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In search of draught cattle: An identification method

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ABSTRACT

Draught cattle, used for ploughing and carting, contributed to drive social transformations in prehistoric societies by replacing or complementing human power. However, identifying draught cattle from archaeological sites has proven challenging due to the dearth of direct evidence. This paper presents a biometric approach to identifying draught cattle in archaeological assemblages based on metapodials, and first and second phalanges. The analysis includes over 150 modern non-draught cattle encompassing various species and breeds, along with a smaller group of draught cattle. Statistical tests and multivariate analyses were first adopted, revealing distinct morphological differences between the two groups, which do not appear to be highly correlated with age. Although cattle limb bone morphology could vary between breeds, the principal component analysis suggests traction is the predominant factor distinguishing between modern draught and non-draught cattle. Biometric data from metapodials and phalanges were then applied to construct five predictive logistic regression models, with the first phalanges showing the highest balanced accuracy for separating the draught and non-draught groups, a clear advance from Lin et al. (2016)'s pioneering work. The predictive models were then applied to data from two British sites to demonstrate the applicability of the proposed approach to archaeological assemblages. The results show that this biometric approach has the potential to significantly enhance our understanding of draught cattle exploitation in the past.

1. Introduction

The use of cattle as draught animals was an essential agricultural activity before the advent of mechanisation. (Childe (1936: 69) viewed the use of harnessed animals for ploughing and carrying loads as an adaptation that paved the way to the second revolution in the human economy, following the beginning of farming. Later, Sherratt (1981, 1983) developed the Secondary Products Revolution model, which argued that the diversified exploitation of animals, moving from primary products (i.e. meat, blood, bone and hides) to renewable secondary products (i.e. milk, wool and power) was a key driving force behind the substantial changes that occurred between the fourth and third millennium BC in Europe and the Near East. Animal power differs from other secondary products such as wool and milk as the animals replace human force rather than convert their nutrient energy to raw materials (Bogucki, 1993). Since no physical product is directly produced by traction, identifying draught cattle in the archaeological record poses significant challenges. While physical remains like plough marks and wooden ploughs offer valuable evidence of cattle being used for draught purposes, they are relatively rare and confined to specific areas, and the association of the former with cultivation has even been questioned (Rowley-Conwy, 1987). In contrast, osteological remains are often abundant, making morphological and pathological analyses of skeletal remains the best available tool for investigating the use of cattle labour.

Several methods have been developed to record pathological modifications of cattle limb bones. The seminal work by Bartosiewicz et al. (1997) established the Pathological Index, a scoring system for assessing the severity of osseous modifications on cattle metapodials and phalanges. This quantification method has been used in numerous studies (De Cupere et al., 2000; De Cupere and Waelkens, 2002; Johannsen, 2005, 2006, 2017; Telldahl, 2005, 2012; Balasescu et al., 2006; Bartosiewicz, 2006; Deschler-Erb et al., 2006; Thomas, 2008; Vann, 2008; Gaastra et al., 2018; Lin et al., 2018; Holmes et al., 2021a, 2021b; Kamjan et al., 2022; Lin, 2022; Pigière and Smyth, 2023) to identify draught cattle in the archaeological record. However useful this approach may be, scoring based on qualitative criteria inherently leads to inconsistencies. For certain traits, the assigned scores show high coefficients of variation -over 10 % (Bartosiewicz et al., 1997: 55–61).

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Thus, a more objective tool is needed to identify draught cattle in archaeological assemblages.

Pathological conditions, such as osteoarthritis on hip joints, horncore depressions and cranial perforations, have, at times, been considered traction-related (e.g. Ryder, 1970; Armour-Chelu and Clutton-Brock, 1985; Baker and Brothwell, 1980; Milisauskas and Kruk, 1991; Brothwell et al., 1996; Isaakidou, 2006; Bartosiewicz, 2008; Galindo-Pellicena et al., 2017). Although this is not incorrect, some of these pathologies can also be associated with age, trauma, nutrition and genetics (Fabiš and Thomas, 2011; Thomas et al., 2018; Rassadnikov, 2021), thus requiring the use of additional lines of evidence, as some of the above-mentioned authors to some extents do. Relying solely on 'traction pathologies' to infer the presence of draught cattle in an archaeological assemblage runs the risk of overlooking the multifactorial processes of these lesions and may lead to false interpretations.

Bones adjust their structure in response to changes in mechanical loading. This process, a form of somatic adaptation, involves modifications of bone structure without genetic changes to minimise fracture risk (Martin et al., 2015: 280). 'Wolff's Law' describes the nature of bone remodelling under stress by mathematical rules. It suggests that the internal architecture of the trabecular bone accommodates stress from repetitive biomechanical loading, leading to the formation of more robust structures to resist the strain (Wolff, 1986). 'Wolff's Law' has been criticised for assuming bones to be homogeneous and isotropic materials, which is not the case for trabecular bone (Cowin, 2001: 30-10). However, the basic premise is valid; namely, bone adapts to the changing mechanical environment through structural modification (Cowin, 2001: 30-2; Ruff et al., 2006; Rhode, 2013: 205). Based on the principles of bone functional adaptation, cattle limb bones are likely to deform under long-term draught work. Biometry is one of the most effective approaches for identifying such deformities in draught cattle.

A previous study revealed that metapodials of modern draught oxen show a more pronounced asymmetry than in non-draught animals (Bartosiewicz et al., 1993). Recent research on modern cattle demonstrates that the distal breadth (Bd) and e/1 ratio (see Fig. 1 and Table S2) of the distal metapodials is the best combination to distinguish between draught and non-draught cattle (Lin et al., 2016). Although these studies have demonstrated the existence of biometric differences between modern draught and non-draught cattle, a systematic approach to apply these findings to archaeological materials has yet to be undertaken.

This paper aims to establish a biometric approach to identifying draught cattle through metapodial and phalangeal shape ratios using predictive modelling. A sample of modern non-draught and draught cattle was used to build logistic regression models. The applicability of this approach to archaeological assemblages is demonstrated by two British prehistoric sites. However, it is important to acknowledge that the absence of modern female draught cattle in the dataset means that not all possible scenarios for cattle traction use in the past are covered. Access to an ideal skeletal collection of draught animals representing both sexes of the same breed remains a significant challenge.

2. Materials and methods

2.1. Materials

The modern non-draught cattle group used in this study comprises 151 animals, encompassing diverse species (including two American bison, one Banteng, one European bison and one yak) and breeds to capture a broader range of morphological variations. Data were drawn from four modern skeletal reference collections.

1) Bone Laboratory of the University of Leicester (UK)
2) Museum für Haustierkunde Julius Kühn of the Martin Luther University of Halle- Wittenberg (Germany)
3) The Natural History Museum, London (UK)
4) Zooarchaeology Laboratory of the University of Sheffield (UK)

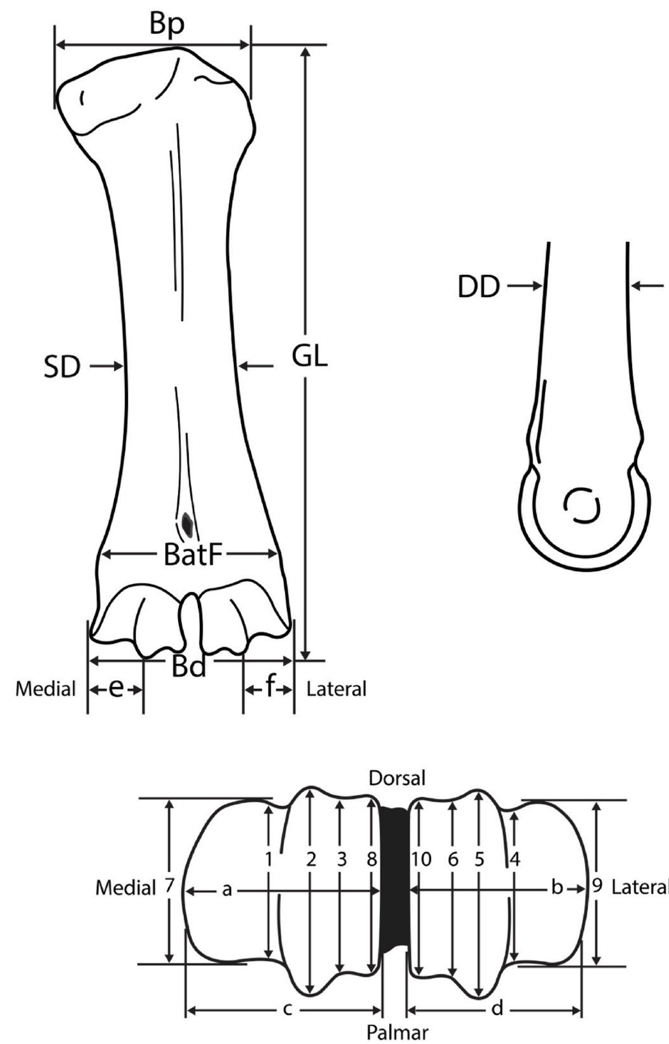

Fig. 1. Measurements taken on metapodials. For a detailed description of each measurement, see Table S2.

All individuals had documented life histories and were recorded by one of the authors (P.L.) (see Table S1 for details).

The draught sample comprises 18 modern Romanian Grey and Brown oxen. The biometric data for the first and second phalanx of these individuals were obtained from Bartosiewicz et al. (1997), while data on the metapodials for the same individuals were sourced from Lin et al. (2016). Additionally, data from six non-draught young bulls belonging to the same crossbreeds as the modern Romanian draught oxen acquired from Bartosiewicz et al. (1997) were also included. Not all modern skeletons were complete.

2.2. Methods

For this study, only the left metapodials were recorded; when absent, the right metapodials were measured instead. For the first and second phalanx, measurements were taken for both the anterior and posterior limbs regardless of their side and their medial or lateral position. To avoid duplications, however, only one digit was selected for each forelimb and hindlimb and only fused elements were recorded. The separation of anterior and posterior limbs was based on the criteria proposed by Dottrens (1946), but the analyses presented here are based on a combination of measurements from both. The choice to combine measurements from anterior and posterior phalanges was made in order to address the uncertainty associated with Dottrens' method when dealing with commingled archaeological assemblages. The third phalanx was omitted from this study for two reasons: 1) this element is more prone than the other two phalanges to extra bone growth even in non-working cattle and 2) the lack of fusion points makes the age attribution for this element uncertain.

Measurements were taken in millimetres, following the guidelines of von den Driesch (1976), Davis (1992), and Lin et al. (2016) (Table S2; Figs. 1 and 2). The Dp measurement of the first and second phalanx is derived from von den Driesch's (1976: 99) description of equids, whereas the GLpe of the second phalanx is equivalent to the GL measurement in von den Driesch (1976: 98).

Shape ratios were used to mitigate the impact of size variation. Various attempts have been made to find the optimal combination of ratios for classifying draught and non-draught cattle. Only the metric pairs that provided the greatest level of separation on each anatomical element are presented here.

Age and sex information was available for most of the studied cattle. In its absence, age was assessed according to mandibular tooth wear and eruption of deciduous fourth premolar (dP4), fourth premolar (P4), and molars. Mandibular tooth wear stages were recorded following Grant (1982) and the age at death was estimated based on Jones and Sadler (2012).

2.2.1. Statistical and multivariate analyses

Statistical and multivariate analyses were first conducted to assess the extent to which variables unrelated to draught work affect skeletal morphology in cattle. Factors such as sex, age, and breed can influence skeletal morphology. However, variation between sexes was not explored in this study due to the limited sample size (all the modern draught cattle are oxen, while only three non-draught cattle are oxen, making the two samples incomparable in terms of sex composition).

Non-parametric tests were applied due to the small sample size and the potential non-normal distribution of the data. The Mann-Whitney *U* test was adopted to test whether the difference between shape ratios of modern draught and non-draught groups was significant while the Spearman's rank correlation was used to investigate the correlations between shape modification and ageing. Since the sample size of each breed is insufficient to perform traditional hypothesis-testing statistical analyses on the effect of breed on metapodial and phalangeal morphologies, the principal component analysis (PCA) was used to identify morphological differences and similarities between cattle breeds.

2.2.2. Logistic regression model

The primary objective of this study is to develop predictive models for identifying probable archaeological draught cattle based on the shape of metapodials and phalanges. Logistic regression is a supervised model for binary classification tasks, estimating the probability of class membership based on predictor variables. This probability-based model is one of the simplest learning models suitable for small sample sizes and requires less computational time than more complex models. It is well-suited for addressing the imbalanced data of this study: the non-draught cattle sample is much larger than the draught group. The biometric data of the modern draught and non-draught cattle were used to build the models for classifying archaeological specimens.

The logistic regression equation determines the decision boundary in the model. This equation predicts the probability of a specimen belonging to draught cattle (Class 1) based on two shape ratios. The logistic regression equation is expressed by Equation (1).

$$P\,(Y=1)=\frac{1}{1+e^{-\left(\beta^0+\beta^1X^1+\beta^2X^2+\ldots+\beta^pX^p\right)}} \qquad [1]$$

In Equation [1], $P\,(Y=1)$ is the probability of a specimen being classified as Class 1 (i.e. draught cattle). β^0 represents the constant term, and $\beta^1, \beta^2, \ldots, \beta^p$ are the coefficients associated with the predictor variables $X^1, X^2, \ldots, X^p$. The logistic regression equation represents the boundary on the scatter plots for visualising the classification results (as in section 3.3).

The common threshold in logistic regression is 0.5. Hence, when *P* is 0.5 or higher, the specimen is assigned to Class 1 (draught cattle). If the *P* falls below 0.5, the specimen is assigned to Class 0 (non-draught cattle).

2.2.3. Performance evaluation

The Brier score was first calculated to test determines if a logistic regression model accurately captures the difference between model-predicted event rates and observed event rates for the classification

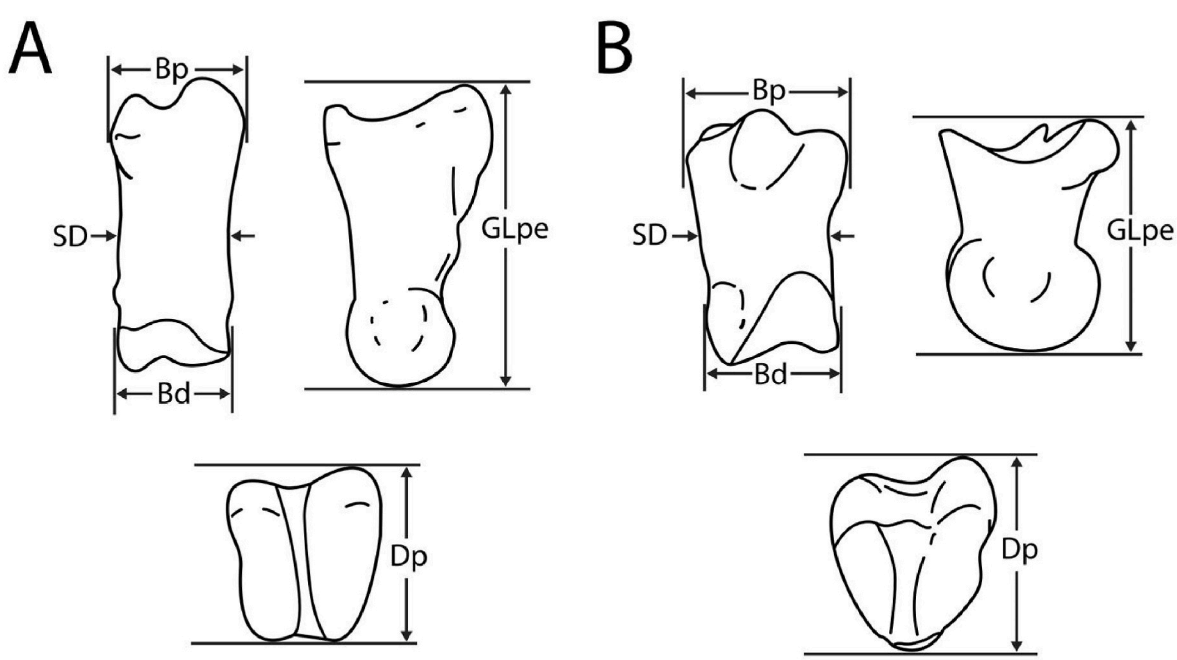

Fig. 2. Measurements taken on (A) first phalanx and (B) second phalanx. For a detailed description of each measurement, see Table S2. Note that GLpe of the second phalanx is equivalent to the GL measurement suggested by von den Driesch (1976: 98).

between draught and non-draught cattle. The model's performance was then evaluated using four metrics.

1) Sensitivity: this evaluates the model's ability to predict correctly the actual positive cases as positive.
2) Specificity: this assesses the model's ability to predict correctly the actual negative cases as negative.
3) Balanced Accuracy: this is calculated as the average of sensitivity and specificity. Balanced Accuracy is a more effective metric than Accuracy, especially when the dataset is unbalanced.
4) F-score: the F-score is a weighted average of precision and recall, providing a balanced measure of the model's performance. It is useful in datasets with imbalanced classes as it considers both false positives and false negatives, giving equal importance to both types of errors.

All data analyses were conducted using RStudio (2023.03.1 + 446). The dataset of modern non-draught cattle, including detailed information on breed, age, and sex for each individual, as well as the R scripts for the logistic regression models used in this paper, are available at http://doi.org/10.17632/7722hz4z4x.

3. Results

3.1. Statistical analyses

3.1.1. Shape ratio differences between draught and non-draught cattle

Statistical results are only presented for the variables discussed in the later section. Table 1 presents the results of the Mann-Whitney *U* test when comparing draught and non-draught cattle for each shape ratio on each anatomical element. All the tested ratios show a very highly significant difference between the two groups of cattle.

3.1.2. Effect of age on shape variations

A Spearman's rank correlation tested the correlation between age and shape ratios in cattle limb bones. Table 2 indicates that the current data does not provide strong evidence for a correlation between age and shape ratios on the metacarpal. Conversely, a few ratios on the metatarsals (e/1 and f/4), first phalanx (Bd/GLpe), and second phalanx (Bp/GLpe and Bd/GLpe) show a higher probability that such correlation exists.

Since the average age of the draught cattle group (10.2 years) is higher than that of the non-draught group (7.4 years), the imbalanced age distribution may lead to the erroneous assumption that the morphological changes could be solely attributed to ageing. A multivariable linear regression analysis was applied to the four ratios which were significantly correlated with age in Table 2 to address this issue and consider potential confounding factors. This test examines the simultaneous influence of multiple independent variables, therefore assessing which variable most affects the difference between the two groups. The results illustrate that while age does not seem to have a significant association with the shape indices, the draught or non-draught use of the animals in the sample does (Table 3). Therefore, the type of use of the cattle, rather than age itself, likely had a more substantial impact on the morphological changes in draught cattle.

Table 1
Results of Mann-Whitney *U* test carried out on each ratio of measurements between type of cattle (draught and non-draught).

Element	Ratio	Draught cattle (n)	Non-draught cattle (n)	W	*P*
Metacarpal	e/1	13	128	1619	0.00 ***
	f/4	13	128	1620	0.00 ***
Metatarsal	e/1	13	132	1591	0.00 ***
	f/4	13	132	1643	0.00 ***
	Bd/GL	13	113	1447	0.00 ***
First phalanx	Bp/Dp	31	197	1962	0.00 ***
	Bd/GLpe	31	197	6459	0.00 ***
Second phalanx	Bp/GLpe	31	199	5917	0.00 ***
	Bd/GLpe	31	199	5948	0.00 ***

*** = very highly significant ($P \leq 0.001$).

Table 2
Summary of Spearman's rank correlation analysis between age and shape ratios.

Element	Ratio	R	*P*
Metacarpal	e/1	0.13	0.16 **NS**
	f/4	0.16	0.08 **NS**
Metatarsal	e/1	0.28	0.00 *
	f/4	0.33	0.00 **
	Bd/GL	0.11	0.27 **NS**
First phalanx	Bp/Dp	−0.003	0.96 **NS**
	Bd/GLpe	0.20	0.00 **
Second phalanx	Bp/GLpe	0.28	0.00 ***
	Bd/GLpe	0.19	0.01 *

*** = very highly significant ($P \leq 0.001$), ** = highly significant ($P \leq 0.01$), * = significant ($P \leq 0.05$), NS = non-significant ($P > 0.05$).

3.2. Principal component analysis on shape ratio and breed

Breed is known as a potential contributing factor to morphological differences in cattle bones (Berteaux and Guintard, 1995; Albarella, 1997). It is important to note that the draught group consists only of Romanian Grey and Brown cross-bred oxen. The homogeneity of this group means that the difference in shape ratios between the draught oxen and the non-draught group (see section 3.1.1) may be entirely a consequence of the inherent robustness of this specific crossbreed.

Principal component analysis (PCA) was performed to explore the overall biometric data structure and the relationship between breeds and morphological changes. PCA is an unsupervised data reduction technique, capturing the maximum variance without utilising class labels in the computation. It reduced datasets containing various shape ratios (Table S3) to two dimensions for recognising breed/type clusters with similar morphological characteristics.

The Chartley and Chillingham cattle were isolated from the non-draught group for breed analysis as these two breeds of cattle are unique herds local to Britain. The Chillingham is a semi-feral herd that has been genetically isolated for at least 300 years (Hudson et al., 2012), while the Chartley cattle were crossed with Longhorns in the early 20th century (Whitehead, 1953: 25, 69). Despite being crossed with the Longhorn, Chartley cattle retain characteristics like those seen in the old herds, in which the bull is particularly strong and large (Whitehead, 1953: 72).

Fig. 3 shows the PCA results for each anatomical element. Ratios on

Table 3
Results of multiple linear regression considering two variables (age and type) on shape ratios in modern draught and non-draught cattle.

Element	Ratio	Variable	T	P
Metatarsal	e/1	Age	1.37	0.17 **NS**
		Type	−7.97	0.00 ***
	f/4	Age	2.11	0.14 **NS**
		Type	−7.07	0.00 ***
First phalanx	Bd/GLpe	Age	0.42	0.67 **NS**
		Type	−12.74	0.00 ***
Second phalanx	Bp/GLpe	Age	1.42	0.16 **NS**
		Type	−12.96	0.00 ***
		Age	0.79	0.43 **NS**
	Bd/GLpe	Type	−15.72	0.00 ***

*** = very highly significant (P ≤ 0.001), NS = non-significant (P > 0.05).

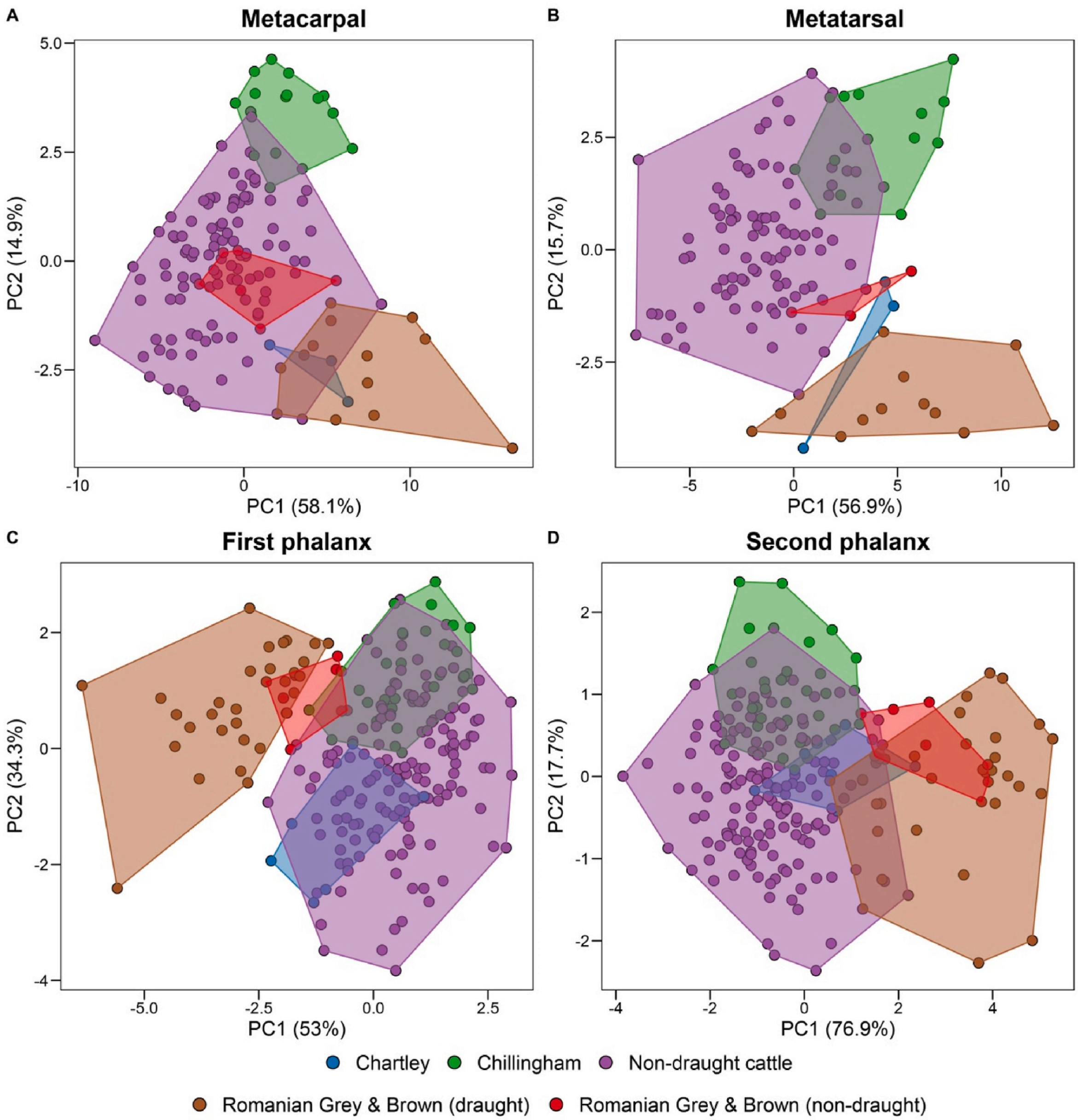

Fig. 3. Principal component analysis results on shape ratios show the first component (PC1) captures the direction of maximum variance in the data, while the second component (PC2) captures additional variability, which is orthogonal to PC1. See Fig. S1 for the contributions of variables to PC1 and PC2.

the metapodials clearly distinguish between non-draught cattle and draught oxen, although a few non-draught cattle overlap with the draught cluster (Fig. 3A and B). The Romanian non-draught bulls fall well within the non-draught group and are separated from the draught cattle belonging to the same crossbreed. These discernible morphological differences within the same crossbreed indicate that draught work is the main factor affecting the morphology of metapodials. Interestingly, the Chartley bulls plot within the draught oxen cluster. Although the sample size for the Chartley group is small, the PCA results suggest that this breed may share similar morphological characteristics with the draught group. The slight overlap between non-draught and working cattle suggests that some cattle breeds may have intrinsic skeletal robustness comparable to that seen in the draught group.

PCA results on the first and second phalanx are shown in Fig. 3C and D. The first phalanges of the draught oxen are completely separate from most of the non-draught group (Fig. 3C). The Romanian non-draught bulls (red cluster) however, tend to plot between the draught and non-draught cattle groups, partially overlapping with both. A similar pattern is observed for the second phalanx (Fig. 3D). The overlap of the Romanian non-draught bulls with the Romanian draught group suggests that this breed may have a distinct phalanx morphology. Nonetheless, the significant separation observed between the non-draught and draught cattle clusters suggests that breed has a minor effect on the classification.

3.3. Logistic regression model and scatter plots

Multiple pairs of ratios have been tested to identify the optimal combination for distinguishing between draught and non-draught cattle for each anatomical element. Only the combinations that yielded the highest balanced accuracy and show the most distinct clusters between the two groups are presented here. In metatarsals the best combination involves the Bd/GL ratio, however, considering that metapodial lengths are rarely available in archaeological specimens, two different combinations are provided for metatarsals.

The logistic regression model is visualised through a scatter plot, which shows the relationships between predictor variables and the probability of the outcome occurring. A decision boundary is established through logistic regression, representing the optimal delineation between draught and non-draught cattle based on two shape ratios. It is important to consider that the boundary is merely based on probability and should not be interpreted as a rigid threshold.

Fig. 4 shows a fairly good separation between draught and non-draught cattle in the metacarpals. The working animals tend to cluster at the top right corner of the graph, showing higher ratio values for both distal metacarpal condyles compared to the non-draught group (lower left corner). The pronounced elongation of trochlear condyles explains the higher values, which are likely due to draught work. Three non-draught cattle marginally plot within the draught area, including two Chartley bulls and one male yak. This result aligns with previous PCA analyses (Fig. 3A), suggesting that the Chartley bulls present similar morphological characteristics to draught oxen. It is unsurprising that the yak is consistent with the draught cattle, given the distinct shape of its distal metacarpal. Fig. 5 indicates that this yak specimen could be pathological, which may further influence the biometric pattern.

The condyle shape ratios of the metatarsals are less effective in distinguishing the two groups, as shown by the considerable overlap between the two clusters (Fig. 6A). The e/1 ratio largely determines the classifications, suggesting that traction may have a greater effect on the medial than the lateral portion of the metatarsal condyles. The Bd/GL ratio is higher in the draught group (Fig. 6B) because of the splaying of the distal end. Along with the f/4 ratio, it provides a promising combination for distinguishing between draught and non-draught cattle. Fig. 6B also shows that sex could be a possible confusing factor in determining traction cattle, as non-draught bulls may have similar morphological characteristics to draught oxen, indicated by the high Bd/GL ratio.

While the separated analyses of anterior and posterior phalanges enhance classification performance their distinction can be difficult in archaeological assemblages. Bartosiewicz (1993) used a biometrical approach in trying to separate anterior and posterior cattle phalanges. However, the results indicate that such distinction is difficult, particularly for the second phalanges. Analyses performed on the modern cattle used in this study align with the previous results, highlighting the uncertainty in reliably separating anterior and posterior phalanges (for further discussion, see Supplementary Part C). The presented results are, therefore, based on a combined analysis (see Supplementary Part B for results of the separated analysis).

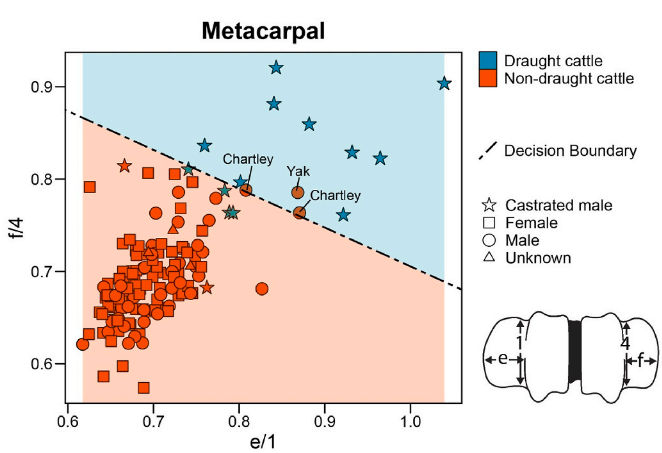

Fig. 4. Shape ratios from metacarpal condyles of draught and non-draught cattle. Ratio of the greatest breadth from medial condyle ridge to medial articulation edge (e) and the antero-posterior diameter of the external trochlea of the medial condyle (1) against ratio of the greatest breadth from lateral condyle ridge to lateral articulation edge (f) and the antero-posterior diameter of the external trochlea of the lateral condyle (4). Decision Boundary at $P = 0.5$.

Fig. 7 shows that the Bp/Dp and Bd/GLpe ratios from the first phalanx almost completely separate draught from non-draught animals (only two non-draught bulls plot inside the draught cattle area). It should be noted that the separation between the two groups is almost exclusively determined by the Bd/GLpe ratio. The working cattle sample clearly presents higher Bd/GLpe ratio values than the non-draught animals, suggesting that long-term additional strain affected the distal end of their first phalanx.

Encouraging results were also obtained from the second phalanx (Fig. 8). The draught cattle cluster generally shows higher Bp/GLpe and Bd/GLpe ratio values than non-draught cattle. Fig. 8 also shows that all non-draught specimens plotting in the draught area for the second phalanx are bulls. These patterns suggest that bulls possess a robust bone structure comparable to that of draught cattle, regardless of their work history. Thus, caution should be taken when interpreting archaeological specimens, as even non-working bulls may be confused with draught animals.

The Brier score was calculated to indicate the overall accuracy of probabilistic predictions. Table 4 shows the results for models presented in the previous section, with the metatarsal (Bd/GL and f/4) and the first phalanx (Bp/Dp and Bd/GLpe) being the most promising for classifying draught and non-draught cattle.

Table 5 shows the performance metrics of the five models illustrated in section 3.3. Among the four elements considered, the first phalanx yields the best classification performance, indicated by a high Balanced Accuracy and F-score (see section 2.3.1). The metatarsals present fair results, with the condyle ratios (e/1 and f/4) showing a relatively low sensitivity. However, the performance improves significantly with the Bd/GL and f/4 ratios, achieving a Sensitivity of 0.92.

The consistently higher specificity than sensitivity across all models indicates that the models correctly identify the majority negative class (non-draught cattle) but demonstrate relative weakness in accurately identifying the positive class (draught cattle). This result can be explained by the imbalance in the dataset, which may lead the models to favour the majority class (non-draught cattle), resulting in a generally higher specificity than sensitivity.

3.4. Application to archaeological material

The decision boundaries in the previous scatter plots (section 3.3) were established through logistic regression, which was built using data from modern draught and non-draught cattle. The logistic regression equation consists of three components: the constant term (β^0), coefficients (β^1 and β^2), and the relevant predictor variables (X^1 and X^2) (Equation [1]).

Table 6 presents the constant terms and coefficients of each decision boundary in the plots illustrated in section 3.3. These logistic regression models predict the class membership for new data from archaeological assemblages. For example, Fig. 7 shows the classification result based on the predictor variables Bp/Dp and Bd/GLpe from the first phalanx. By substituting the constant term and coefficients provided (Table 7), the decision boundary equation for this model is expressed by Equation (2).

$$P(Y=1) = \frac{1}{1 + e^{-\left(-10.09 + (-49.73)\left(\frac{Bp}{Dp}\right) + 105.48\left(\frac{Bd}{GLpe}\right)\right)}} \qquad [2]$$

Data recorded from two British prehistoric sites were used to demonstrate the application of the predictive model. West Row Fen is an Early Bronze Age site (2290–1780 cal. BC (Olsen, 1994: 116)) in Suffolk, while Potterne is a Late Bronze Age/Early Iron Age transition site (the beginning of the tenth century to the end of the sixth century cal. BC (Lawson et al., 2000: 261)) in Wiltshire. Measurements taken from Specimen 47 from West Row Fen, for example, show a Bp/Dp ratio of 0.95 and a Bd/GLpe ratio of 0.52 (Table 7). Substituting these shape ratios into Equation [2], the calculation of the probability of Specimen

Fig. 5. Comparison of the right distal metacarpal between (A) a yak (*Bos grunniens*) and (B) non-draught domestic cattle (Holländer cow). The yak metacarpal could be deformed due to pathology.

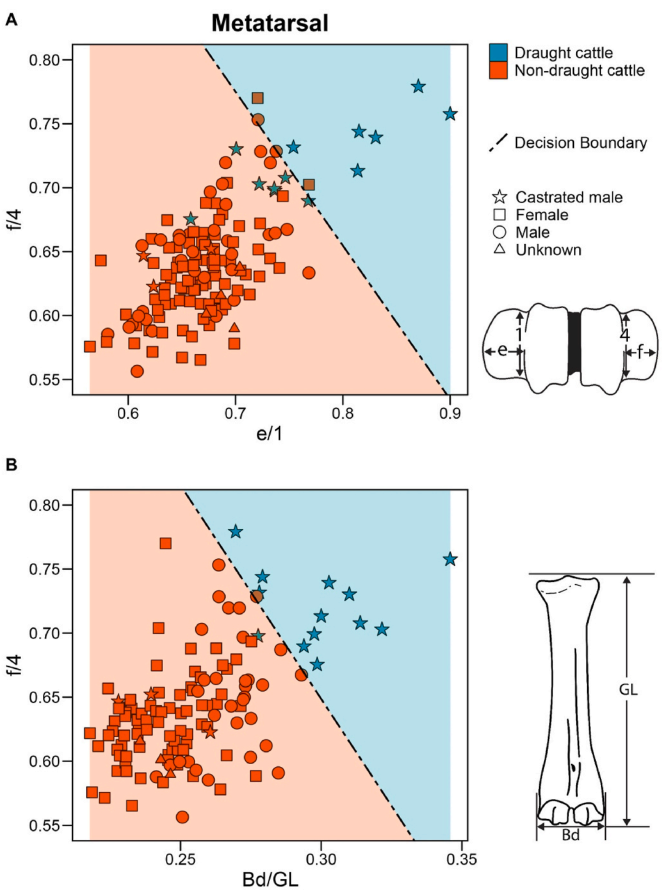

Fig. 6. Shape ratios from metatarsal condyles of draught and non-draught cattle: **(A)** ratio of the greatest breadth from medial condyle ridge to medial articulation edge (e) and the antero-posterior diameter of the external trochlea of the medial condyle (1) against a ratio of the greatest breadth from lateral condyle ridge to lateral articulation edge (f) and the antero-posterior diameter of the external trochlea of the lateral condyle (4); **(B)** ratio of the greatest breadth of the distal end (Bd) and the greatest length (GL) against ratio of the greatest breadth from lateral condyle ridge to medial articulation edge (f) and the antero-posterior diameter of the external trochlea of the lateral condyle (4). Decision Boundary at $P = 0.5$.

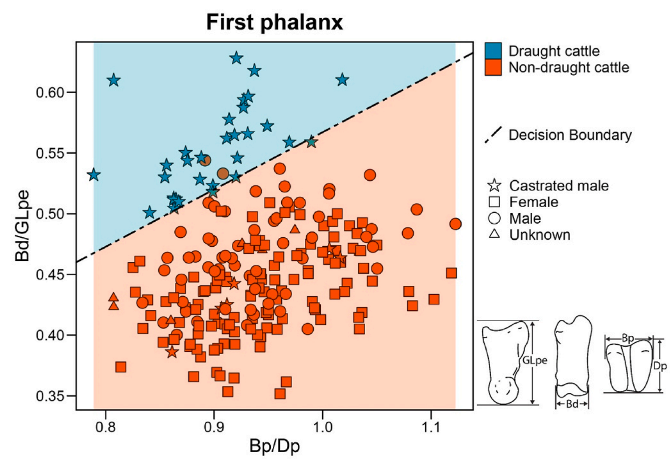

Fig. 7. Shape ratios from first phalanx of draught and non-draught cattle. Ratio of the greatest breadth of the proximal end (Bp) and the depth of the proximal end (Dp) against ratio of the greatest breadth of the distal end (Bd) and the greatest length of the peripheral (abaxial) half (GLpe). Decision Boundary at $P = 0.5$.

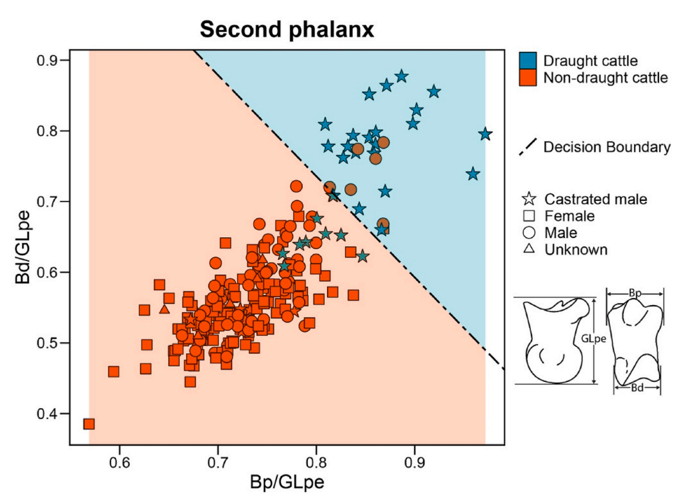

Fig. 8. Shape ratios from second phalanx of draught and non-draught cattle. Ratio of the greatest breadth of the proximal end (Bp) and the greatest length of the peripheral (abaxial) half (GLpe) against ratio of the greatest breadth of the distal end (Bd) and the greatest length of the peripheral (abaxial) half (GLpe). Decision Boundary at $P = 0.5$.

Table 4
Brier score for the models.

Model	Brier score
Metacarpal (e/1 and f/4)	0.03
Metatarsal (e/1 and f/4)	0.04
Metatarsal (Bd/GL and f/4)	0.01
First phalanx (Bp/Dp and Bd/GLpe)	0.02
Second phalanx (Bp/GLpe and Bd/GLpe)	0.05

Table 5
Model performance metrics.

Model	Sensitivity	Specificity	Balanced Accuracy	F-score
Metacarpal (e/1 and f/4)	0.69	0.97	0.83	0.88
Metatarsal (e/1 and f/4)	0.46	0.97	0.71	0.54
Metatarsal (Bd/GL and f/4)	0.92	0.99	0.95	0.92
First phalanx (Bp/Dp and Bd/GLpe)	0.90	0.98	0.94	0.90
Second phalanx (Bp/GLpe and Bd/GLpe)	0.67	0.96	0.82	0.71

Table 6
Decision boundary of the logistic regression models for classification based on shape ratios.

Figure	β^0	β^1	X^1	β^2	X^2
Fig. 4	−58.33	21.79	e/1	51.80	f/4
Fig. 6A	−45.02	33.49	e/1	27.84	f/4
Fig. 6B	−157.77	319.15	Bd/GL	95.64	f/4
Fig. 7	−10.09	−49.73	Bp/Dp	105.48	Bd/GLpe
Fig. 8	−30.67	23.34	Bp/GLpe	16.31	Bd/GLpe

Table 7
Shape ratios of two archaeological specimens and probability of draught cattle classification.

Specimen	Bp/Dp	Bd/GLpe	*P* (Draught cattle)
West Row Fen (ID: 47)	0.95	0.52	0.08
Potterne (ID: 375)	0.86	0.54	0.98

47 being draught cattle proceeds as Equation (3):

$$P(Draught\ cattle) = \frac{1}{1 + e^{-(-10.09 + (-49.73)(0.95) + 105.48(0.52)}} \quad [3]$$

$$P(Draught\ cattle) = 0.08$$

Given that $P = 0.07$, the probability of this specimen belonging to the draught cattle group is smaller than the threshold probability of 0.5. Thus, Specimen 47 from West Row Fen is classified as non-draught cattle.

In contrast, Specimen 375 from Potterne exhibits a Bp/Dp ratio of 0.88 and a Bd/GLpe ratio of 0.53 (Table 7). A probability of 0.80 is determined (as calculated in Equation (4)), indicating a high likelihood that Specimen 375 belongs to the draught cattle group.

$$P(Draught\ cattle) = \frac{1}{1 + e^{-(-10.09 + (-49.73)(0.86) + 105.48(0.54)}} \quad [4]$$

$$P(Draught\ cattle) = 0.98$$

Fig. 9 visualises the classification results when the model was applied to all the West Row Fen and Potterne specimens. The decision boundaries represent $P = 0.5$. Specimen 47 from West Row Fen plots below the line in the non-draught category, while Specimen 88 from Potterne is above the boundary. The probability of a specimen belonging to draught cattle is represented by the colour scale, in which a specimen leaning more towards blue is more likely to be a draught animal while a specimen leaning more towards red indicates it is less likely to be a draught animal.

Overall, cattle in West Row Fen were unlikely to have been used for draught work (Fig. 9A). Potterne, however, shows a different pattern, indicating that it is highly likely that draught cattle were present at the site, although most were non-draught animals. Some non-draught bulls may be included in the draught group, but they are unlikely to dominate that cluster as no sensible husbandry strategy would encourage the keeping of many entire males.

These two archaeological examples show how the logistic regression models built through modern biometric data can be used to identify potential draught cattle in archaeological assemblages. The R codes of all models established in this study are accessible at http://doi.org/10.17632/7722hz4z4x and are readily available for use in predicting archaeological specimens.

4. Discussion and conclusion

Draught cattle were a key component in shaping past human

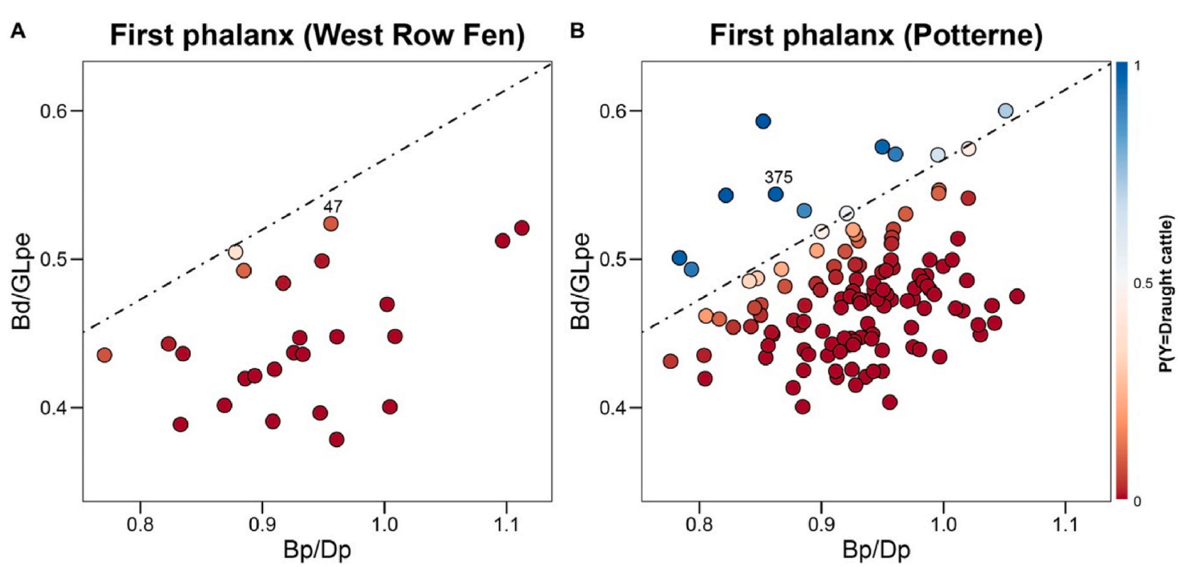

Fig. 9. Classification results using Bp/Dp and Bp/GLpe ratios on the first phalanx in (**A**) West Row Fen and (**B**) Potterne. Decision Boundary at $P = 0.5$.

societies, but the question remains: how can draught cattle be identified in archaeological contexts? This study presents a first-of-its-kind approach, employing logistic regression modelling based on biometric data of metapodials and phalanges to identify draught cattle in the archaeological record.

Remarkably, considering that previous studies have focused mainly on metapodials, the shape ratios from the first phalanx show this anatomical element to be the most powerful for distinguishing between draught and non-draught groups. All shape ratios of the metapodials and phalanges tested in this study show significant variation between modern draught and non-draught cattle. However, the findings of this study suggest that age does not appear to be highly correlated with shape ratios. Due to insufficient non-draught oxen, statistical tests were not performed to analyse the relationship between sex and shape ratios. The scatter plots, however, reveal that non-draught bulls often show a skeletal morphology similar to that of draught oxen, likely due to the robustness of males. This result highlights the importance of considering sex as a potential confounding factor in detecting draught work from archaeological assemblages.

Cattle breed is also a factor that affects skeletal morphology. The draught cattle in this study belong to a single crossbreed of Romanian Grey and Brown varieties. It was, therefore, necessary to consider the possibility that this homogeneity within the draught group could be the sole reason for its distinctiveness. The PCA results, however, refute this possibility, as the Romanian non-draught young bulls from the same crossbreed predominantly exhibit similar metapodial morphologies to the other non-draught cattle. The young bulls also show intermediate phalangeal shapes between the non-draught group and the draught cattle within the same crossbreed. Although breed contributes to morphological variations in cattle limb bones, the PCA results support the assumption that traction is the predominant factor distinguishing between modern draught and non-draught cattle. The results do, however, confirm the previous point that non-draught bulls may show a robust structure comparable to draught animals. The Chartley bulls in particular have metapodial shapes comparable to the draught herd. Thus, caution is needed when interpreting biometric results from archaeological materials, as stocky morphological features may in some cases be associated with sex and breed rather than the working history of the animals.

The findings of the current study align with previous research by Lin et al. (2016), indicating that the e/1 ratio in the metapodials of the draught group is significantly higher compared to the non-draught group. The distal condyles' ratios (e/1 and f/4) were employed to mitigate the potential impact of size variations, demonstrating effective discrimination in the metacarpal. A promising separation can also be observed while comparing the Bd/GL ratio with the f/4 ratio in the metatarsal. Lin et al. (2016) suggest that the e/1 ratio can be used with distal breadth (Bd) measurements in a scatter plot to determine sex preferences when selecting draught animals. This paper, however, questions the validity of sexing draught cattle based on metapodial distal width.

Whilst distal metapodials in cattle do exhibit sexual dimorphism, with bulls generally having a wider distal width than cows (Higham, 1969; Thomas, 1988; Albarella, 1997: 38; Davis et al., 2018), the broadening of the distal metapodials (especially the metacarpals) has also been identified as a feature in modern working herds (Bartosiewicz et al., 1997). An archaeological specimen displaying a wide distal end and a high e/1 ratio could therefore come from a cow or ox used for traction, which could have been deformed through use, or a non-draught bull, due to their inherent robustness. This study has shown that bulls without a working history may have shape ratios comparable to their draught counterparts. This supports traction as a possible confusing factor in sexing cattle metacarpals, as has been highlighted in previous studies (Thomas, 1988; Davis et al., 2018). The potential impact of castration time and draught work on skeletal morphology further complicates the attribution of sex and working history to archaeological metapodials.

The e/1 ratio on metapodials has been adopted by later works as a 'diagnostic index' to identify draught individuals when it equals or exceeds 0.75 (Gaastra et al., 2018; Pigière and Smyth, 2023). The rationale behind choosing this value as a threshold is, however, unclear as 0.75 is the median e/1 value for the metatarsal of the modern traction cattle as calculated in Lin et al. (2016) (Table 7). The present study reveals that an e/1 ratio of 0.75 is a typical value for non-draught cattle metapodials, especially for bulls. Thus, rather than arbitrarily selecting a threshold value, this study proposes a more robust approach by adopting logistic regression to establish a decision boundary based on the evaluation of two shape ratios.

Thus far, phalanges have been less commonly used than metapodials to identify draught cattle in archaeological material. A comparison of phalanges from the Romanian draught herds with domestic cattle from archaeological sites by Helmer et al. (2018) suggested that the differences between traction animals and the non-draught cattle are characterised by a decrease in the greatest length of the peripheral (abaxial) half (GLpe) and widening at both ends (Bd and Bp). Unfortunately, the linear measurements are affected mainly by the absolute size of the cattle, which is irrelevant for identifying draught animals. The present study shows that shape ratios on phalanges do, however, yield compelling results in distinguishing between draught and non-draught cattle. Notably, the ratios of Bp/Dp against Bd/GLpe in the first phalanx and Bp/GLpe against Bd/GLpe in the second phalanx provided a pronounced separation between the two groups.

One major challenge in studying the morphological changes in draught cattle bones is the limited availability of modern materials for analysis. While the precise threshold of work intensity needed to induce detectable skeletal modifications is not yet fully understood, the modern draught cattle included in this study were extensively used for traction prior to their slaughter. The modern draught cattle, therefore, may not necessarily mirror the conditions of prehistoric times. The intensity of draught work, determined by the number of years cattle were used and the duration of work per year, could contribute to varying degrees of morphological changes. It is also worth noting that while oxen are preferred for draught work due to their strength and docility, draught cows were also used in the past (Armour-Chelu and Clutton-Brock, 1985; Isaakidou, 2006). Since the modern draught group in this study comprises only oxen, the models could potentially be less effective in detecting draught cows. Nevertheless, the non-draught cattle dataset generated in this study will be a helpful baseline for future comparisons with archaeological materials, as well as for understanding the impact of draught activities on skeletal morphology.

Concurring with prior research, this study revealed the influence of variables, particularly sex and, to some extent, breed on skeletal morphology. Thus, it is imperative to emphasise that no single ratio or pathology can be regarded as an absolute 'traction pathology' or 'diagnostic index'. Even though the decision boundary established by the logistic regression defines the optimal cut-off point between draught and non-draught cattle, it should not be viewed as a strict threshold. The potential complex interplay of biological factors, breed, sex, live weight, and external factors (such as terrain) on limb bone morphology must be considered when interpreting archaeological materials. If feasible, assessing all anatomical elements is advisable to ensure a conclusive identification of draught cattle in an archaeological assemblage.

In conclusion, this paper introduces a new biometric approach for identifying draught cattle in archaeological assemblages. By using biometric data from modern draught and non-draught cattle the study builds predictive models applicable to metapodials and phalanges. Although this method needs to be applied alongside other lines of enquiry, the proposed approach is a highly effective tool for future analyses, advancing the understanding of draught cattle exploitation in past societies.

CRediT authorship contribution statement

Phoebe Liu: Writing – review & editing, Writing – original draft, Visualization, Validation, Software, Resources, Project administration, Methodology, Investigation, Funding acquisition, Formal analysis, Data curation, Conceptualization. **Lenny Salvagno:** Writing – review & editing, Supervision, Formal analysis, Conceptualization. **Benjamin Wimmer:** Writing – review & editing, Software, Methodology, Formal analysis, Conceptualization. **Umberto Albarella:** Writing – review & editing, Supervision, Resources, Project administration, Methodology, Investigation, Funding acquisition, Formal analysis, Conceptualization.

Data availability statement

The data that support the findings of this study are openly available in Mendeley Data at http://doi.org/10.17632/7722hz4z4x and Github at https://github.com/Phoebe-WCLiu/draught_cattle_biometry.

Reproducible results

The Associate Editor for Reproducibility downloaded all materials and could reproduce all of the results presented by the author.

Declaration of competing interest

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

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.jas.2025.106229.

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