered at 3/4 and 9/10 month

Table 1
Breakdown of Shetland sheep slaughter groups by age, sex and nutrition.

Cohort	Age (months)	Male	Castrate	Female unbred	Female early bred	Female late bred	Total
Low plane of nutrition							
1	7	8	8	8	0	0	24
2	16	4	4	4	0	0	12
3	19	4	4	4	0	0	12
4	28	4	4	4	4	0	16
5	31	6	6	6	6	0	24
6	40	4	4	4	4	4	20
7	43	6	6	6	6	6	30
8	52	4	4	4	4	4	20
9	55	4	4	4	4	4	20
Total		44	44	44	28	18	178
High plane of nutrition							
1	7	8	8	8	0	0	24
2	16	4	4	4	0	0	12
3	19	4	4	4	0	0	12
4	28	4	4	4	4	0	16
5	31	6	6	6	6	0	24
6	40	4	4	4	4	4	20
7	43	6	6	6	6	6	30
8	52	4	4	4	4	4	20
9	55	4	4	4	4	4	20
Total		44	44	44	28	18	178
Grand Total							356

intervals in August/September and November/December, in order to avoid periods of gestation, lambing (late April–early June) and suckling. The resulting age structure includes groups aged approximately 7, 16, 19, 28, 31, 40, 43, 52, and 55 months at death. Within each slaughter group age varies slightly with a difference of 14–35 days between the youngest and oldest animal (in only a few cases the difference is higher).

Preparation of the 356 sheep skeletons was undertaken by Mick Revill at the English Heritage Zooarchaeology Laboratory, Portsmouth, following Davis and Payne (1992), with modifications described in Revill (2005). Detailed records are available for each skeleton.

2.2. Recording epiphyseal fusion and metrics

The state of epiphyseal fusion for each fusion plane was recorded using four fusion stages: unfused (u), fusing (fg), fusion line open (fo), and fused (fu) as defined in Table 2 (after Davis, 2000). Stages u and fg are subdivisions of the basic unfused state while fo and fu are subdivisions of the fused state.

Measurements were taken based on von den Driesch (1976), Davis (1996), Greenfield (2006) and the Sheep/goat working party recommendations (unpublished), or defined for this study. They are illustrated in Figs. 1–5 and described in Table 3. Raw data are presented online in Supplementary Table A.1. Illustration and definition of the measurements taken for this study is deemed necessary to avoid potential ambiguity in comparative works. All measurements were taken on the left side of the body unless a pathology or breakage existed in which case measurements from the whole element were taken from the right side. Intra- and inter-observer measurement error was tested on 20 complete

sheep skeletons to ensure the accuracy of the recording protocol (Fig. 6). Generally, inter-observer error is slightly larger than intra-observer error. Overall, the intra- and inter-observer error rates are within acceptable limits. Mandibular tooth eruption and wear were recorded following Payne (1987) and will be addressed in a forthcoming study.

3. Results and discussion

3.1. Epiphyseal fusion timing

Fusion ranges of the sheep in this study are presented in Table 4 separated by sex and nutrition plane. An epiphysis is considered fused if it is recorded as either fo or fu.

The first four fusion planes in Table 4, proximal radius, scapula coracoid process, distal humerus and pelvis acetabulum are all fused by seven months, except for the scapula coracoid process in low males (88% fused) and all males combined (94% fused). Without a slaughter time earlier than seven months it is impossible for us to determine when fusion in these planes begins. By examining the ratio of fu:fo fusion states we can be sure, however, that the order in which we have listed the elements is the order in which they complete their fusion; the proximal radius first and pelvis acetabulum last. At seven months proximal radii of all sex and nutrition groups are fully fused (fu), while the scapula (excluding a single unfused element in low rams), distal humerus and pelvis have fu:fo ratios of 1:1, 0.4:1 and 0.3:1 respectively. Females have a higher fu:fo ratio than males or castrates for the scapula, distal humerus and pelvis indicating that they are further advanced in their fusion at a very early age. Castrates have an equal fu:fo ratio relative to males for the scapula, a slightly higher ratio for the distal humerus and a slightly lower ratio for the pelvis.

Second (medial) phalanges are all under 95% unfused by seven months. As with the other early fusing elements we are unable to determine when fusion of this plane begins. It is clear that the females are in a more advanced fusion state than the males and castrates and that males are slightly more advanced than castrates at seven months.

There are clear differences in the timing of fusion between castrates, males and females confirming earlier observations on epiphyseal fusion in sheep (Davis, 2000; Moran and O'Connor, 1994). Within each slaughter group almost every fusion point is at a less advanced fusion stage in castrates than in males or females. The few exceptions include the coracoid process of the scapula and the distal humerus. For the later fusing epiphyses, fusion commenced later and/or lasted longer in castrates by up to 12 months (exceptionally up to 21 months) relative to males and by 21 months relative to females. For almost all fusion points, females show the earliest onset of fusion and the earliest completion of fusion compared to castrates and males.

For all fusion points, except the *caput femoris*, fusion in the high nutrition castrates is advanced compared to the low nutrition castrates. Fusion in high nutrition males is advanced compared to low nutrition males with the exception of the distal metacarpal, which begins fusion earlier (though ends fusion later) in low nutrition males. In almost all cases, fusion is at a more advanced

Table 2
Definition of fusion states.

Fusion state	Abbreviation	Definition
Unfused	u	Epiphysis and diaphysis completely separate
Fusing	fg	Spicules of bone join epiphysis to diaphysis but the two can be separated by finger force
Fusion line open	fo	Suture opening clearly visible but sufficiently fused that epiphysis cannot be broken away with finger force
Fused	fu	Fusion line is closed but bone remodelling may still be visible
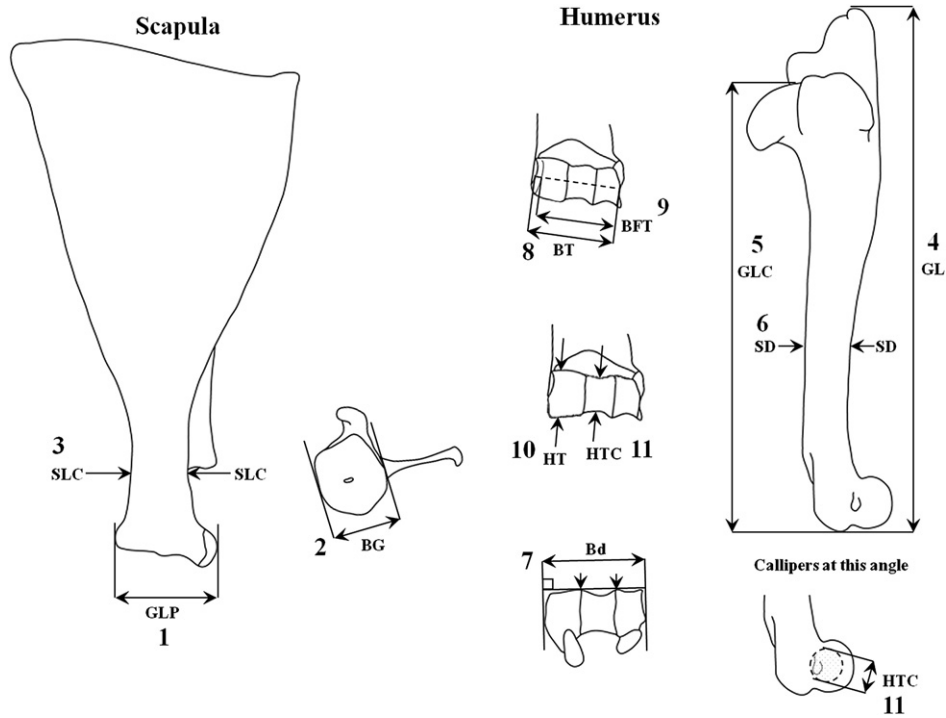
Fig. 1. Humerus measurements (see Table 3 for definitions).

stage in high nutrition females than in low nutrition females. For the later fusing epiphyses, the onset and/or completion of fusion occurs between 3 and 12 months later in low nutrition females than in high nutrition females. The only exception is the *caput femoris* which, as with castrates, begins fusion earlier in the low nutrition group.

Differences in plane of nutrition affect when fusion begins and how long it lasts. This study shows that there is a tendency to

a greater duration of the fusion process in the low nutrition relative to the high nutrition groups. The potential effect of nutrition must be recognized in the comparative analysis of archaeological data. Future research should focus on elucidating whether or not there is a consistent pattern (i.e. an increase or decrease) in fusion duration throughout the growth of an individual or cohort.

How do our fusion data compare with published sources? Table 5 shows sheep fusion data from Silver (1969), chosen because
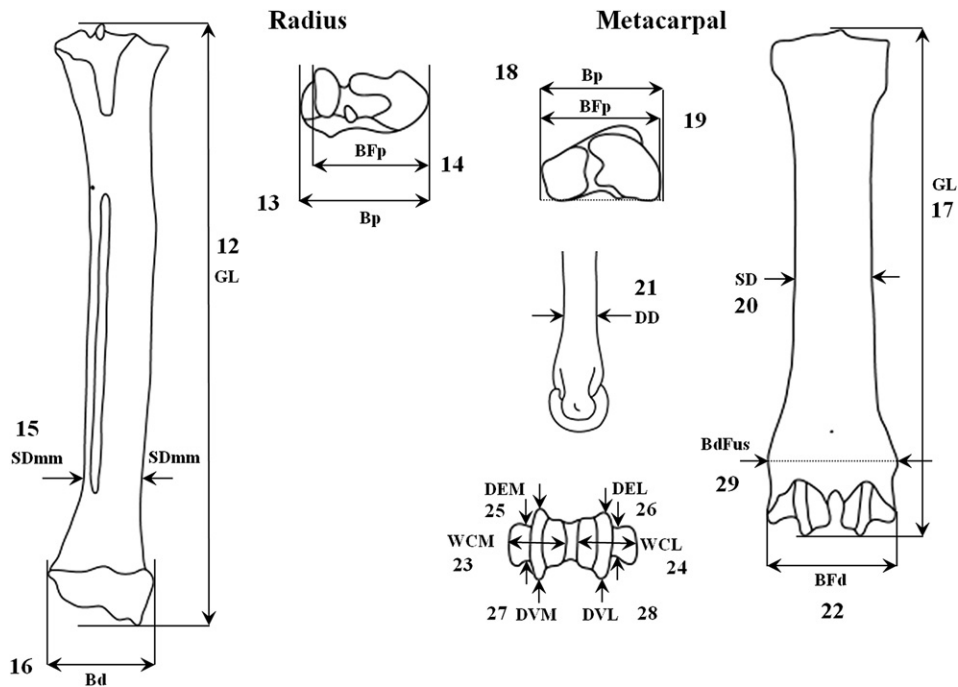
Fig. 2. Radius and metacarpal measurements (see Table 3 for definitions).
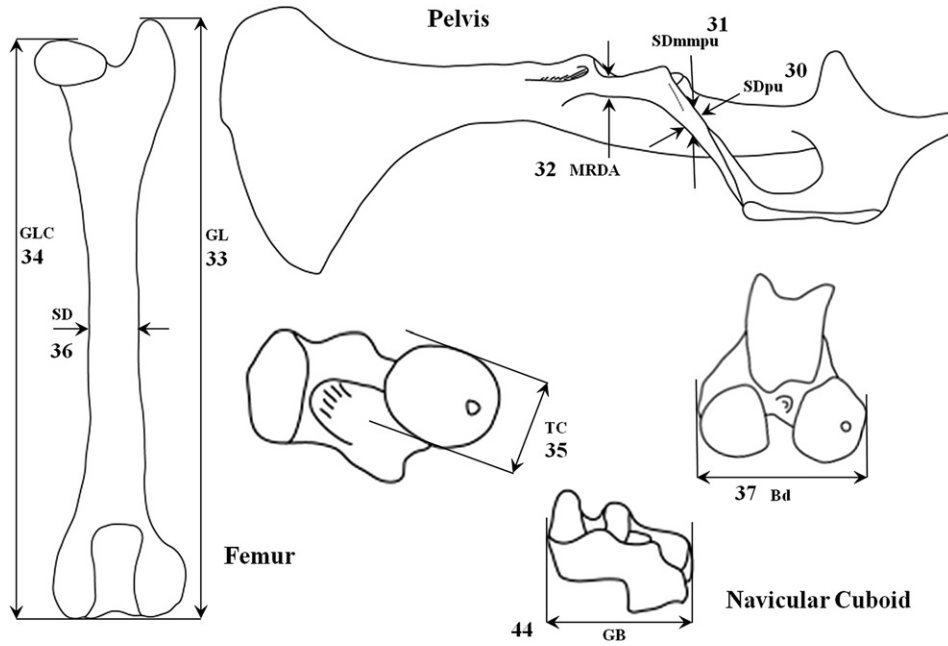
Fig. 3. Femur and pelvis measurements (see Table 3 for definitions).

it remains the most commonly cited reference, Hatting (1983) as it is based on known sample sizes for each of the three sexes of a single unimproved breed, Moran and O'Connor (1994) chosen because it includes males, females and castrates and Zeder (2006) as it is a recent source including both male and female sheep. It is apparent that there is only a rough correspondence between our data and these four published sources. Our data indicate that fusion begins earlier and ends later in most instances when the whole flock is considered, though the end times of our later fusing epiphyses in the male and female category are a reasonable match for Moran and O'Connor's data. Silver's fusion ranges are sufficiently narrow to indicate they likely represent a single sex, possibly castrates. Zeder's data are not based on animals of known age and have been aligned with tooth eruption and wear categories limiting their use as well. On the basis of our data, and until further refinement is possible, we suggest that on sites where castrates may have been present our whole flock data, though broad, represent the most realistic sheep epiphyseal fusion ranges available. Where castrates are unlikely to be present, our combined male and female fusion ranges may securely be used.
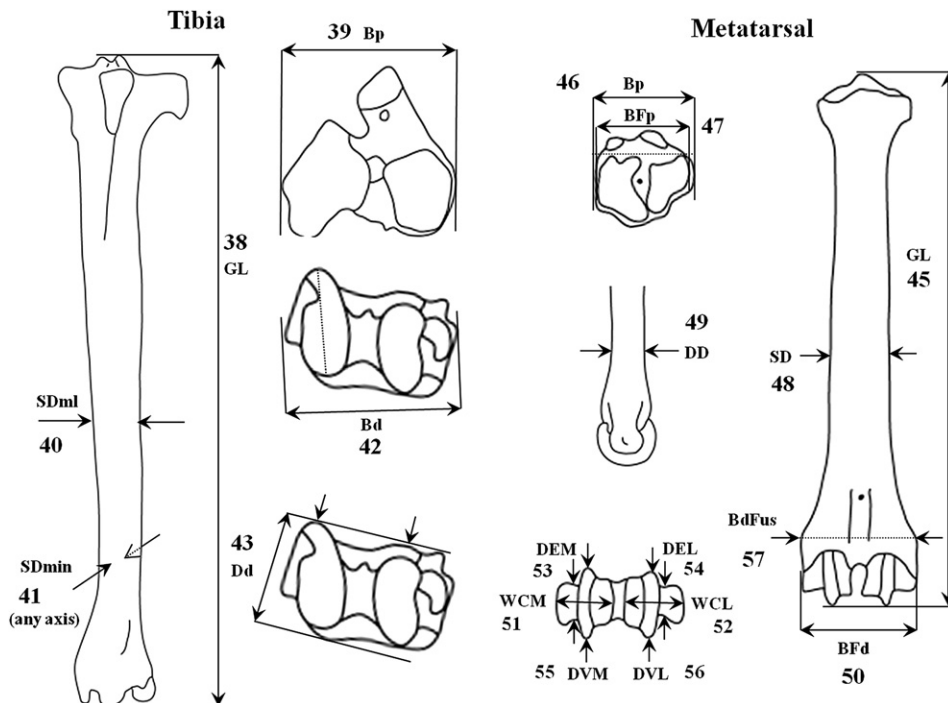
Fig. 4. Tibia and metatarsal measurements (see Table 3 for definitions).
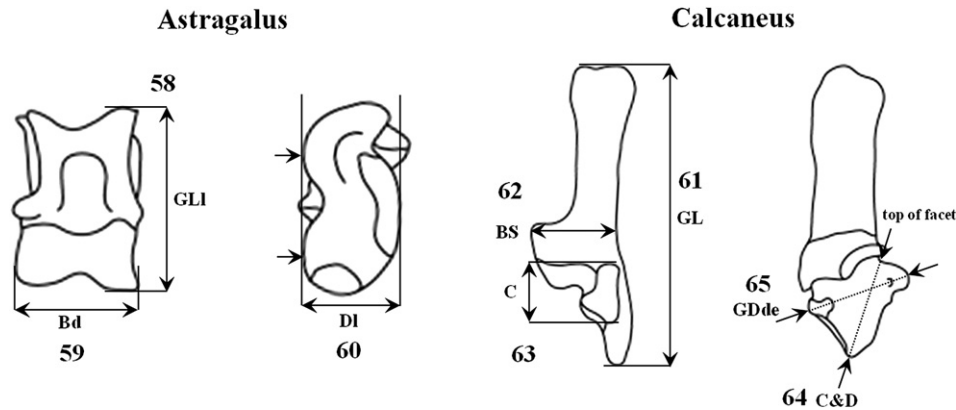
Fig. 5. Tarsal measurements (see Table 3 for definitions).

3.2. Bone growth and age

Bone growth in mammals is non-linear and best modelled with a sigmoidal curve such as Gompertz growth curve (Humphrey, 1998). Because of this, correlations between measurements and age are investigated with the Kendall Tau correlation analysis here (contra Davis, 2000). The Kendall Tau does not assume a linear relationship (as the Pearson's correlation coefficient does) nor equidistance on an ordinal scale of the ranking positions of the variables (millimetres and days at death) (as in Spearman's correlation coefficient).

Tables 6–8 show the correlation between growth and age for all three sexes, separated by plane of nutrition, when considering all specimens together and only fused (fu and fo) specimens. Two general patterns emerge. Firstly, low nutrition animals exhibit more correlations between growth and age than high nutrition individuals. Secondly, females exhibit fewer correlations between growth and age than castrates who in turn exhibit fewer correlations than males. These patterns are apparent when all specimens and only the fused specimens are considered.

Beginning with the first point, low nutrition animals have a slower growth rate, and a more prolonged growth period, than high nutrition animals. Growth in low nutrition individuals progresses less rapidly across time leading to more correlations relative to high nutrition animals that grow more rapidly and reach their maximum growth potential earlier in life. When maximum growth has been reached, and the growth rate through time is effectively nil, no correlation between growth and age will be observed.

Addressing the second point, females reach their maximum growth potential before castrates and males leading to longer periods of life where no growth is occurring across time limiting the number of correlations. Males continue to grow post-fusion, particularly in the breadth dimension, as they gain weight leading to more frequent correlations between size of breadth measurements and age.

This analysis confirms Davis's (1996) findings that certain areas of bone continue to grow post-fusion so should be used with caution when conducting animal size comparisons. Not surprisingly these areas of bone often fuse early in the animal's life. The following measurements show significant post-fusion growth in at least one sex: scapula GLP, BG, SLC; humerus Bd, BT, BFT, HT, HTC; radius Bp, BFp; metacarpal Bp, BFp; pelvis SDpu, SDmmpu, MRDA; navicular cuboid GB; astragalus Bd, Dl; metatarsal Bp, BFp. Metatarsal and metacarpal BdFus and pelvis SDpu show significant post-fusion shrinkage in females and castrates.

Davis (2000) notes several measurements of Shetland castrates that his data show to be 'age independent' within the 7–52 month

range: humerus HTC, tibia Bd and Dd, astragalus GLl and Dl, and pelvis MRDA. There is partial agreement between our data and Davis's though our humerus HTC (low nutrition), tibia Bd (low nutrition) and pelvis MRDA (high nutrition) do show significant correlation between growth and age across this age range. Davis suggests that these measurements can be used to compare sheep body size at different sites and across periods. This proposal holds true if the bones can be positively identified as deriving from castrates. Our data indicate that the only truly age independent measure for all sexes, nutrition planes and ages is the astragalus GLl. Measurements not listed here as showing significant post-fusion growth can be considered to have reached full adult size for all nutrition planes and sex groups upon fusion or, for measurements not associated with a fusion plane, when all associated epiphyses are fused, and may securely be used for comparative purposes. The archaeological implication of our biometric data is that the measurements with significant post-fusion growth in at least one sex should be avoided when investigating adult sheep size because, while adult in appearance, they may not be indicative of maximum adult size.

3.3. Intra-element growth relative to sex and plane of nutrition

Growth does not occur equally across all skeletal elements or in all directions across an individual element. To investigate how sex and plane of nutrition affect growth in different axes on individual elements we compare measurements of high and low nutrition groups of females, castrates and males using an independent samples t-test. We also test low nutrition castrates against low nutrition males, high nutrition castrates against high nutrition males, and all castrates against all males to investigate the effect of castration on growth. Only fused (fu and fo) elements are considered for all groups. We used a one-tailed test when comparing planes of nutrition within individual sex groups (females, castrates, males) because previous research indicates low nutrition groups are smaller than high nutrition groups (Davis, 1996). A two-tailed test was used for tests between castrates and males. Tables 9–12 show results of the tests on greatest lengths, shaft widths, and proximal and distal breadths. All t-tests for females versus male and females versus castrates (high versus high, low versus low and all versus all) of greatest length, diaphysis breadth, proximal breadth and distal breadth are significantly different at the $p < 0.001$ level with females being absolutely smaller in size; these data are not included in the tables. The single exception is the low nutrition female and castrate scapula SLC which are significantly different at a lower level ($t = -3.17$ df $= 66$, $p = 0.002$).

Table 3

Measurement definitions; also see accompanying illustrations; * = ease of measurement; + = easy; − = difficult; ** = area of callipers to use; or 'board' if measuring board is required; SGWG = Sheep and Goat Working Group (unpublished).

#	Measurement	Definition	Reference 1	Reference 2	Original name	*	**
Scapula							
1	GLP	Greatest length of the glenoid process (glenoid cavity plus tuber scapulae). Taken as a true maximum	von den Driesch, 1976			+	Flat
2	BG	Breadth of the glenoid cavity. This measurement is effectively a minimum (unlike von den Driesch) using the lateral border of the glenoid cavity as an anchor as in von den Driesch	von den Driesch, 1976			+	Flat
3	SLC	Smallest length (depth) of the neck of the scapula	von den Driesch, 1976			+	Blade
Humerus							
4	GL	Greatest length (long axis). Depending on medial-distal projection, the distal face of the bone may not sit flush against the measuring board	von den Driesch, 1976			+	Board
5	GLC	Greatest length from the caput (long axis)	von den Driesch, 1976	SGWG		+	Board
6	SD	Smallest diameter of the diaphysis regardless of orientation		SGWG		+	Flat
7	Bd	Greatest breadth of the distal end. Not taken at right angle to the longitudinal axis of the humerus but perpendicular to the anterior face of the trochlea and capitulum. Excludes lateral tubercle	von den Driesch, 1976			−	Flat
8	BT	Greatest breadth of the trochlea, parallel to the axis of rotation of the joint. Trochlea is measured in the centre of the anterior face at a right angle to the capitular ridge and includes both outer borders	von den Driesch, 1976	SGWG		−	Blade
9	BFT	Greatest breadth of the Facies articularis distalis. Measured on the same line as BT	This study			−	Tips
10	HT	Maximum height of the trochlea taken with callipers in an anterio-posterior orientation parallel to capitular ridge (similar to HTC)	This study			−	Blade
11	HTC	Diameter of the trochlea at its central constriction. Callipers must not be place too close to the anterior face of the trochlea as this will result in an artificially low value		SGWG		+	Blade
Radius							
12	GL	Greatest length (long axis)	von den Driesch, 1976	SGWG		+	Board
13	Bp	Greatest breadth of the proximal end of the radius including muscle attachments, measured perpendicularly to the sagittal groove	von den Driesch, 1976	SGWG		+	Flat
14	BFp	Greatest breadth of the proximal articular surface, in the same line as Bp	von den Driesch, 1976	SGWG		+	Tips/Blade
15	SDmm	Minimax diameter of the diaphysis; maximum value obtained by rotating the caliers 10-20 degrees around the narrowest point	Name change this study	SGWG	SD	+	Flat
16	Bd	Greatest breadth of the distal end (true maximum)	von den Driesch, 1976			+	Blade
Metacarpal							
17	GL	Greatest length (long axis). Depending on distal articular surfaces bone may not be flush against measuring board	von den Driesch, 1976			+	Board
18	Bp	Greatest breadth of the proximal end including muscle attachments measured perpendicularly to proximal articular surfaces rather than medio-lateral axis	von den Driesch, 1976			+	Flat
19	BFp	Greatest breadth of the proximal articular surface in same line as Bp		SGWG		+	Blade
20	SD	Smallest breadth of the diaphysis (medio-lateral)	von den Driesch, 1976	SGWG		+	Flat
21	DD	Smallest depth of the diaphysis (anterio-posterior)	von den Driesch, 1976			+	Flat
22	BFd	Greatest breadth of the distal articulations combined (medio-lateral). Taken with callipers held at right angle to long axis of the bone		SGWG		+	Flat
23	WCM	Medio-lateral width of the medial condyle measured in the centre of the condyle (not a maximum width). May require pointed jaw callipers	Davis, 1996			+	Blade
24	WCL	Medio-lateral width of the lateral condyle measured in the centre of the condyle (not a maximum width). May require pointed jaw callipers	Davis, 1996			+	Blade
25	Dem	Depth of the external trochlea on the medial side (anterio-posterior). Found by placing the callipers softly against the verticillus and gently tightening them so they slide to a natural minimum within the hollow of the articulation		SGWG		+	Blade
26	Del	Depth of the external trochlea on the lateral side (anterio-posterior). Taken in a similar fashion to Dem		SGWG		+	Blade
27	Dvm	Diameter of the verticillus of the medial condyle (anterio-posterior). Taken using flats of callipers when possible		SGWG		+	Flat/Blade
28	Dvl	Diameter of the verticillus of the lateral condyle (anterio-posterior). Taken using flats of callipers when possible		SGWG		+	Flat/Blade
29	BdFus	Greatest breadth of the diaphysis along distal line of fusion (medio-lateral). Callipers held perpendicularly to long axis of the bone	This study			+	Flat
Pelvis							
30	SDpu	Minimum diameter of the pubis shaft	Name change this study	SGWG	SHPu	+	Blade
31	SDmmpu	Minimax diameter of the pubis shaft measured at SDpu. Found by rotating the callipers around point of SDpu allowing the bone to open them until the maximum diameter of the shaft at that point is found.	Name change this study	SGWG	SBPu	+	Blade
32	MRDA	Depth of the medial rim of the acetabulum. Hold innominate with ilium towards you and acetabulum facing up. Rest the tip of the calliper near the centre of the acetabulum and flat/blade (depending on bone size) on the upper medial rim at line of ilio-pubic fusion. Hold the calliper in place with your thumb and gently close it. This measure often incorporates the medio-dorsal acetabular bulge and in particular the arcuate line (insertion for the psoas minor)	This study	cf. Greenfield, 2006		−	Flat

Table 3 (continued)

#	Measurement	Definition	Reference 1	Reference 2	Original name	*	**
Femur							
33	GL	Greatest length (long axis)	von den Driesch, 1976			+	Board
34	GLC	Greatest length from the caput (long axis). May be longer than GL in young animals	von den Driesch, 1976	SGWG		+	Board
35	TC	Greatest thickness of the caput using the caput rather than the medio-lateral axis of the bone as the line of symmetry	This study			+	Flat
36	SD	Smallest breadth of the diaphysis (medio-lateral). Uses the axis of the caput-greater trochanter to define medio-lateral	von den Driesch, 1976	SGWG		+	Flat
37	Bd	Greatest breadth of the distal end measured perpendicularly to the distal condyles. Taken (using callipers) with the femur upside-down and the distal condyles facing towards you	This study			−	Flat
Tibia							
38	GL	Greatest length (long axis).	von den Driesch, 1976			+	Board
39	Bp	Greatest breadth of the proximal end (perpendicular to the condylar axis). Taken with tibia upright and posterior face towards you	von den Driesch, 1976			+	Flat
40	SD	Smallest breadth of the diaphysis (medio-lateral)	von den Driesch, 1976	This study		+	Flat
41	SDmin	Smallest diameter of the diaphysis (true minimum) in any direction. Typically found near an anterio-posterior orientation	This study			+	Flat
42	Bd	Greatest breadth of the distal end measured perpendicularly to the long axes of the distal cochlea	von den Driesch, 1976	SGWG		+	Flat
43	Dd	Greatest depth of the distal end with two contacts of anterior face against callipers. Not necessarily at right angle to Bd	von den Driesch, 1976	SGWG		+	Flat
Navicular Cuboid							
44	GB	Greatest breadth (perpendicular to articular fossas)	von den Driesch, 1976			+	Flat
Metatarsal							
45	GL	Greatest length (long axis). Depending on distal articular surfaces bone may not be flush against the board	von den Driesch, 1976			+	Board
46	Bp	Greatest breadth of the proximal end including muscle attachments (perpendicular to posterior axis of articular surfaces)	von den Driesch, 1976			+	Flat
47	BFp	Greatest breadth of the proximal articular surface (same orientation as Bp)		SGWG		+	Blade
48	SD	Smallest breadth of the diaphysis (medio-lateral)	von den Driesch, 1976	SGWG		+	Flat
49	DD	Smallest depth of the diaphysis (anterio-posterior)	von den Driesch, 1976			+	Flat
50	BFd	Greatest breadth of the distal articulations combined (medio-lateral). Taken with callipers held at right angle to long axis of the bone		SGWG		+	Flat
51	WCM	Medio-lateral width of the medial condyle measured in the centre of the condyle (not a maximum width). May require pointed jaw callipers	Davis, 1996			+	Blade
52	WCL	Medio-lateral width of the lateral condyle measured in the centre of the condyle (not a maximum width). May require pointed jaw callipers	Davis, 1996			+	Blade
53	Dem	Depth of the external trochlea on the medial side (anterio-posterior). Found by placing the callipers softly against the verticillus and gently tightening them so they slide to a natural minimum within the hollow of the articulation		SGWG		+	Blade
54	Del	Depth of the external trochlea on the lateral side (anterio-posterior). Taken in a similar fashion to Dem		SGWG		+	Blade
55	Dvm	Diameter of the verticillus of the medial condyle (anterio-posterior). Taken using flats of callipers when possible		SGWG		+	Flat/Blade
56	Dvl	Diameter of the verticillus of the lateral condyle (anterio-posterior). Taken using flats of callipers when possible		SGWG		+	Flat/Blade
57	BdFus	Greatest breadth of the diaphysis along distal line of fusion (medio-lateral). Callipers held perpendicularly to long axis of the bone	This study			+	Flat
Astragalus							
58	GLl	Greatest length of the lateral side. Taken as a true maximum	von den Driesch, 1976	SGWG		+	Flat
59	Bd	Greatest breadth of the distal end (perpendicular to condylar axis)	von den Driesch, 1976	SGWG		+	Flat
60	Dl	Greatest depth of the lateral side with two contacts of the anterior face against the callipers	von den Driesch, 1976	SGWG		+	Flat
Calcaneus							
61	GL	Greatest length (true maximum)	von den Driesch, 1976			+	Flat
62	BS	Breadth of sustentaculum. Taken with callipers at right angle to the long axis of the bone. Calcaneus is held loosely with sustentaculum facing up while callipers are gently closed allowing calcaneus to find a natural resting position	von den Driesch, 1976			+	Flat
63	C	Greatest length of the articular facet on the lateral process (true maximum)		SGWG		+	Tips
64	C&D	Greatest length from the proximal end of the articular facet to the distal tip of the lateral process (likely not same axis as C)		SGWG		+	Tips
65	GDde	Greatest depth of the distal extremity. True maximum	This study			+	Flat

3.3.1. Greatest lengths

Nutrition: Female high nutrition greatest lengths are significantly larger than low nutrition greatest lengths for all elements except the astragalus. There is no significant difference between high and low nutrition castrate greatest lengths. Only radius and tibia male high nutrition greatest lengths are significantly larger than low nutrition lengths.

Castration: Lengths of the humerus, femur, astragalus and calcaneus are not significantly affected by castration. Distal limb bones (radius, tibia and metapodials) are all significantly longer in
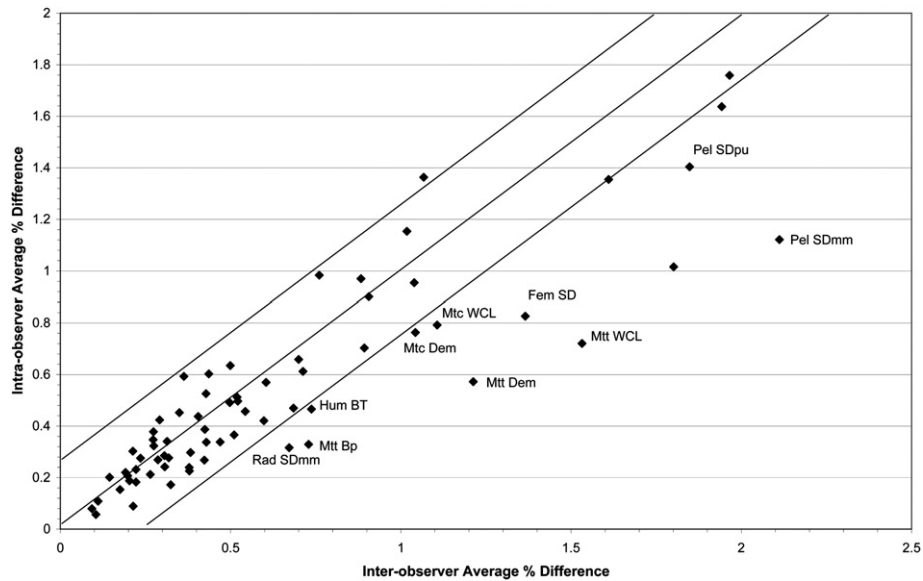
Fig. 6. Comparison of Intra-Observer and Inter-Observer Average % Difference (without Pel MRDA) showing ±0.25% boundaries.

castrates relative to males, except for the high nutrition radius which narrowly misses the 0.05 significance level.

3.3.2. Diaphysis breadth

Nutrition: Female high nutrition SDs are significantly larger than low nutrition SDs for every element. Castrate metacarpal and femur SDs are significantly larger in the high nutrition group relative to the low nutrition group. All male high nutrition group SDs are significantly larger than low nutrition SDs except for the femur. Tibia SDmin shows a significant difference but the traditional tibia SDml does not.

Castration: Forelimb element SDs are always significantly larger in males than in castrates. There is variation in the hind limb depending on plane of nutrition but metatarsal SD is never significantly different between males and castrates.

3.3.3. Proximal breadth

Nutrition: At least one measure of proximal breadth in female high nutrition elements is significantly larger than low nutrition proximal breadths on the radius, metacarpal and metatarsal. There is no difference between high and low nutrition female tibia Bps. Castrate metatarsal proximal breadth measurements show no significant differences between high and low nutrition groups. At least one radius, metacarpal and tibia proximal breadth measurement is significantly larger in high nutrition groups relative to low nutrition groups. All male high nutrition proximal breadth measurements are significantly larger than low nutrition measurements except for the tibia.

Castration: Radius and metacarpal proximal breadths never show significant differences between males and castrates. Male tibia and metatarsal proximal breadths are significantly larger than

Table 4
Fusion range in months; first figure is age when 100% of elements are unfused, second figure is age when 100% of elements are fused; where a single figure is presented, this refers to age when 100% of elements are fused; Males and Females and Whole Flock are the maximum range of fusion including the earliest and latest timings for these groups; *1Phl: 100% fused at 16 months but slightly lower % fused at 19 months (88–94%), 100% fused at 28 months; **P Hum: 100% fused at 40 months but only 82% fused at 43 months, 100% fused at 52 months; ***P Tib: 100% fused at 40 months but only 50% fused at 43 months, 100% fused at 52 months. Element abbreviations: P Rad − proximal radius; D Hum − distal humerus; Pelvis − acetabulum; 2Phl − middle phalange; 1Phl − proximal phalange; D Tib − distal tibia; P Calc − proximal calcaneus; D Mtc − distal metacarpal; D Mtt − distal metatarsal; Fem gtr − femur greater trochanter; Fem caput − femur caput; D Rad − distal radius; D Fem − distal femur; P Hum − proximal humerus; P Tib − proximal tibia.

Sex	Castrates			Males			Females			Males and females	Whole flock
Nutrition	High	Low	All	High	Low	All	High	Low	All	All	All
N skeletons	n = 44	n = 44	n = 88	n = 44	n = 44	n = 88	n = 90	n = 90	n = 180	n = 268	n = 356
P Rad	<7	<7	<7	<7	<7	<7	<7	<7	<7	<7	<7
Scapula	<7	<7	<7	<7	<7−16	<7−16	<7	<7	<7	<7	<7
D Hum	<7	<7	<7	<7	<7	<7	<7	<7	<7	<7	<7
Pelvis	<7	<7	<7	<7	<7	<7	<7	<7	<7	<7	<7
2Phl	<7−16	<7−16	<7−16	<7−16	<7−16	<7−16	<7−16	<7−16	<7−16	<7−16	<7−16
1Phl	7−16	7−28*	7−28*	7−16	7−16	7−16	7−16	7−16	7−16	7−16	7−16
D Tib	7−19	16−28	7−28	7−19	7−19	7−19	7−16	7−16	7−16	7−19	7−28
P Calc	7−28	19−40	7−40	16−28	19−28	16−28	7−16	7−28	7−28	7−28	7−31
D Mtc	16−31	19−43	16−40	16−19	7−28	7−28	7−16	16−28	7−28	7−28	7−31
D Mtt	19−28	19−40	19−40	16−19	16−28	16−28	7−19	7−28	7−28	7−28	7−31
Fem gtr	19−28	19−43	19−43	19−28	19−28	19−28	7−19	7−28	7−28	7−28	7−31
Fem caput	28−40	19−43	19−43	16−28	19−40	16−40	16−19	7−31	7−31	16−31	16−43
D Rad	28−40	31−43	28−43	19−31	19−31	19−31	16−28	19−31	16−31	16−31	16−43
D Fem	28−40	31−52	28−52	19−28	19−40	19−40	28−31	19−31	19−31	19−40	19−52
P Hum	28−52**	31−52	28−52	19−31	19−40	19−40	16−28	19−31	16−31	16−40	16−52
P Tib	28−52***	31−52	28−52	19−31	28−40	19−40	19−28	19−31	19−40	19−40	19−52

Table 5

Comparative sheep fusion data (age in months). Element abbreviations as in Table 4. <: fusion completed by; >: fusion completed after. For Hatting (1983) and Moran and O'Connor (1994) the first figure refers to lowest age at which all specimens are still unfused, and the second figure is the highest age at which all specimens are fused. Sample size: Silver (1969) sample size unknown, sex unknown; Hatting (1983) males 27, females 23, castrates 23; Moran and O'Connor (1994) males 50 (5 complete, 45 incomplete), females 63 (10 complete, 53 incomplete), castrates 41 (6 complete, 35 incomplete); Zeder (2006) males 31, females 30. Species: all samples are domestic sheep (*Ovis aries*) except Zeder (2006): 41 Asiatic mouflon (*Ovis orientalis*), 15 urials (*Ovis vigni*), 5 domestic sheep (*Ovis aries*).

Element	Silver (1969)	Hatting (1983)		Moran and O'Connor (1994)		Zeder (2006)
	Sex unknown	Males and females	Males, females and castrates	Males and females	Males, females and castrates	Males and females
P Rad	10	2−4	2−22	<4.5−6	<4.5−11	0−6
Scapula	6−8	na	na	<6−9	<6−11	6−12
Pelvis	6−10	na	na	na	na	6−12
D Hum	10	2−4	2−22	5.5−10.5	5.5−11	6−12
2Phl	13−16	5−6	5−8	na	na	12−18
1Phl	13−16	6−9	6−22	<11	<11−12	12−18
D Tib	18−24	13−15	13−23	13−23	13−30	18−30
P Calc	30−36	15−18	15−30	13−23	13−30	30−48
D Mtc	18−24	15−22	15−23	15−24	15−30	18−30
D Mtt	20−28	15−23	15−23	15−30	15−30	18−30
P Fem	30−36	15−23	15−30	23−37	23−37	30−48
D Rad	36	15−30	15−>35	23−40	23−40	30−48
D Fem	36−42	15−23	15−>35	25−40	25−42	30−48
P Tib	36−42	15−30	15−>35	36−45	30−45	30−48
P Hum	36−42	15−30	15−>35	36−42	32−42	>48

castrate proximal breadths except in the low nutrition group where metatarsals show no difference.

3.3.4. Distal breadth

Nutrition: At least one measure of distal breadth in female high nutrition elements is significantly larger than low nutrition distal breadths on the humerus, radius, metacarpal, tibia, metatarsal and astragalus. Only two castrate elements, humerus and tibia, show significantly larger high nutrition distal breadth measurements relative to low nutrition distal breadth measurements. Every high nutrition group male distal breadth measurement is significantly larger than the low nutrition group equivalent except for the femur.

Castration: The femur Bd is the only male distal breadth measurement that is significantly larger than the castrate equivalent in all nutrition groups. All elements, except the astragalus, have at least one distal breadth measurement that is significantly larger in males relative to castrates.

3.3.5. Summary of intra-element growth

Our data demonstrate that bone growth is not consistent across the skeleton; areas and planes of bone growth of each element are affected in different ways depending on the sex, nutrition and castration status of the animal. By way of example we can point out several areas of bone that react differently to similar stimuli: the metacarpal SD is very reactive and its size is significantly affected by nutrition in all sexes, as well as by castration; the size of the tibia Bd is similarly significantly affected by nutrition in all sexes, as well as by castration generally, though not castration in low nutrition animals; forelimb Bps are significantly affected by both nutrition and sex (in terms of female versus male) but are not significantly influenced by castration; and finally, the femur Bd is not significantly affected by nutrition in any sex but is always significantly affected by castration. Sex has the strongest influence on skeletal growth in all areas with females being significantly smaller than both males and castrates of all nutrition planes. Bimodal distributions in individual measurements may thus indicate sexual dimorphism though this should be considered in concert with additional analyses such as assemblage variance (see Section 3.5).

Considering castration, it is often stated that castrates have long and slender limbs relative to males with short, stout limbs, and females with short, slender limbs (Davis, 2000). While generally true, our data indicate that the situation is more complex than this.

In terms of length, castrate elements are always significantly longer than female elements but are not significantly longer than the male humerus, femur, astragalus or calcaneus regardless of nutrition. In terms of breadth, when animals are fed on a low nutrition plane there is no significant size difference between castrate and male proximal or distal breadths save for in the knee joint (the tibia Bp and the femur Bd). Apart from this joint, low nutrition castrate breadth measurements have the potential to be larger than equivalent male measurements. Diaphysis breadths are more affected by castration with male forelimbs always being significantly larger than castrate forelimbs though other elements vary with nutrition and the metatarsal SD never shows a significant difference.

Considering nutrition, within the boundaries of our study, that is avoiding malnourishment of the animals, the largest difference between the three sexes is seen in the effect on length measurements. Females on a high nutrition plane always have significantly longer limb bones than those on a low nutrition plane (excluding the astragalus), while nutrition has no effect on length of limb bones of castrates and only affects the male radius and tibia. While low nutrition delays female epiphyseal fusion somewhat, it seems that this delay is not sufficient to allow growth in low nutrition females to approximate growth in high nutrition animals.

Plane of nutrition does not significantly affect the upper range of a cohort's withers height but a low plane of nutrition leads to an increase in the amount of relatively short female limb bones. Withers heights calculated with the humerus and femur will be smaller than those calculated with the radius, tibia and metapodials when castrates are present in an assemblage because the humerus and femur do not reflect the significant extra growth of castrates relative to males found in the other limb bones.

Most zooarchaeological samples are accumulated over many years, if not generations. Inevitably, this leads to variation in the nutritional regime sheep encountered even if all sheep deposited on a site were treated equally, due, for example, to occasional years of drought and hardship, deliberate husbandry decisions and different supply networks. It may be most practical to treat archaeological samples of sheep bones as a mixture of high and low nutrition animals unless it can be proven otherwise. In this case, the tibia is the limb bone with the most potential for recognizing castration in growth patterns.

Significant size differences ($p < 0.001$) also exist between pelvis measurements of all three sexes for each nutrition plane and both combined. The best metric separation of sexes is achieved by

Table 6
Correlation between female age and growth; * = significant at 0.05 level; ** = significant at 0.01 level.

Female Element	Measure	fu and fo low		fu and fo high		Fused + unfused low		Fused + unfused high	
		N	t (tau)	N	t (tau)	N	t (tau)	N	t (tau)
Scapula	GLP	90	0.224**	90	0.077	90	0.224**	90	0.077
	BG	90	0.085	90	0.052	90	0.085	90	0.052
	SLC	90	0.307**	90	0.251**	90	0.307**	90	0.251**
Humerus	GL	71	−0.102	75	−0.056	90	0.165*	90	0.137
	GLC	71	−0.134	75	−0.087	90	0.126	90	0.114
	SD	71	−0.026	75	−0.075	90	0.190**	90	0.107
	Bd	90	0.177*	90	0.172*	90	0.177*	90	0.172*
	BT	90	0.170*	90	0.135	90	0.170*	90	0.135
	BFT	90	0.137	90	0.111	90	0.137	90	0.111
	HT	90	0.195**	90	0.119	90	0.195**	90	0.119
	HTC	90	0.063	90	0.002	90	0.063	90	0.002
Radius	GL	72	−0.079	75	−0.068	90	0.143*	90	0.125
	Bp	90	0.285**	90	0.200**	90	0.285**	90	0.200**
	BFp	90	0.154*	90	0.128	90	0.154*	90	0.128
	SDmm	72	−0.057	75	−0.061	90	0.192**	90	0.132
	Bd	72	−0.015	75	−0.044	90	0.136	90	0.066
Metacarpal	GL	75	−0.131	82	−0.053	90	0.071	90	0.121
	Bp	90	0.130	90	0.069	90	0.130	90	0.069
	BFp	90	0.073	90	0.034	90	0.073	90	0.034
	SD	75	−0.001	82	−0.050	90	0.151*	90	0.106
	BFd	75	0.004	82	−0.062	90	0.154*	90	0.048
	WCM	75	−0.013	82	−0.090	90	0.118	90	−0.001
	WCL	75	0.028	82	−0.091	90	0.133	90	−0.022
	Dem	75	0.032	82	−0.062	90	0.133	90	0.041
	Del	75	0.049	82	−0.023	90	0.143*	90	0.067
	Dvm	75	−0.006	82	−0.019	90	0.103	90	0.088
	Dvl	75	0.042	82	−0.032	90	0.145*	90	0.060
	BdFus	75	−0.050	82	−0.166*	90	−0.026	90	−0.163*
Pelvis	SDpu	90	−0.041	90	−0.147*	90	−0.041	90	−0.147*
	SDmmpu	90	0.289**	90	0.085	90	0.289**	90	0.085
	MRDA	90	0.086	90	0.016	90	0.086	90	0.016
Femur	GL	72	−0.055	74	−0.086	90	0.131	90	0.108
	GLC	72	−0.051	74	−0.053	90	0.113	90	0.113
	TC	75	0.076	78	−0.079	90	0.148*	90	0.000
	SD	72	0.058	74	−0.047	90	0.207**	90	0.105
	Bd	72	0.032	74	0.029	90	0.171*	90	0.188**
Tibia	GL	71	−0.053	74	−0.038	90	0.130	90	0.114
	Bp	71	0.040	74	0.048	90	0.240**	90	0.221**
	SDml	71	0.065	74	−0.041	90	0.230**	90	0.164*
	SDmin	71	0.115	74	−0.015	90	0.183*	90	0.098
	Bd	82	0.034	82	−0.056	90	0.155*	90	0.039
	Dd	82	0.026	82	−0.081	90	0.108	90	−0.035
NavCub	GB	90	0.095	90	0.068	90	0.095	90	0.068
Astragalus	GLI	90	0.023	90	−0.043	90	0.023	90	−0.043
	Bd	90	0.072	90	−0.031	90	0.072	90	−0.031
	Dl	90	0.046	90	−0.086	90	0.046	90	−0.086
Calcaneus	GL	77	−0.073	82	−0.026	90	0.104	90	0.113
	BS	77	0.035	82	−0.009	90	0.126	90	0.099
	C	77	0.095	82	0.029	90	0.161*	90	0.093
	C&D	77	−0.047	82	0.021	90	0.074	90	0.087
	GDde	77	−0.056	82	−0.033	90	0.059	90	0.025
Metatarsal	GL	78	−0.109	81	−0.051	90	0.071	90	0.133
	Bp	90	0.076	90	0.085	90	0.076	90	0.085
	BFp	90	0.052	90	0.046	90	0.052	90	0.046
	SD	78	−0.015	81	−0.002	90	0.153*	90	0.177*
	BFd	78	0.004	81	−0.064	90	0.117	90	0.042
	WCM	78	−0.035	81	−0.067	90	0.032	90	−0.010
	WCL	78	0.069	81	−0.101	90	0.115	90	−0.013
	Dem	78	0.038	81	−0.021	90	0.117	90	0.078
	Del	78	0.061	81	−0.026	90	0.147*	90	0.087
	Dvm	78	−0.018	81	−0.059	90	0.088	90	0.044
	Dvl	78	0.003	81	−0.094	90	0.099	90	0.019
	BdFus	78	−0.037	81	−0.174*	90	−0.026	90	−0.182*

plotting pelvis SDpu by MDRA (Fig. 7). Males and females are completely separated while castrates fall neatly between them. Given a sufficient sample size it may be possible to determine whether castration was practiced regularly at a site in this fashion; the validity of such assertions will be strengthened where admixture of different breeds/types can be excluded.

3.4. Discriminant analysis

In an attempt to determine which combination of measurements most effectively separate the sexes a Discriminant Analysis was performed on all combinations of measurements for each element in a three group test and a two group test (females versus

Table 7
Correlation between castrate age and growth; *significant at 0.05 level; **significant at 0.01 level.

Castrate Element	Measure	fu and fo low		fu and fo high		Fused + unfused low		Fused + unfused high	
		N	t (tau)	N	t (tau)	N	t (tau)	N	t (tau)
Scapula	GLP	44	0.539**	44	0.249*	44	0.539**	44	0.249*
	BG	44	0.389**	44	0.283**	44	0.389**	44	0.283**
	SLC	44	0.558**	44	0.513**	44	0.558**	44	0.513**
Humerus	GL	15	−0.010	20	−0.133	44	0.665**	44	0.428**
	GLC	15	−0.087	20	−0.065	44	0.624**	44	0.433**
	SD	15	−0.115	20	−0.138	44	0.495**	44	0.415**
	Bd	44	0.434**	44	0.311**	44	0.434**	44	0.311**
	BT	44	0.417**	44	0.325**	44	0.417**	44	0.325**
	BFT	44	0.445**	44	0.386**	44	0.445**	44	0.386**
	HT	44	0.425**	44	0.311**	44	0.425**	44	0.311**
	HTC	44	0.278**	44	0.050	44	0.278**	44	0.050
Radius	GL	16	−0.203	20	−0.081	44	0.604**	44	0.495**
	Bp	44	0.561**	44	0.449**	44	0.561**	44	0.449**
	BFp	44	0.425**	44	0.369**	44	0.425**	44	0.369**
	SDmm	16	0.025	20	−0.164	44	0.570**	44	0.401**
	Bd	16	−0.159	20	−0.206	44	0.385**	44	0.246*
Metacarpal	GL	25	0.030	28	0.043	44	0.431**	44	0.398**
	Bp	44	0.405**	44	0.154	44	0.405**	44	0.154
	BFp	44	0.331**	44	0.048	44	0.331**	44	0.048
	SD	25	0.127	28	−0.027	44	0.516**	44	0.296**
	BFd	25	0.067	28	−0.093	44	0.359**	44	0.157
	WCM	25	0.092	28	0.054	44	0.366**	44	0.155
	WCL	25	0.071	28	0.021	44	0.351**	44	0.137
	Dem	25	0.157	28	0.005	44	0.327**	44	0.134
	Del	25	0.063	28	−0.032	44	0.210	44	0.182
	Dvm	25	0.050	28	0.127	44	0.321**	44	0.173
	Dvl	25	0.070	28	0.056	44	0.314**	44	0.206*
	BdFus	25	0.050	28	−0.286*	44	0.100	44	−0.221*
Pelvis	SDpu	44	−0.073	44	−0.234*	44	−0.073	44	−0.234*
	SDmmpu	44	0.139	44	0.054	44	0.139	44	0.054
	MRDA	44	−0.182	44	−0.217*	44	−0.182	44	−0.217*
Femur	GL	14	−0.199	21	−0.034	44	0.600**	44	0.435**
	GLC	14	−0.246	21	0.000	44	0.571**	44	0.417**
	TC	20	−0.005	22	0.026	44	0.275**	44	0.113
	SD	14	−0.199	21	−0.024	44	0.517**	44	0.541**
	Bd	14	−0.309	21	−0.010	44	0.427**	44	0.339**
Tibia	GL	14	−0.045	16	−0.025	44	0.562**	44	0.453**
	Bp	14	−0.243	16	−0.276	44	0.459**	44	0.390**
	SDml	14	−0.088	16	−0.075	44	0.592**	44	0.497**
	SDmin	14	0.133	16	0.176	44	0.492**	44	0.371**
	Bd	29	0.178	34	0.107	44	0.287**	44	0.186
	Dd	29	0.126	34	−0.158	44	0.173	44	−0.040
NavCub	GB	44	0.393**	44	0.185	44	0.393**	44	0.185
Astragalus	GLl	44	0.082	44	−0.008	44	0.082	44	−0.008
	Bd	44	0.281**	44	0.145	44	0.281**	44	0.145
	Dl	44	0.139	44	0.023	44	0.139	44	0.023
Calcaneus	GL	26	−0.129	30	0.071	44	0.372**	44	0.231*
	BS	26	−0.055	30	−0.037	44	0.295**	44	0.108
	C	26	0.068	30	0.069	44	0.270**	44	0.169
	C&D	26	0.099	30	0.242	44	0.217*	44	0.239*
	GDde	26	0.043	30	0.099	44	0.162	44	0.132
Metatarsal	GL	25	0.010	28	0.094	44	0.408**	44	0.380**
	Bp	44	0.435**	44	0.147	44	0.435**	44	0.147
	BFp	44	0.373**	44	0.107	44	0.373**	44	0.107
	SD	25	0.117	28	0.021	44	0.515**	44	0.379**
	BFd	25	0.010	28	0.008	44	0.291**	44	0.204
	WCM	25	0.000	28	0.162	44	0.336**	44	0.206
	WCL	25	0.082	28	0.112	44	0.312**	44	0.210*
	Dem	25	0.195	28	−0.056	44	0.257*	44	0.480
	Del	25	0.047	28	−0.013	44	0.163	44	0.133
	Dvm	25	0.070	28	0.056	44	0.286**	44	0.147
	Dvl	25	0.030	28	0.056	44	0.218*	44	0.174
	BdFus	25	0.090	28	−0.059	44	0.098	44	−0.211*

males and castrates). The most successful results are shown in Table 13. Elements that fuse early and show significant post-fusion growth, in particular the scapula and astragalus, are poor distinguishers of sex when using fused bones. The calcaneus is also a poor distinguisher of sex. In almost every case a greatest length measurement must be included in the analysis for a high rate of correct classification to be achieved. Therefore, the application of DA will be most successful where entire/part skeletons were deliberately buried and whole bones preserved or where craft/industrial activities result in the discard of whole elements. For example, caches of metapodials are occasionally recovered and represent excellent case material for this type of analysis.

Almost every female is correctly classified as a female, as a result of their relatively small size, but not every case

Table 8
Correlation between male age and growth; * = significant at 0.05 level; ** = significant at 0.01 level.

Male Element	Measure	fu and fo low		fu and fo high		Fused + unfused low		Fused + unfused high	
		N	t (tau)	N	t (tau)	N	t (tau)	N	t (tau)
Scapula	GLP	43	0.356**	44	0.327**	44	0.384**	44	0.327**
	BG	43	0.395**	44	0.315**	44	0.422**	44	0.315**
	SLC	43	0.533**	44	0.476**	44	0.554**	44	0.476**
Humerus	GL	22	0.238	27	0.115	44	0.540**	44	0.412**
	GLC	22	0.180	27	0.116	44	0.475**	44	0.371**
	SD	22	0.043	27	0.134	44	0.513**	44	0.462**
	Bd	44	0.472**	44	0.373**	44	0.472**	44	0.373**
	BT	44	0.477**	44	0.319**	44	0.477**	44	0.319**
	BFT	44	0.463**	44	0.396**	44	0.463**	44	0.396**
	HT	44	0.418**	44	0.328**	44	0.418**	44	0.328**
	HTC	44	0.163**	44	0.234*	44	0.163	44	0.234*
Radius	GL	25	−0.020	26	0.106	44	0.584**	44	0.598**
	Bp	44	0.515**	44	0.520**	44	0.515**	44	0.520**
	BFp	44	0.440	44	0.367**	44	0.440**	44	0.367**
	SDmm	25	0.003	26	0.121	44	0.656**	44	0.671**
	Bd	25	−0.027	26	0.142	44	0.567**	44	0.536**
Metacarpal	GL	30	0.016	32	−0.037	44	0.415**	44	0.275**
	Bp	44	0.371**	44	0.319**	44	0.371**	44	0.319**
	BFp	44	0.346	44	0.256*	44	0.346**	44	0.256*
	SD	30	−0.046	32	0.241	44	0.400**	44	0.485**
	BFd	30	−0.002	32	0.144	44	0.367**	44	0.351**
	WCM	30	0.040	32	0.066	44	0.391**	44	0.298**
	WCL	30	0.030	32	0.118	44	0.262*	44	0.316**
	Dem	30	0.136	32	−0.030	44	0.221*	44	0.252**
	Del	30	0.195	32	0.036	44	0.275**	44	0.295**
	Dvm	30	0.134	32	−0.024	44	0.306**	44	0.186
	Dvl	30	0.180	32	0.049	44	0.367**	44	0.276**
	BdFus	30	−0.055	32	0.038	44	0.166	44	0.146
Pelvis	SDpu	44	0.291	44	0.131	44	0.291**	44	0.131
	SDmmpu	44	0.234	44	0.304**	44	0.234*	44	0.304**
	MRDA	44	0.071	44	0.084	44	0.071	44	0.084
Femur	GL	24	−0.036	28	0.131	44	0.458**	44	0.404**
	GLC	24	−0.091	28	0.123	44	0.423**	44	0.352**
	TC	25	−0.050	29	0.185	44	0.244*	44	0.138
	SD	24	0.072	28	0.181	44	0.485**	44	0.436**
	Bd	24	0.196	28	0.042	44	0.557**	44	0.373**
Tibia	GL	19	0.006	26	0.050	44	0.422**	44	0.353**
	Bp	19	0.251	26	0.120	44	0.577**	44	0.444**
	SDml	19	0.000	26	0.151	44	0.503**	44	0.462**
	SDmin	19	0.099	26	0.146	44	0.500**	44	0.433**
	Bd	34	0.223	35	0.094	44	0.401**	44	0.282**
	Dd	34	0.086	35	−0.002	44	0.325**	44	0.214*
NavCub	GB	44	0.325	44	0.278**	44	0.325**	44	0.278**
Astragalus	GLl	44	0.119	44	0.148	44	0.119	44	0.148
	Bd	44	0.276	44	0.200	44	0.276**	44	0.200
	Dl	44	0.214	44	0.173	44	0.214*	44	0.173
Calcaneus	GL	28	0.074	30	0.182	44	0.385**	44	0.380**
	BS	28	0.164	30	0.194	44	0.470**	44	0.342**
	C	28	0.236	30	0.185	44	0.229*	44	0.278**
	C&D	28	0.180	30	0.219	44	0.200	44	0.288**
	GDde	28	0.164	30	0.198	44	0.288**	44	0.251*
Metatarsal	GL	29	0.032	32	−0.025	44	0.418**	44	0.274**
	Bp	44	0.293**	44	0.296**	44	0.293**	44	0.296**
	BFp	44	0.241*	44	0.196	44	0.241*	44	0.196
	SD	29	−0.030	32	0.208	44	0.366**	44	0.451**
	BFd	29	0.030	32	0.075	44	0.275**	44	0.259*
	WCM	29	0.055	32	0.000	44	0.252*	44	0.182
	WCL	29	0.075	32	0.110	44	0.283**	44	0.273**
	Dem	29	0.114	32	0.014	44	0.224*	44	0.184
	Del	29	0.215	32	−0.095	44	0.305**	44	0.108
	Dvm	29	0.192	32	−0.081	44	0.322**	44	0.160
	Dvl	29	0.190	32	−0.051	44	0.320**	44	0.186
	BdFus	29	−0.049	32	−0.012	44	0.079	44	0.040

classified as a female is a female (castrates and less often males are also mistakenly classified as females). Castrates are misclassified more frequently than males. Misclassified castrates are consistently classified as males twice as often as females except in the case of astragalus and calcaneus where the incorrect classifications were equally distributed between the two sexes.

Our data indicate that differences between sexes (i.e. entire males and castrates versus females) have a stronger effect on bone growth and morphology than castration. They also emphasise the fact that females show less variation in bone growth and morphology maintaining their 'femaleness' while males and especially castrates show greater variability and often appear female in size and shape.

Table 9
t-test one-tail Fu and Fo single sex between high and low nutrition; Figures in bold are significant at 0.05; *Equal variance not assumed; ^one-tailed *t*-test; ** two-tailed *t*-test.

Measure	Female low versus high^			Castrate low versus high^			Male low versus high^			Low castrate versus low male**			High castrate versus high male**			All castrate versus all male**		
	t	df	p	t	df	p	t	df	p	t	df	p	t	df	p	t	df	p
Hum GL	−2.41	144	**0.009**	0.24	33	0.406	−1.54	47	0.065	1.19	35	0.242	−0.62	45	0.542	0.19	82	0.850
Hum GLC	−2.05	144	**0.022**	0.44	33	0.331	−1.61	47	0.058	1.80	35	0.080	−0.36	45	0.724	0.72	82	0.475
Rad GL	−3.36	145	**0.001**	−0.92	34	0.182	−1.89	49	**0.034**	2.59	39	**0.014**	1.95	44	0.058	3.24	85	**0.002**
Mtc GL	−3.52	155	**0.001**	−1.20	51	0.118	−0.90	60	0.186	2.69	53	**0.010**	3.38	58	**0.001**	4.29	113	**<0.001**
Fem GL	−3.52	144	**0.001**	0.07	33	0.475	−1.32	50	0.097	1.61	36	0.116	0.32	47	0.749	1.31	85	0.193
Fem GLC	−3.16	144	**0.001**	−0.06	33	0.478	−1.11	50	0.137	1.52	36	0.136	0.59	47	0.572	1.45	85	0.150
Tib GL	−3.09	143	**0.002**	−1.44	28	0.081	−1.92	43	**0.031**	2.44	31	**0.021**	2.11	40	**0.041**	2.99	73	**0.004**
Mtt GL	−3.51	157	**0.001**	−1.14	51	0.130	−1.04	59	0.152	2.74	52	**0.008**	3.06	58	**0.003**	4.11	112	**<0.001**
Ast GL	−1.19	178	0.118	−0.37	86	0.356	−1.63	86	0.052	−0.20	77*	0.842	−1.62	86	0.110	−1.36	158*	0.177
Cal GL	−1.80	157	**0.036**	0.78	54	0.220	−1.34	56	0.093	1.87	52	0.067	−0.21	48*	0.834	1.19	99*	0.237

Table 10
t-test one-tail Fu and Fo single sex between high and low nutrition; Figures in bold are significant at 0.05; *Equal variance not assumed; ^one-tailed *t*-test; ** two-tailed *t*-test.

Measure	Female low versus high^			Castrate low versus high^			Male low versus high^			Low castrate versus low male**			High castrate versus high male**			All castrate versus all male**		
	t	df	p	t	df	p	t	df	p	t	df	p	t	df	p	t	df	p
Hum SD	−3.29	144	**0.001**	−1.33	33	0.096	−2.01	47	**0.026**	−3.08	35	**0.004**	−2.85	45	**0.007**	−3.86	82	**<0.001**
Rad SDmm	−2.87	145	**0.003**	−1.31	34	0.100	−2.45	49	**0.009**	−3.82	39	**<0.001**	−4.30	44	**<0.001**	−5.43	85	**<0.001**
Mtc SD	−2.29	155	**0.012**	−1.78	51	**0.041**	−1.75	60	**0.043**	−2.30	53	**0.026**	−2.29	58	**−0.026**	−3.14	113	**0.002**
Fem SD	−3.08	139*	**0.001**	−1.82	33	**0.039**	−1.36	50	0.090	−2.17	36*	**0.037**	−1.79	47	0.080	−2.59	85*	**0.011**
Tib SDml	−3.78	143	**<0.001**	−1.45	28	0.079	−1.45	43	0.078	−1.86	31	0.073	−1.76	40	0.086	−2.58	73	**0.012**
Tib SDmin	−2.53	143	**0.006**	−1.14	28	0.133	−2.66	43	**0.006**	−1.80	31	0.081	−2.95	40	**0.005**	−3.41	73	**0.001**
Mtt SD	−2.41	157	**0.009**	−1.51	51	0.069	−2.63	59	**0.006**	−0.48	52	0.633	−1.58	58	0.121	−1.45	112	0.149

Table 11
t-test one-tail Fu and Fo single sex between high and low nutrition; Figures in bold are significant at 0.05; *Equal variance not assumed; ^one-tailed *t*-test; ** two-tailed *t*-test.

Measure	Female low versus high^			Castrate low versus high^			Male low versus high^			Low castrate versus low male**			High castrate versus high male**			All castrate versus all male**		
	t	df	p	t	df	p	t	df	p	t	df	p	t	df	p	t	df	p
Rad Bp	−2.13	178	**0.018**	−2.00	86	**0.025**	−2.12	86	**0.019**	−0.88	86	0.383	−1.48	78*	0.143	−1.64	164*	0.103
Rad BFp	−2.32	178	**0.011**	−2.16	86	**0.017**	−2.15	86	**0.017**	−1.00	86	0.322	−1.45	80*	0.150	−1.69	174	0.093
Mtc Bp	−1.76	178	**0.040**	−1.84	76*	**0.035**	−2.17	86	**0.017**	−0.67	86	0.505	−1.62	71*	0.110	−1.56	163*	0.122
Mtc BFp	−1.38	178	0.085	−1.65	86	0.052	−1.84	86	**0.035**	−1.00	86	0.320	−1.60	77*	0.113	−1.81	166*	0.072
Tib Bp	−0.95	143	0.172	−2.01	28	**0.027**	−0.23	43	0.412	−3.84	31	**0.001**	−2.13	40	**0.039**	−4.07	73	**<0.001**
Mtt Bp	−2.24	178	**0.013**	−1.45	81	0.075	−2.11	86	**0.019**	−1.11	86	0.269	−2.24	86	**0.028**	−2.27	174	**0.024**
Mtt BFp	−1.52	178	0.065	−1.32	86	0.086	−2.04	86	**0.022**	−1.06	86	0.290	−2.07	86	**0.041**	−2.16	174	**0.032**

Table 12
t-test one-tail Fu and Fo single sex between high and low nutrition: Figures in bold are significant at 0.05; *Equal variance not assumed; ^one-tailed *t*-test; ** two-tailed *t*-test.

Measure	Female low versus high^			Castrate low versus high^			Male low versus high^			Low castrate versus low male**			High castrate versus high male**			All castrate versus all male**		
	t	df	p	t	df	p	t	df	p	t	df	p	t	df	p	t	df	p
Hum Bd	−1.23	178	0.110	−1.85	86	**0.034**	−1.94	86	**0.028**	−1.52	86	0.132	−2.23	80*	**0.029**	−2.58	174	**0.011**
Hum BT	−1.15	178	0.127	−2.16	86	**0.017**	−2.10	86	**0.019**	−1.12	86	0.264	−1.61	81*	0.112	−1.87	174	0.063
Hum BFT	−1.68	178	**0.047**	−1.98	86	**0.026**	−2.11	86	**0.019**	−0.73	86	0.465	−1.23	86	0.221	−1.35	174	0.179
Rad Bd	−1.99	145	**0.024**	−0.41	34	0.341	2.05	49	**0.023**	−1.76	39	0.086	−3.25	44	**0.002**	3.64	84*	**<0.001**
Mtc BFd	−1.25	155	0.106	−0.13	51	0.447	−1.87	60	**0.033**	−0.42	53	0.676	−2.46	58	**0.017**	−2.07	108*	**0.041**
Mtc BdFus	−3.01	155	**0.002**	−0.25	51	0.403	−2.37	60	**0.011**	−0.67	53	0.506	−3.11	54*	**0.003**	−2.67	109*	**0.009**
Fem Bd	−1.00	144	0.159	−0.34	33	0.367	−1.18	50	0.122	−2.24	36	**0.031**	−3.48	47	**0.001**	−4.31	85*	**<0.001**
Tib Bd	−2.92	162	**0.002**	−2.26	61	**0.014**	−2.07	67	**0.021**	−1.46	61	0.150	−2.30	67	**0.025**	−2.47	125*	**0.015**
Mtt BFd	−1.48	157	0.071	−0.18	51	0.429	−2.06	59	**0.022**	0.51	52	0.613	−1.53	58	0.132	−0.74	111*	0.462
Mtt BdFus	−2.57	157	**0.006**	−0.16	51	0.438	−2.29	59	**0.013**	−0.03	52	0.977	−2.28	58	**0.026**	−1.65	112	0.103
Ast Bd	−2.43	178	**0.008**	−1.13	86	0.131	−1.90	86	**0.032**	−0.06	86	0.956	−1.23	86	0.221	−0.85	165*	0.399

A problem for the application of DA to archaeological material using the Shetland data as a baseline is that changes in sheep size and shape due to breed differences will mimic shifts in sex ratios. If more than one sheep breed is present at a site this will confuse matters further. We demonstrate in Section 3.5, however, that analysis of variance can indicate the potential admixture of breeds, increasing the usefulness of DA.

3.5. Variance

Table 14 shows coefficient of variation (CV) values for all measurements taken on fused (fu and fo) areas of bone of the three sex groups separated by plane of nutrition. Females and castrates have the same amount of overall variability in their measurements while males have a slightly higher amount.
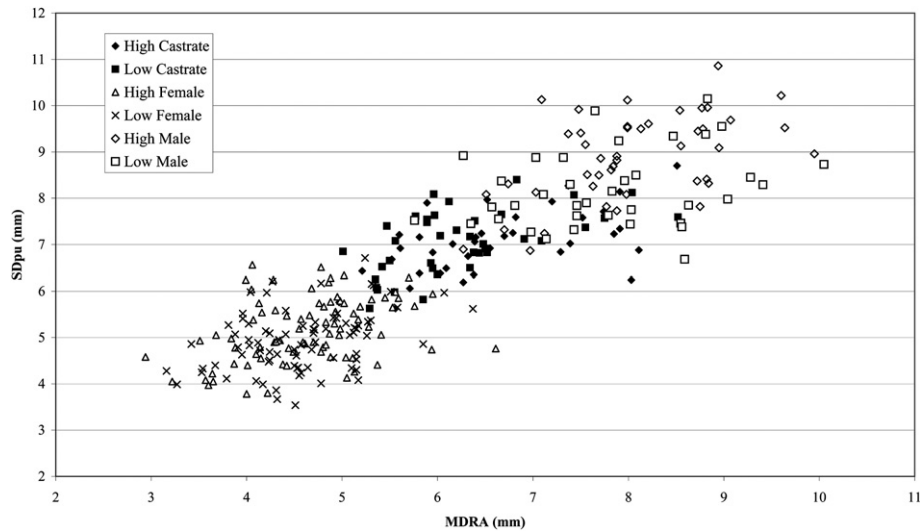
Fig. 7. Pelvis measurements by sex and nutritional plane.

Plane of nutrition has little effect on variation within any sex group.

The variation in the pelvis is high for all sexes and nutritional planes due in part to this area's continued growth in life and in part to the difficulty in recording the measurement. In agreement with Davis (2000), mid-diaphysis measurements (SDs) tend to have higher than average CVs and Radius BP and Scapula SLC are also high, reflecting the continued growth of these areas of bone after fusion.

CVs calculated for adult (fu and fo) females, castrates, males and whole flocks of both planes of nutrition combined are as follows: females without pelvis: 4.2; females with pelvis: 4.6; castrates without pelvis: 4.2; castrates with pelvis: 4.5; males without pelvis: 5.1; males with pelvis: 5.4; whole flock without pelvis: 5.8; whole flock with pelvis: 6.6.

Most mammal bone CVs are between 3 and 5 for a single sex (Yablokov, 1974), figures that match well with our data. The increase in CV value of the whole flock is expected because of the greater range in the absolute values of the measurements when all sexes are combined. It is hypothesised that when two or more breeds of sheep with different shapes are recovered at a site, or when a single breed of sheep underwent a significant size change during an 'analytical' time period (e.g. post medieval), the average CV value of the adult (fused) specimens, excluding the pelvis, will be greater than 6. We can test our hypothesis by comparing sheep CVs at sites dating from the late Saxon period to the post medieval period.

There is evidence, both zooarchaeological and documentary, to suggest that the late medieval and post medieval periods saw 'improvement' to sheep breeds in England leading to a size increase (Albarella and Davis, 1996; Thomas, 2005; Vann and Grimm, 2010). The exact timing and nature of the agricultural revolution and concomitant livestock improvement is still under debate, as indeed is the concept of the improvement as a 'revolution' considering its lengthy nature. Of interest here is the

Table 13
Discriminant analysis classifying sex via metrics; all measures are fu or fo.

Element	Measurements	Total[a]	Female[a]	Castrate[a]	Male[a]	Total[b]	Females[b]	Males and Castrates[b]
Scapula	GLP, BG	63.8	93.3	11.4	55.7	81.2	85.6	76.7
Humerus	GLC, SD, BT	87.8	99.3	60.0	73.5	95.2	97.9	90.5
Humerus	GL, SD, BT	87.4	99.3	51.4	77.6	94.8	97.9	89.3
Humerus	GLC, SD, BFT	87.0	99.3	57.1	71.4	94.3	97.9	88.1
Humerus	GL, SD, BFT	86.5	99.3	51.4	73.5	95.2	98.6	89.3
Humerus	SD, BFT, BT	85.2	97.3	48.6	75.5	94.8	97.3	90.5
Radius	GL, SDmm	86.3	94.6	69.4	74.5	91.0	92.5	88.5
Radius	Bp, SDmm	83.3	94.6	50.0	74.5	89.3	94.6	80.5
Metacarpal	GL, Bp, SD, Dvm	84.9	95.5	64.2	75.8	na	na	na
Metacarpal	GL, Bp, SD	82.7	95.5	54.7	74.2	94.1	94.9	93.0
Metacarpal	GL, BFp, SD	82.0	95.5	54.7	71.0	93.0	94.9	90.4
Pelvis	SDpu, MRDA	86.2	98.3	65.9	81.8	94.9	100.0	89.8
Femur	GL, TC, Bd	86.7	97.3	60.0	75.0	95.7	97.3	93.1
Femur	GL, SD, Bd	83.7	98.6	45.7	67.3	89.3	94.5	80.5
Tibia	GL, SDmin, Dd	91.8	98.6	66.7	86.7	95.9	97.9	92.0
Tibia	GL, SDml, Dd	91.4	98.6	70.0	82.2	95.9	98.6	90.7
Tibia	GL, SDml, Bd	89.1	98.6	63.3	75.6	94.5	97.9	88.0
Tibia	GL, SDmin, Bd	86.8	96.6	56.7	75.6	92.3	95.9	85.3
Metatarsal	GL, Bp, SD, BFd, WCM, Dvm, BdFus	84.2	97.5	56.6	73.8	na	na	na
Metatarsal	GL, Bp, SD, Dvm	82.8	96.9	56.6	68.9	na	na	na
Metatarsal	GL, Bp, SD	80.2	96.9	50.9	62.3	91.6	96.2	85.1
Astragalus	GLl, Bd	64.0	90.6	20.5	53.4	80.3	82.8	77.8
Calcaneus	GL, BS	72.9	91.8	46.4	46.6	84.2	88.7	78.1

[a] % Cross-validated grouped cases of females, males and castrates correctly classified.
[b] % Cross-validated grouped cases of females and males + castrates correctly classified.

Table 14
Coefficient of variation calculated for all measurements on fused (fo, fu) areas of bone.

Element	Female low fu fo		Female high fu fo		Castrate low fu fo		Castrate high fu fo		Male low fu fo		Male high fu fo	
	N	CV	N	CV	N	CV	N	CV	N	CV	N	CV
Sca_GLP	90	4.3	90	3.8	44	5.2	44	4.3	43	4.9	44	5.9
Sca_BG	90	5.7	90	5.0	44	6.8	44	5.3	43	7.3	44	6.4
Sca_SLC	90	7.0	90	6.4	44	9.2	44	9.2	43	9.9	44	11.3
Hum_GL	71	3.2	75	3.1	15	2.4	20	4.0	22	3.7	27	4.2
Hum_GLC	71	3.2	75	3.3	15	2.7	20	4.0	22	3.4	27	4.2
Hum_SD	71	4.8	75	4.8	15	4.0	20	5.6	22	4.1	27	6.4
Hum_Bd	90	4.5	90	4.1	44	5.1	44	4.2	44	6.0	44	5.5
Hum_BT	90	4.3	90	3.8	44	5.0	44	4.1	44	5.7	44	5.2
Hum_BFT	90	4.6	90	4.0	44	5.7	44	4.9	44	6.3	44	5.8
Hum_HT	90	4.9	90	4.2	44	5.6	44	4.5	44	6.4	44	5.7
Hum_HTC	90	4.3	90	4.2	44	4.2	44	4.3	44	5.1	44	5.0
Rad_GL	72	4.0	75	3.8	16	3.9	20	3.6	25	4.1	26	4.2
Rad_Bp	90	4.9	90	4.4	44	6.3	44	5.6	44	7.3	44	7.6
Rad_BFp	90	4.6	90	4.2	44	5.8	44	4.8	44	6.3	44	6.3
Rad_SDmm	72	4.4	75	4.7	16	3.1	20	4.7	25	4.2	26	4.6
Rad_Bd	72	4.2	75	3.8	16	3.3	20	3.8	25	4.0	26	4.4
Mtc_GL	75	3.8	82	4.0	25	3.9	28	3.4	30	4.5	32	4.1
Mtc_Bp	90	4.2	90	4.0	44	4.7	44	3.2	44	5.0	44	5.2
Mtc_BFp	90	3.9	90	3.7	44	4.0	44	3.2	44	4.3	44	4.6
Mtc_SD	75	4.3	82	4.8	25	4.4	28	5.0	30	5.4	32	6.1
Mtc_BFd	75	4.0	82	4.1	25	3.2	28	3.3	30	4.7	32	4.5
Mtc_WCM	75	4.1	82	4.1	25	3.0	28	3.2	30	4.2	32	4.3
Mtc_WCL	75	4.5	82	4.2	25	2.9	28	3.8	30	5.3	32	4.9
Mtc_Dem	75	4.2	82	3.9	25	4.4	28	4.3	30	5.0	32	4.5
Mtc_Del	75	4.7	82	4.4	25	5.5	28	4.9	30	5.2	32	4.9
Mtc_Dvm	75	3.4	82	4.0	25	3.3	28	3.8	30	4.2	32	3.6
Mtc_Dvl	75	3.7	82	3.9	25	3.4	28	3.8	30	4.1	32	3.7
Mtc_BdFus	75	4.3	82	4.3	25	4.1	28	3.7	30	4.9	32	5.3
Pel_SDpu	90	12.7	90	13.2	44	11.3	44	10.7	44	9.9	44	10.6
Pel_SDmmpu	90	9.6	90	8.4	44	8.7	44	8.3	44	12.7	44	10.2
Pel_MRDA	90	13.9	90	14.3	44	13.2	44	14.3	44	12.5	44	10.7
Fem_GL	72	3.4	74	3.0	14	2.8	21	3.3	24	3.7	28	4.0
Fem_GLC	72	3.3	74	3.2	14	3.1	21	3.3	24	3.8	28	4.2
Fem_TC	75	4.0	78	3.8	20	4.3	22	2.9	25	3.9	29	4.8
Fem_SD	72	4.5	74	5.4	14	3.2	21	4.7	24	6.1	28	6.7
Fem_Bd	72	3.5	74	3.4	14	2.9	21	2.9	24	3.8	28	3.9
Tib_GL	71	3.7	74	3.5	14	3.9	16	3.2	19	3.6	26	4.4
Tib_Bp	71	3.3	74	3.3	14	2.8	16	3.2	19	3.6	26	4.1
Tib_SDml	71	4.3	74	4.1	14	4.0	16	4.6	19	4.7	26	5.4
Tib_SDmin	71	5.0	74	4.8	14	5.0	16	5.1	19	4.6	26	5.6
Tib_Bd	82	3.6	82	4.0	29	3.6	34	3.3	34	5.2	35	3.9
Tib_Dd	82	4.3	82	4.0	29	3.4	34	2.5	34	4.4	35	4.4
Navcu_GB	90	4.1	90	4.9	44	4.7	44	4.6	44	5.0	44	5.5
Mtt_GL	78	4.2	81	4.2	25	4.4	28	4.6	29	4.9	32	4.6
Mtt_Bp	90	3.7	90	3.4	44	4.4	44	3.4	44	4.6	44	4.2
Mtt_BFp	90	3.7	90	3.5	44	4.3	44	3.4	44	4.2	44	4.2
Mtt_SD	78	4.5	81	4.5	25	4.6	28	5.2	29	5.1	32	5.4
Mtt_BFd	78	4.0	81	4.2	25	3.7	28	3.4	29	4.4	32	4.3
Mtt_WCM	78	4.2	81	4.0	25	3.7	28	3.2	29	3.8	32	4.5
Mtt_WCL	78	4.4	81	4.2	25	3.6	28	4.1	29	4.2	32	4.2
Mtt_Dem	78	4.6	81	4.7	25	5.7	28	4.9	29	5.7	32	5.4
Mtt_Del	78	5.1	81	4.9	25	5.7	28	6.1	29	6.4	32	5.5
Mtt_Dvm	78	3.5	81	4.1	25	3.9	28	4.3	29	4.7	32	4.1
Mtt_Dvl	78	3.8	81	4.3	25	3.8	28	4.4	29	4.6	32	4.0
Mtt_BdFus	78	3.9	81	4.1	25	4.0	28	3.8	29	4.4	32	4.5
Ast_GLl	90	3.8	90	4.1	44	3.1	44	3.7	44	4.4	44	5.0
Ast_Bd	90	3.9	90	4.1	44	4.4	44	3.5	44	5.2	44	4.7
Ast_Dl	90	4.5	90	4.9	44	4.1	44	4.0	44	4.7	44	5.0
Cal_GL	77	3.5	82	3.4	26	3.0	30	2.6	28	4.2	30	4.2
Cal_BS	77	4.7	82	4.7	26	4.2	30	3.1	28	4.9	30	4.7
Cal_C	77	5.0	82	5.1	26	4.3	30	4.1	28	5.6	30	5.9
Cal_C&D	77	3.8	82	4.1	26	3.7	30	3.2	28	4.7	30	4.9
Cal_GDde	77	3.7	82	3.9	26	3.8	30	3.2	28	4.6	30	4.2
Average wo pelvis		4.2		4.1		4.2		4.1		4.9		5.0
Average with pelvis		4.6		4.5		4.5		4.4		5.2		5.2

increase in CVs at sites in the post medieval period (and as early as the late medieval period) at numerous sites (Table 15). This increase cannot be explained by a shift in the plane of nutrition, sex ratios or an increase in castration, as our data show these changes will not push the CV up beyond 6, but must result from a size shift in the animals, potentially through a concerted breeding programme or an introduction of new breeds at the site.

Table 15
Post-cranial CVs (coefficient of variation) from a variety of sites showing an increase in sheep size variability through time. Data include sheep and/or sheep/goat but not goat measurements. Pelvis is excluded. Lincoln data from Dobney et al. (1996), with some modifications; Norwich, Castle Mall data from Albarella et al. (2009); Launceston Castle data from Albarella and Davis (1996); other data from ABMAP.

Population/Site	Unimproved Shetlands	Late Saxon	High Medieval		Late Medieval	Early Post medieval	Late Post medieval
Date	Modern	10th–11th C.	12th–13th C.	13th–14th C.	14th–16th C.	16th–18th C.	18th–19th C.
Sheep project flock	5.8						
Lincoln		5		5.2	7.4	6.6	7.4
Norwich, Castle Mall					5.3	7.5	
Reading, Bridge St. E. and Reading Library					7.5	6.7	9.4
Southampton, Newtown			5.7		6		
Winchester, Victoria Rd. 3				5.9		5.8	
Launceston Castle				5	5.3	6.2	8.4

4. Conclusions

This research has demonstrated that attributing age based on post-cranial epiphyseal fusion must take into account a number of potential influences and use appropriate age protocols. At sites where sheep castration was, or may have been, occurring and where nutrition may have been low, even in occasional years, zooarchaeologists are advised to employ the very broad range of epiphyseal fusion timings determined for our 'whole flock' sample. Accounting for sex (castration) and nutrition in this fashion limits the precision of ageing via epiphyseal fusion significantly relative to other published sources but reflects the reality of the situation – at least for the Shetland breed. Other breeds may have a more narrow epiphyseal fusion range though there is currently no evidence to support this supposition. Our fusion data may confidently be used to assign broad age ranges to archaeological material but more detailed ages at death must be captured from dental eruption and wear, a topic we will cover in a forthcoming publication.

We have demonstrated that sheep bone growth is a nuanced process dependant on skeletal element, axes of growth, area of growth, nutrition, sex and castration. Our study of post-fusion growth has allowed us to clarify the range of appropriate, age independent, measurements for comparative biometric analysis thus improving the interpretive potential of zooarchaeological datasets. Given a sufficient sample size the presence of castration may be detected through a combination of length and breadth measurements, particularly SDs, of the radius, tibia and metacarpal, regardless of plane of nutrition. The large overlap in element sizes means few individual elements will be sexable but the overall plot has the potential to indicate whether two or three 'types' (sexes) of element are present. To improve the usefulness of this approach, it will be necessary to assess whether different body forms are present in the assemblage. We have demonstrated that the presence of different breeds/types can be tested for through an analysis of measurement CVs. The combined use of both raw data and summary CVs represents a potentially powerful tool for identifying castration of sheep in the zooarchaeological record. The best metric separation between the sexes is achieved by plotting pelvis SDpu versus MDRA. This plot fully separates males from females and indicates the presence of castrates where they exist. Where preservation of fragmented zooarchaeological assemblages is excellent or in the unusual circumstance of large numbers of entire skeletons being preserved, it may be possible to use these pelvis measurements, in tandem with group CVs, to explore flock demography. Wherever possible pelvis SDpu and MDRA should be incorporated into the suite of measurements recorded. Discriminant Analysis may potentially be used for sex differentiation and would be most reliably interpreted in conjunction with additional analyses such as analysis of variance. In order to establish the usefulness of these approaches an essential avenue of further research is to determine how sex (including castration) manifests itself in the different skeletal elements in other sheep breeds.

The data and analysis presented here represent a major advance in the understanding of sheep skeletal development. Though expensive and time consuming, it is recommended that further studies of this nature are conducted as they represent the best and perhaps only way to gather the quantities of data necessary to address the complex issues of biometry and epiphyseal fusion while controlling for the most common modifying factors including sex, nutrition and castration. It is vital that zooarchaeologists recognize and account for the effect of numerous biological and environmental factors on skeletal development in order that we may better model sheep management and, by extension, human practices in the past.

Appendix. Supplementary material

Supplementary data related to this article can be found online at doi:10.1016/j.jas.2012.01.018.

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