



Identifying draught cattle in the past: Lessons from large-scale analysis of archaeological datasets

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ABSTRACT

Purpose: Improve understanding of the links between biological variables (sex, body size and anatomical position) and adaptive remodelling of autopodia, and the identification of traction use in the archaeological record. **Methods:** A modified version of the recording system for identifying draught cattle in the archaeological record (Bartosiewicz et al., 1997) was applied to a sample of 1509 bones from six sites from medieval England. Analysis focused on identifying correlations between pathological and sub-pathological changes in lower-limb bones in relation to anatomy, sex and body mass.

Results: A correlation between sex, body mass and lower limb bone changes was demonstrated. The need to consider anterior and posterior limb bone elements separately to maximise the potential for identifying cattle used for traction was identified. Changes in hindlimb elements were highlighted as the most useful indicator of draught use.

Contribution: This study provides new, detailed evidence for a previously poorly understood correlation between the effects of anatomical position, sex and body size and the nature of skeletal changes traditionally associated with draught cattle. It pulls together findings and makes comprehensive suggestions for future studies.

Limitations: This is a purely methodological paper. Although general results are presented, there is insufficient space to include a full case study. This will be published separately within the results of the FeedSax project.

Further research: Future studies into the use of cattle for draught purposes in the past should take in to account the sex and size of the animals under consideration, and analyse anterior and posterior elements separately.

1. Introduction

Understanding how the power of domestic cattle (*Bos taurus* L., 1758) was harnessed for ploughing, carting and related activities by past communities, remains a vibrant area of scholarship within zooarchaeology (e.g. Baker, 1984; Bartosiewicz et al., 1997; Carlson Dietmeier, 2018; de Cupere et al., 2000; Gaastra et al., 2018; Groot, 2005; Higham et al., 1981; Johannsen, 2005, 2006, 2011, 2017; Lin et al., 2016; Sherratt, 1981; Telldahl, 2005, 2012; Thomas, 2008; Thomas et al., 2021). Much of this work has concentrated attention on recording pathological and sub-pathological changes in cattle feet, because the biomechanical strain generated from draught use can precipitate adaptive remodelling of skeletal tissues (e.g. Currey, 1984; Goodship et al., 1979; Lanyon and Rubin, 1985) and be observed in archaeological specimens.

Recent emphasis has focussed on quantifying such changes, to move

away from the qualitative description of affected bones and encourage consistent and systematic inter- and intra-site analysis (Thomas and Mainland, 2005). The method developed by Bartosiewicz et al. (1997) was pioneering in this respect, enabling the severity of a suite of pathological and sub-pathological osseous changes in complete metapodials and phalanges to be scored following visual comparison against published reference sequences (Bartosiewicz et al., 1997: Figs. 19–40; Table 1). Metapodials and phalanges are amongst the most useful bones for this purpose for three reasons: 1) they are susceptible to remodelling because of their role in transmitting power and absorbing stress during locomotion; 2) they have a high survival potential because they are dense skeletal elements (Lyman, 1994, Table 7.6); and 3) they are less frequently fragmented by butchering (unlike the pelvis), so they are found complete more often than other skeletal elements.

The application of single scores to categorise continuous data can be difficult, especially when specimens present intermediate or slight levels

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of change (Bartosiewicz et al., 1997: 53–55; Johannsen, 2005: 41). Nevertheless, follow-up studies have demonstrated the benefit of applying this method and provided useful insights into the origin and changing intensity of cattle use for traction (Carlson Dietmeier, 2018; de Cupere et al., 2000; Gastra et al., 2018; Johannsen, 2005, 2006; Lin et al., 2016; Marković and Bulatović, 2013; Telldahl, 2005, 2012; Thomas, 2008; Vann, 2008). Subsequent applications of the method have also recommended refinements to take into account the fragmentary nature of archaeological samples (Carlson Dietmeier, 2018).

Interpreting the pathological index values generated by the method of Bartosiewicz et al. (1997) is not straightforward, however. One particular challenge is separating primary physiological remodelling due to age, sex and body mass, from changes linked to traction use, because the underlying skeletal processes are the same (Molnar et al., 2011). For this reason, benchmarking datasets using animals of known history have been analysed to clarify the links between pathological and sub-pathological changes and biological variables (e.g. Bartosiewicz et al., 1997; Thomas et al., 2021). While these studies have developed understanding, a recognised limitation is that the samples are often small, and the study populations genetically narrow.

In this study, an alternative approach is taken to overcome these limitations: analysing a substantial corpus of archaeological data from medieval England to explore the links between pathological index values and biological variables that can be determined zooarchaeologically: body size, sex and anatomical position. Using archaeological data in this way also permits another variable to be explored – the impact of uneven element representation.

2. Materials and methods

An ongoing project investigating the timing and causes of an increase in agricultural production in England between the 6th and 13th centuries AD (Hamerow et al., 2020, 2019) includes the systematic recording of pathological and sub-pathological changes of the lower limb bones of cattle. The aim of this analysis is to establish when the “heavy” mouldboard plough was introduced into England and understand its subsequent role in the transformation of agricultural practice. Six sites from the English medieval period are incorporated into this analysis (Table 1), dated between CE 600 and 1500, though some cover more than one phase. Over 1500 elements are included (Table 1), of which first phalanges are most common, with similar quantities of metapodials and slightly fewer second phalanges.

The focus of this paper is methodological, to demonstrate the effect of anatomical and biological variables on the adaptive remodelling of the lower limb bones of cattle, rather than providing a case study or details of changes through time. The interpretation of results against the background of agricultural development in medieval England is too detailed to present here, but is a principal focus of the FeedSax project.

Pathological and sub-pathological changes of fused, complete metapodials and phalanges were recorded using an adapted version of the method pioneered by Bartosiewicz et al. (1997) to identify draught cattle in the archaeological record (Thomas et al., 2021). The method involves scoring the severity of a suite of pathological and sub-pathological osseous changes (Table 2) following visual comparison against published reference sequences (Bartosiewicz et al., 1997;

Figs. 19–40). Most alterations are scored on a scale from one to four: a score of one indicates the absence of change (i.e. ‘normal’ bone), while a score of four indicates the severest form of change observed in the original study population (Figs. 1–6). Other variables are recorded on a scale of one to three (e.g. palmar depressions on metapodials) or on a presence/absence basis only (e.g. ankylosis of the second and third metacarpal).

A Pathological Index (PI) is calculated for each skeletal element when all characteristics are present by entering the total score into a formula:

$$PI = (\text{sum of scores} - \text{number of variables}) / (\text{maximum score} - \text{number of variables})$$

A PI of zero indicates that no change has affected the element, while a score of one indicates the most pronounced form of change in all observed variables.

A subsequent study by Thomas et al. (2021) recommended the adoption of a modified Pathological Index (mPI) formula, following analysis of semi-feral cattle, which revealed that some of the changes captured by the method developed by Bartosiewicz et al. (1997) are strongly correlated with age: broadening of the distal metacarpal, proximal and distal exostoses in the metatarsal, distal exostoses of the first phalanx, and proximal lipping and exostoses of the third phalanx. This modified method is followed here: thus, complete, selected characters from Bartosiewicz et al. (1997) are recorded for fused cattle first (proximal) and second (medial) phalanges and complete proximal and distal metapodials. Third (distal) phalanges are excluded as they are highly susceptible to age-related changes in all characters (Thomas et al., 2021). The PI was further modified to maximise the amount of data realised from fragmentary metapodials: thus, the PI was calculated separately for proximal and distal ends of metapodials (Carlson Dietmeier, 2018). The formulae employed can be summarised as follows (see Table 2 for a description of abbreviations used):

- Proximal metacarpal mPI = (sum of PEX + PLIP + PEB + FUS + FAC – 5)/8
- Distal metacarpal mPI = (sum of DEX + DEPR + DEB – 3)/6
- Proximal metatarsal mPI = (sum of PLIP + PEB + STR – 3)/4
- Distal metatarsal mPI = (sum of BRD + DEPR + DEB – 3)/6
- First phalanx mPI = (sum of PEX + PLIP + PEB + DEB – 4)/8
- Second phalanx mPI = (sum of PEX + PLIP + PEB + DEX + DEB – 5)/11

Anterior and posterior phalanges were separated using the criteria of Dottrens (1946). Sex was determined using the ratio of shaft diameter to greatest length and distal width to greatest length in the metacarpal following Davis et al. (2012). Measurements were taken following the standards of (von den Driesch, 1976). These included the narrowest width (diameter) of the shaft (SD) of the first phalanx, breadth of proximal end (Bp) and greatest length (GL) of metacarpals and metatarsals. Other commonly used measurements such as the length and proximal breadth of the first phalanx and breadth of distal end of the metapodials were not used because these areas of the bones are commonly affected by the characters being examined. The shaft

Table 1
Details of case study sites giving the number of elements for each site.

Site Name	County	Period (AD)	Metacarpal	Metatarsal	1st phalanx	2nd phalanx
28 Bow Street, London	Middlesex	600–750	16	21	11	6
Eynsham Abbey	Oxfordshire	500–1330	115	104	127	55
French Quarter, Southampton	Hampshire	900–1350	80	84	111	36
Lyninge	Kent	400–1200	43	30	101	77
Stoke Quay, Ipswich	Suffolk	700–1500	79	82	131	57
Stratton	Northamptonshire	600–1350	49	41	39	14
Total			382	362	520	245

Table 2
Recording protocol for cattle feet (Bartosiewicz et al 1997). Scoring range given in parentheses. Shaded cells = measurements used in the modified pathological index (Thomas et al., 2021).

Variable	Description	Metacarpal	Metatarsal	1st phalanx	2nd phalanx
Proximal exostosis (PEX)	New bone formation near the proximal articulation. This encompasses enthesal as well as osteophytic changes	(1-4)	(1-4)	(1-4)	(1-4)
Proximal lipping (PLIP)	Functional extension of the proximal articular surface due to new bone formation.	(1-3)	(1-3)	(1-4)	(1-4)
Distal exostosis (DEX)	New bone formation near the distal articulation. This encompasses enthesal as well as osteophytic changes	(1-4)	(1-4)	(1-4)	(1-4)
Broadening (BRD)	Broadening of the distal (primarily medial) condyle of the metapodial, likely as an adaptation to loading	(1-4)	(1-4)		
Depression (DEPR)	Depressions on the palmar/plantar surface of the distal shaft of metapodials	(1-3)	(1-3)		
Proximal eburnation (PEB)	Eburnation on the proximal articular surface, pathognomonic of osteoarthritis	(1-2)	(1-2)	(1-2)	(1-2)
Distal eburnation (DEB)	Eburnation on the distal articular surface, pathognomonic of osteoarthritis	(1-2)	(1-2)	(1-2)	(1-2)
Striation (STR)	Transverse striations on the medio-proximal surface of metatarsals near the attachment site for the <i>musculus extensor digitorum brevis</i>		(1-2)		
Striated facet (FAC)	Striations on the triangular facet for the attachment of the <i>ligamentum accessorium</i>	(1-2)			
Fusion of 2nd metacarpal (FUS)	Ankylosis of the vestigial second metacarpal with the medial side of the third metacarpal	(1-2)			



Fig. 1. Example of a proximal metatarsal exhibiting no lesions (left), mPI 0, compared to a metatarsal with stage 3 proximal exostosis (PEX) and stage 3 lipping (PLIP), mPI 0.75. See Table 2 for full description.

diameter of metapodials was also considered unsuitable as this is more sexually-dimorphic than the breadth of the proximal end (Davis et al., 2012, Table 2; Higham, 1969, 65)

Results were tested for statistical significance using the PAleontological STatistics (PAST) package (Hammer et al., 2001). Correlations between size and pathology used Pearson’s r, while investigations into



Fig. 2. Example of a distal metacarpal exhibiting no lesions (left), mPI 0, compared to a metacarpal with stage 4 distal exostosis (DEX) and stage 4 broadening of the distal epiphysis (BRD), mPI 0.67. See [Table 2](#) for full description.



Fig. 3. Example of a distal metacarpal exhibiting no lesions (left), mPI 0, compared to a metacarpal with stage 2 depressions (DEPR) and stage 2 broadening of the distal epiphysis (BRD), mPI 0.33. See [Table 2](#) for full description.

the incidence of pathologies on fore- and hindlimbs used a non-parametric Mann-Whitney test following a Shapiro-Wilk test for normal distribution. Results were considered to be significant when probability was less than or equal to 0.05.

3. Results

3.1. Differences in results between fore- and hindlimbs

In previous studies, a greater PI has been observed in forelimb elements, compared to those of the hindlimb ([Telldahl, 2005](#); [Thomas,](#)

[2008](#); [Thomas et al., 2021](#)), reflecting the fact that approximately two thirds of a cattle's weight is supported by the front legs ([Bartosiewicz, 2008, 154](#); [Helmer et al., 2019](#)). This trait is observed in non-draught cattle, such as the semi-feral herd at Chillingham ([Thomas et al., 2021](#)), while in draught cattle, the addition of a yoke or other type of wither harness places even more load on the forelimbs ([Bartosiewicz et al., 1997, 27 and 79](#)).

In the medieval sample considered here, there were statistical differences in the incidence of pathological/ sub-pathological changes in the fore- and hindlimbs ([Table 3](#)), with higher mPIs recorded on forelimb elements ([Fig. 7](#)). Although higher maximum values were recorded



Fig. 4. Example of a first phalanx exhibiting no lesions (left), mPI 0, compared to those with stage 2 proximal (PEX) and distal (DEX) exostosis (centre), mPI 0.38, and stage 4 proximal (PEX) and distal (DEX) exostosis (right), mPI 1. See [Table 2](#) for full description.



Fig. 5. Example of a first phalanx exhibiting no lesions (left), mPI 0, compared to one with stage 4 lippling (PLIP), mPI 0.5. See [Table 2](#) for full description.

for the metatarsal than the metacarpal, the mean of the latter was greater.

The mPIs for each pathological/sub-pathological character per element were tested statistically to understand what was driving the difference between the fore- and hindlimb ([Table 4](#)). Key results were as follows:

- the incidence of proximal lippling (PLIP) and depressions of the distal shaft (DEPR) was greater on the metacarpal than the metatarsal;
- in first phalanges, only proximal lippling (PLIP) was significantly different for the anterior and posterior elements – proximal and distal exostoses (PEX and DEX) showed no significant difference;
- in the second phalanges, only eburnation of the proximal and distal ends (PEB and DEB) did not show significant differences between the front and hindlimbs.

3.2. Effect of body mass

Previous studies have demonstrated a correlation between bone size and pathological index values ([Telldahl, 2012; Thomas et al., 2021](#)). This, in part, reflects the link between adaptive remodelling and body mass: heavier animals experience greater biomechanical stress to joints and associated connective tissues. This phenomenon was also recognised by [Bartosiewicz et al. \(1997: 68\)](#), who demonstrated a strong positive correlation between individual pathological index values and live weight in modern draught oxen from Romania. Body mass will vary according to age, sex and genotype, all, or some of which may combine to affect the likelihood of adaptive remodelling in lower limb bones. This correlation was investigated in two ways. Firstly, the sexual composition of cattle within archaeological assemblages was assessed, since males (bulls and castrates) will have a higher body mass than cows. This was achieved using measurements of the metacarpals, which are the most sexually dimorphic elements ([Albarella, 1997; Higham, 1969](#)).



Fig. 6. Example of a first phalanx exhibiting no lesions (left), mPI 0, compared to one with stage 4 proximal exostosis (PEX) and stage 4 lipping (PLIP), mPI 0.64. See Table 2 for full description.

Table 3

Mann-Whitney results comparing the incidence of pathologies of the fore (anterior) and hind (posterior) limbs. P = probability; shaded cells = statistically significant results.

Element		Total N	Mean mPI	P
Metacarpal		476	0.13	<0.0001
Metatarsal		383	0.10	
1st phalanx	anterior	232	0.19	0.0028
	posterior	208	0.14	
2nd phalanx	anterior	134	0.21	<0.0001
	posterior	107	0.09	

Secondly, the links between pathological/ sub-pathological characters and the size of individual elements were considered. The width of the bones of bovids is strongly correlated to body mass (Scott, 1983, 1990), which means such measurements can be used as a proxy for the weight of the animal loading the joint, and the likelihood that larger elements correspond to larger overall body mass. The length of bones does not necessarily correspond to body weight, as it can be dependent on other factors such as genetics, health and nutritional status (Webster, 1986; Yablokov, 1974, 268).

In analysing associations between pathological/sub-pathological osseous changes in the autopodia and cattle size, forelimb and hindlimb elements have been considered separately in view of the statistically significant difference observed above.

3.2.1. Males vs females

There is a general bias towards female cattle at all sites in the

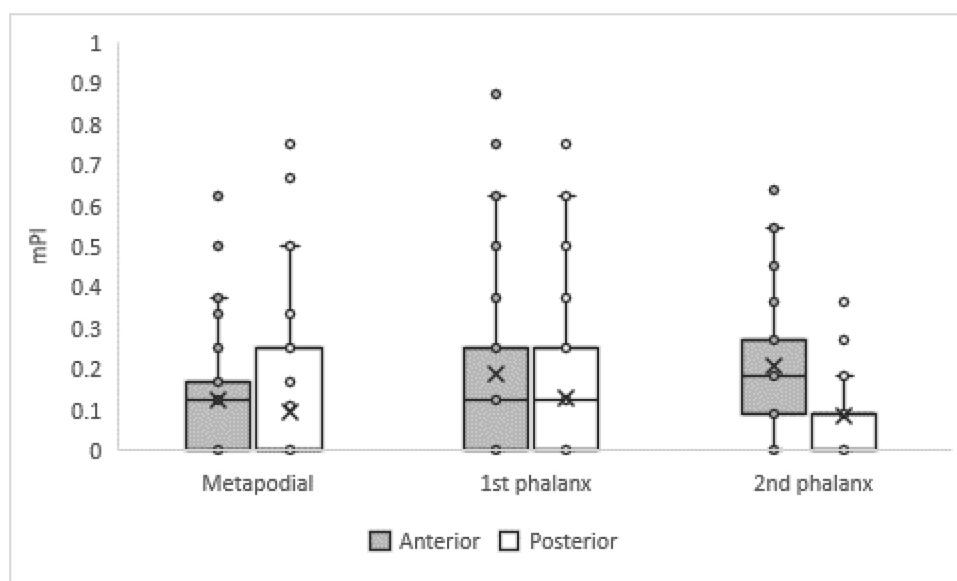


Fig. 7. Box and whisker plot of mPI for bones from the fore (anterior) and hind (posterior) limbs.

Table 4

Statistical analysis (Mann-Whitney U test) of pathological index values for individual characters in the fore (anterior) and hind (posterior) limbs. See Table 2 for abbreviations. P = probability; shaded cells = statistically significant results.

Element	Pathology	Anterior		Posterior		P
		N	Mean	N	Mean	
Metapodial	PLIP	295	1.4	271	1.3	0.0027
	PEB	296	1.2	271	1.2	0.3392
	DEPR	193	1.5	132	1.1	<0.0001
	DEB	197	1.1	164	1.1	0.2716
1st phalanx	PEX	232	1.2	227	1.2	0.2326
	PLIP	232	2.0	227	1.6	<0.0001
	PEB	232	1.2	227	1.2	0.6301
	DEB	231	1.2	227	1.1	0.0820
2nd phalanx	PEX	134	1.2	107	1.0	0.0003
	DEX	134	1.4	106	1.1	<0.0001
	PLIP	134	2.3	107	1.7	<0.0001
	PEB	134	1.2	107	1.1	0.0543
	DEB	134	1.1	106	1.1	0.0951

medieval study (Fig. 8), which means that more data are available for females than males (bulls and castrates). Nevertheless, the data show that male cattle are more likely to have a higher mPI than females (Fig. 9): a statistically significant difference was observed between the lesions observed on the metacarpals of male and female cattle, for both the proximal and distal ends (Table 5).

3.2.2. Overall size

Statistically significant correlations exist between nearly all measured dimensions of metapodials and the severity of lesions of the proximal and distal ends (Table 6): mPI values increase as bones get bigger (Figs. 10 and 11). The exception to this is the distal metacarpal, which exhibited no correlation between size (length or breadth) and mPI (Table 6). A strong correlation exists between the size of the first phalanx and mPI (Table 6). This is illustrated in Fig. 12, where an increase in mPI is observed with an increase in shaft width.

The effect of size on each type of pathological/sub-pathological change was investigated (Table 7). Proximal exostosis (PEX) and proximal lipping (PLIP) on metacarpals increase in severity with length and breadth measurements. The incidence of striations on the proximal facet (FAC) is also affected by the breadth of the proximal end. Only the eburnation of the proximal end (PEB) showed a correlation with the length of metatarsals (Table 7). Metatarsals with the broadest proximal ends were more likely to exhibit higher scores for proximal lipping (PLIP), broadening of the distal end (BRD) and eburnation of the distal

end (DEB). All variables recorded for the first phalanx are positively affected by size.

4. Discussion

A significant difference is observed in the frequency and severity of lesions affecting the forelimbs (higher) and hindlimbs (lower). This is not unexpected given the unequal distribution of body weight, and has been identified in the pathological indices of semi-feral and wild cattle (aurochs) (Johannsen, 2006; Thomas et al., 2021).

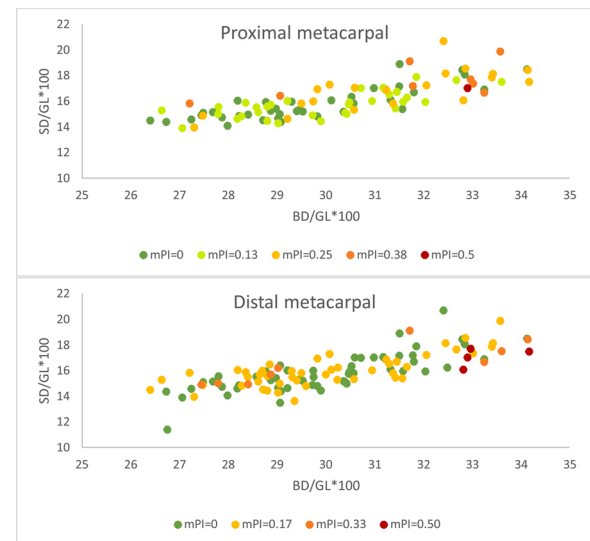


Fig. 9. Plot of mPI against shape of metacarpals, see Fig. 8 for distribution of males and females (after Davis 2012).

Table 5

Statistical analysis (Mann-Whitney U test) of mPI values in male and female cattle (based on Davis 2012). P = probability; shaded cells = statistically significant results.

Metacarpal	Sex	N	Mean	P
Proximal	Female	69	0.1	0.0386
	Male	24	0.2	
Distal	Female	85	0.1	0.0004
	Male	26	0.2	

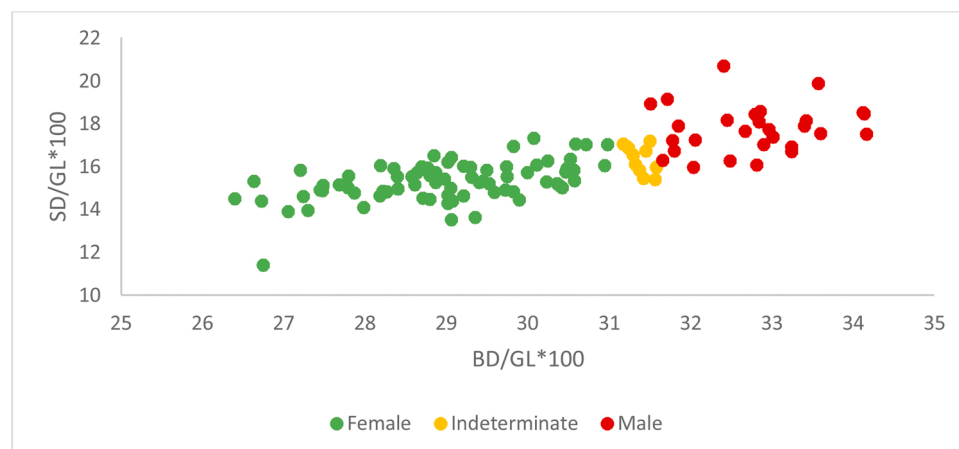


Fig. 8. Plot of metacarpal measurements to show sex distinction based on Davis et al (2012).

Table 6
Correlation (Pearson’s *r*) between mPI and size showing correlation coefficient (CCe) and probability (P). Shaded cells = statistically significant results.

Element	Area	Measurement	N	CCe	P
1st phalanx	anterior	SD	205	0.4826	<0.0001
	posterior	SD	204	0.4361	<0.0001
Metacarpal	proximal	GL	112	0.2307	0.0144
	distal	GL	124	-0.0322	0.7229
Metatarsal	proximal	GL	71	0.2824	0.0170
	distal	GL	72	0.2465	0.0368
Metacarpal	proximal	Bp	277	0.3292	<0.0001
	distal	Bp	108	0.1024	0.2916
Metatarsal	proximal	Bp	238	0.2708	<0.0001
	distal	Bp	65	0.4330	0.0003

Archaeological studies of cattle that were likely to have been used for draught work (Johannsen, 2006; Telldahl, 2012; Thomas, 2008) produced higher pathological index values for hindlimb elements, reflecting the additional strain placed on the pelvic extremity during draught work (Thomas et al., 2021). Bartosiewicz (2008) showed that greater movement and flexibility of the anterior vertebral column and thoracic girdle

means that the hip joint is used as “a pivot between the heavier front half of the body and the artificial load that often exceeds by many times the animal’s own weight” (*ibid*, 157). This study has shown that the biomechanical strain is more likely to be observed in bone remodelling in the autopodia through extension of proximal articular surfaces, proximal exostoses and metapodial depressions caused by inflammation loading of the hindlimb in draught cattle will therefore reduce the difference between the pathological indices observed in the fore- and hindlimb elements, and will be a useful indicator of animals used for draught work. Although the majority of metapodial mPI values in the dataset are greater for the forelimb elements, three of the five highest values come from metatarsals (Fig. 7), which are likely to derive from working cattle. Changes in the values between anterior and posterior elements can be observed when the spread of values is considered over time (Fig. 13). The mPI of posterior elements increases relative to those of anterior elements in the later part of the period, which implies greater loading of the hind legs of some cattle and therefore changes in use.

Some studies have assumed there is little difference between changes to the fore and hindlimbs, and the scores of anterior and posterior phalanges are commonly combined (e.g. Carlson Dietmeier, 2018; de Cupere et al., 2000, 261; Gaastra et al., 2018). On the basis of the results

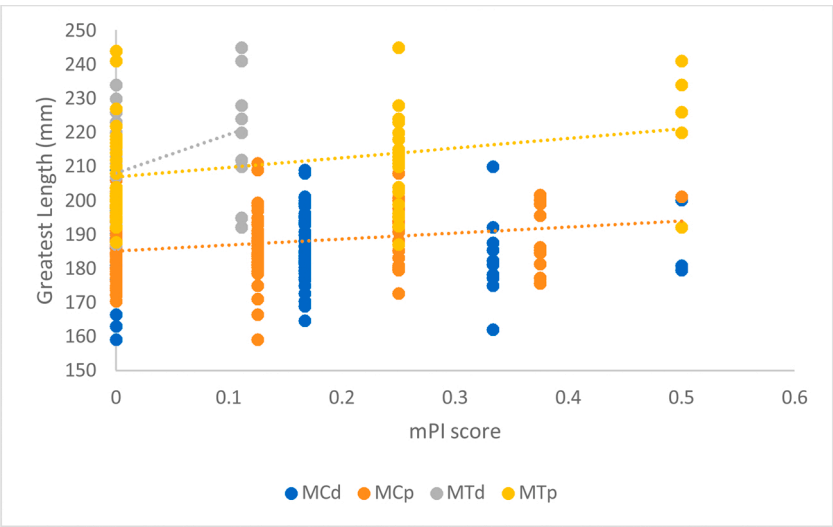


Fig. 10. Plot of mPI scores for proximal and distal metapodials by greatest length. Trendline shown for statistically significant correlations.

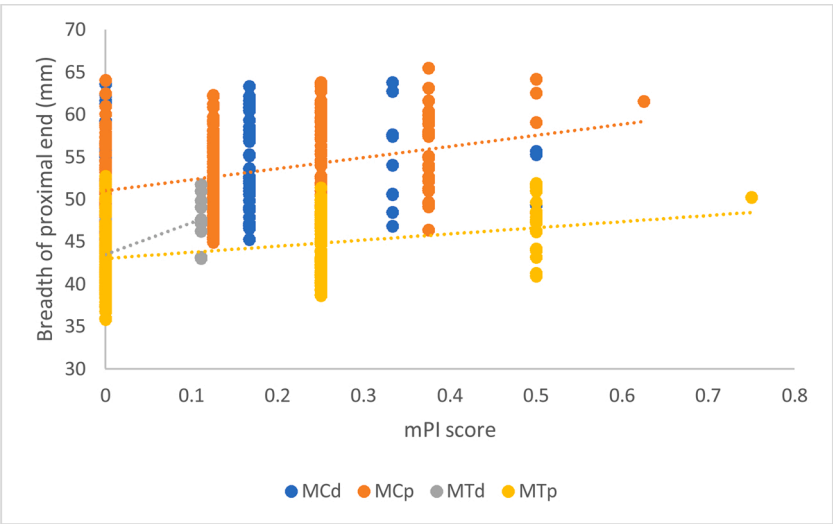


Fig. 11. Plot of mPI scores for proximal and distal metapodials by breadth of the proximal end. Trendline shown for statistically significant correlations.

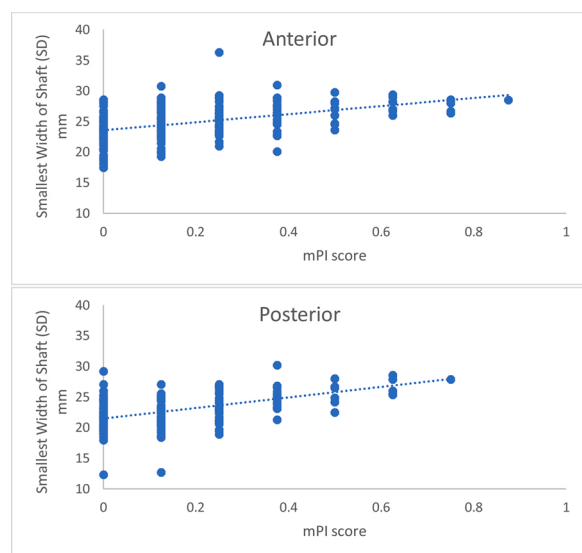


Fig. 12. Correlation between size and mPI of anterior and posterior first phalanges.

presented here, and in previous studies (Johannsen, 2006; Thomas et al., 2021), it is essential that the bones of the anterior and posterior limbs are separated in the application of the method developed by Bartosiewicz et al. (1997) for the identification of draught cattle.

There are clear correlations between bone size and modified pathological index values with male animals and larger bones scoring higher than females and smaller bones. The exception to this is the distal metacarpal, which is affected in a similar way in all animals, regardless of size or sex. Investigation of the effect of size on specific scores revealed that all recorded characters in the first phalanx were correlated

with the shaft diameter, and metapodials exhibited a stronger correlation with breadth than length. Given that, “in general, nonlength dimensions... show higher correlations with body mass than do lengths of distal bones” (Scott, 1990, 301), this evidence indicates that body mass influences the presence and severity of scored characters, supporting previous findings (Bartosiewicz et al., 1997: 68).

The nature of the relationship between the pathological/ sub-pathological changes observed in larger/ male animals is ambiguous and presents a circular argument: are the lesions greater because the animal is larger and/ or male, or are larger and/ or male animals preferred for draught work, and therefore subject to greater loading? The implications of this have been discussed elsewhere (for a good discussion see Bartosiewicz et al., 1997; Telledahl, 2012; Thomas, 2008), but the major possible factors are summarised here, including the role of sex, age, breed and husbandry.

Cattle are sexually dimorphic, and the larger body mass of males increases load on the joints and associated soft tissues, so bulls and oxen will be expected to exhibit higher pathological/sub-pathological scores than cows. The strongest correlations with size are observed in the breadth measurements rather than length. This suggests that the causal factor is body mass rather than size per se, which is consistent with the differences observed between cows and bulls (Higham, 1969, 64).

Larger animals may have also been preferentially selected for draught purposes in the past because cattle with greater body mass have a more efficient working output than smaller animals (Bartholomew et al., 1994). This does not necessarily translate into universal practice, especially in poorer farming communities where cows may be preferentially used given their ability to produce calves and milk as well as power (Johannsen, 2011, 15), and it is always possible that smaller animals that were easier to handle may have been preferred.

Skeletally immature animals will be smaller than full-grown individuals. This is particularly problematic, as the distal metapodials and proximal phalanges fuse at approximately 24–36 and 18 months,

Table 7

Correlation (Pearson's r) between size and individual pathological/ sub-pathological changes. See Table 2 for list of abbreviations. P = probability; shaded cells = statistically significant results.

Element	Pathology	Measurement	Anterior	P	Posterior	P
Metapodial	PEX	Greatest Length	116	0.0078	-	
	PLIP	Greatest Length	116	0.0008	81	0.2474
	DEX	Greatest Length	124	0.4401	-	
	BRD	Greatest Length	-		85	0.1440
	DEPR	Greatest Length	124	0.4762	-	
	PEB	Greatest Length	116	0.1848	81	0.0103
	DEB	Greatest Length	124	0.9616	85	0.0659
	STR	Greatest Length	-		81	0.7027
	FAC	Greatest Length	112	0.1622	-	
	FUS	Greatest Length	114	0.2873	-	
	PEX	Proximal Breadth	283	<0.0001	-	
	PLIP	Proximal Breadth	283	<0.0001	260	<0.0001
	DEX	Proximal Breadth	109	0.2608	-	
	BRD	Proximal Breadth	-		77	<0.0001
	DEPR	Proximal Breadth	285	0.3422	-	
1st phalanx	PEB	Proximal Breadth	282	0.4138	259	0.2938
	DEB	Proximal Breadth	108	0.9508	77	0.0422
	STR	Proximal Breadth	-		255	0.2527
	FAC	Proximal Breadth	278	<0.0001	-	
	FUS	Proximal Breadth	281	0.4377	-	
	PEX	Shaft Diameter	205	<0.0001	204	<0.0001
	PLIP	Shaft Diameter	205	<0.0001	204	<0.0001
	PEB	Shaft Diameter	205	0.0059	204	0.0014
	DEB	Shaft Diameter	205	0.0218	204	0.0237

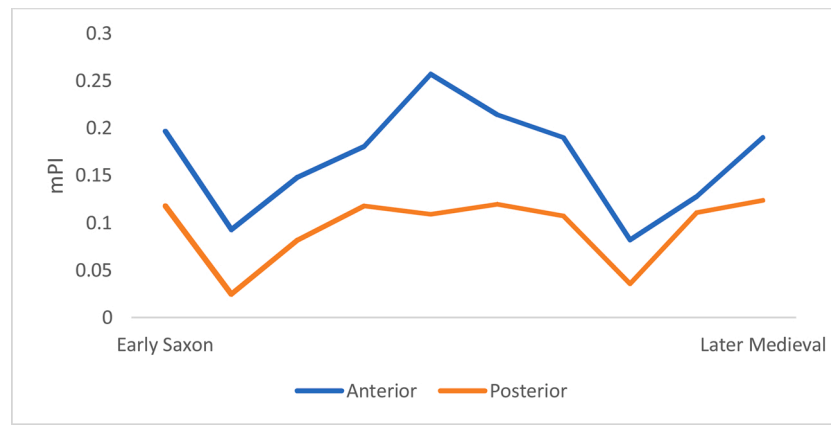


Fig. 13. Plot of MPI scores for anterior and posterior elements.

respectively (Silver, 1969), before the animal reaches full size: it is therefore impossible to assign an age based on these elements alone. There is evidence that animals younger than 6 years are unlikely to have a PI of more than 0.1 (Bartosiewicz et al., 1997, table 18; Thomas et al., 2021, Fig. 3). However, the method used here means that strongly age-correlated lesions (Thomas et al., 2021) were not included in the calculation of the mPI. This was tested by plotting the mPI for various phases of the sites included in the study, against the corresponding ageing data for cattle. Ageing was based on widely used mandibular wear stages (Grant, 1982; Jones and Sadler, 2012), where stage A would correspond to a new born calf, and stage J to an animal between 8 and 13 years old (Jones and Sadler, 2012, Table 8). The data do not show a correlation between the two variables (age and mPI) with some of the oldest groups coinciding with the lowest mPI (Fig. 14), therefore confirming the use of age-independent variables in the calculation of the modified pathological indices.

Other factors that could potentially affect the interpretation of results include the presence of different morphotypes (breeds) that may vary considerably in size (Gidney, 2009), and aspects of animal husbandry such as castration, nutrition, available shelter and level of care that may affect the body weight of animals and their predisposition to health problems (Davis, 2000; Siegel, 1976; Webster, 1986). Many of these variables are hard to observe archaeologically, and the assumption must be that analysis of cattle populations will include a majority of

animals that are treated similarly in terms of animal husbandry.

5. Conclusions

Analysis of a large corpus of medieval cattle autopodia using a modified version of the method for identifying draught cattle in the archaeological record (Bartosiewicz et al., 1997; Thomas et al., 2021) was undertaken to better understand the links between pathological index values and zooarchaeologically determinable biological variables. Correlations exist between the pathological indices of forelimbs (higher) and hindlimbs (lower), as well as variables associated with body weight, where male and larger bones will have greater mPI scores than females and smaller bones.

There is value in continuing investigations into the adaptive remodelling of cattle feet as a proxy for the identification of draught exploitation, but it is vital to consider other variables that are likely to affect the presence and severity of such changes. Therefore, the following steps are recommended for future studies, as it is only by the integration of such data that comparable, robust conclusions can be made based on palaeopathological evidence.

- Quantification of anterior and posterior elements should be carried out before starting analysis. Bias towards either will affect the

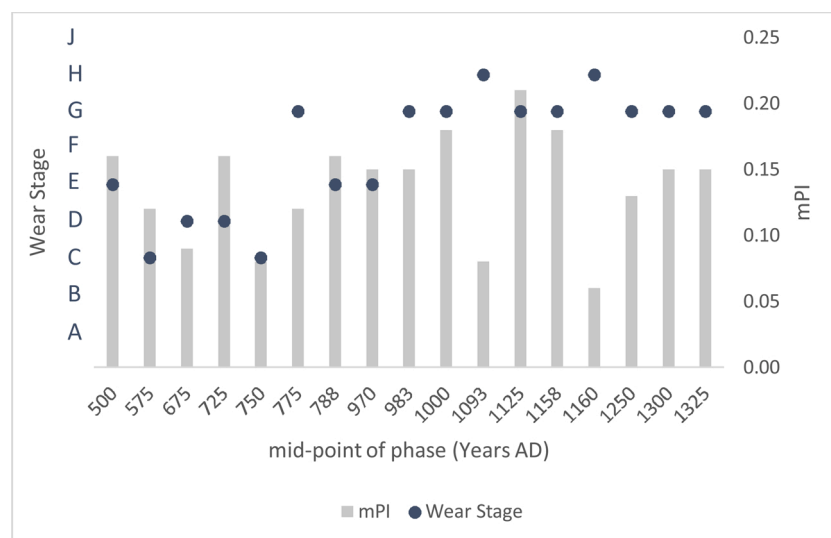


Fig. 14. Comparison of the pathological index and mandible wear stage. The wear stage corresponds to the point where the majority (i.e. 50 % or more) of animals have been culled.

resulting pathological indices, and it is essential that the mPIs of anterior and posterior elements are considered separately.

- Sex profiles of the population should be assessed to understand the likely influence of the male: female ratio on the results, particularly if it is a diachronic or inter-site study.
- Age of populations should be considered to provide an idea of underlying animal husbandry, even though the methods used here mitigate against the inclusion of age-related changes.
- Measurements of bones can be useful to investigate the influence of size, again when considering diachronic or inter-site studies where the importation of new stock is a possibility. Care should be taken not to include measurements that will be affected by the pathological/sub-pathological changes themselves.
- The potential for the bones of the pelvic extremity to be the best indicators of draught animals should be borne in mind for future studies, focusing on the ratio of mPI values between forelimb and hindlimb elements.

It is hoped that this study has provided comprehensive insights into several variables influencing the analysis of pathological/sub-pathological changes in the autopodia of cattle. The findings produced here have potential to be corroborated by future studies on animals of known size, sex and work history.

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