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Research article

Refining the methods for identifying draught cattle in the archaeological record: Lessons from the semi-feral herd at Chillingham Park

Richard Thomas [a,*], Lauren Bellis [a], Rebecca Gordon [b], Matilda Holmes [a], Niels N. Johannsen [c], Meghann Mahoney [d], David Smith [e]

[a] School of Archaeology and Ancient History, University of Leicester, University Road, Leicester, LE1 7RH, UK
[b] Brereton Road, Bedford, MK40 1HU, UK
[c] Department of Archaeology and Heritage Studies, Aarhus University, Moesgård Allé 20, DK-8270, Højbjerg, Denmark
[d] Maryland Science Center, 601 Light St., Baltimore, MD, 21230, USA
[e] Classics, Ancient History and Archaeology, University of Birmingham, Edgbaston, Birmingham, B15 2TT, UK

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ABSTRACT

Objective: This study–> provides a baseline of pathological and sub-pathological changes in the lower-limb bones of a semi-feral herd of domestic cattle. The purpose is to refine an existing method for identifying the use of cattle for traction using zooarchaeological evidence.
Methods: A published recording system for identifying draught cattle was applied to a sample of 15 individuals from Chillingham Park, Northumberland. Correlations were explored between individual pathological index values, the scores obtained for individual pathological/sub-pathological changes, and three biological variables: age, sex and body size.
Results: Pathological index values in the Chillingham cattle were low. Positive correlations between individual pathological index values and age, sex and body size were identified. Broadening of the distal metacarpal, proximal and distal exostoses in the metatarsal, distal exostoses of the proximal phalanx, and proximal lipping and exostoses of the distal phalanx, were strongly correlated with age.
Conclusions: Pathological index scores demonstrate that adaptive remodeling of the autopodia is low in a free-ranging population of cattle, supporting the view that more pronounced changes provide useful identifiers of traction use. Application of modified pathological index formulae to nine archaeological sites from England indicated that cattle were only intensively used for traction in the Roman and later medieval periods.
Significance: This study refines the methods used to identify traction in the archaeological record through the consideration of cows and a wider range of ages than has been considered previously.
Limitations: Only 15 individuals from the Chillingham herd were available for analysis.
Suggestions for further research: The refined formulae should be applied to additional archaeological datasets from different regions and time periods to explore the changing exploitation of cattle for traction.

1. Introduction

Identifying the origin, spread and intensification of domestic cattle (*Bos taurus* L., 1758) traction technology remains an important theme in archaeological research (e.g. Baker, 1984; Bartosiewicz et al., 1993, 1997; de Cupere et al., 2000; Dietmeier, 2018; Gaastra et al., 2018; Galindo-Pellicena et al., 2015; Groot, 2005; Higham et al., 1981; Issakidou, 2006; Johannsen, 2005, 2006, 2017; Lin et al., 2016; Milisauskas and Kruk, 1991; Sherratt, 1981, 1983; Telldahl, 2005, 2012; Thomas, 2008a). While material culture, imagery, the presence of ard/plough marks in soils and demographic profiling using zooarchaeological data are commonly used, these sources can be problematic. Mortality profiles only facilitate a comparison of theoretical models of optimized production in living populations to patterns observed in a time-averaged death assemblage, rather than directly identifying products or services (Thomas and Mainland, 2005: 1). Moreover, it is clear from historical and ethnographic studies (e.g. Groot, 2005; Johannsen, 2005: 45–7) that such models are not universally appropriate: thus, an abundance of older

* Corresponding author.
E-mail addresses: rmt12@le.ac.uk (R. Thomas), laurenbellis0@gmail.com (L. Bellis), rebecca@bonesandantlers.co.uk (R. Gordon), matty@archaeozoology.co.uk (M. Holmes), nnj@cas.au.dk (N.N. Johannsen), meghann.mahoney@gmail.com (M. Mahoney), d.n.smith@bham.ac.uk (D. Smith).

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cattle might reflect the accumulation of large herds as a marker of social prestige rather than a subsistence strategy centering on secondary products. Material culture evidence is often rare, indirect and provides a static picture of past practices. As Johannsen (2005: 39) observes, their contemporaneity with the practices they depict is often difficult to prove and they do not provide any indication of the frequency and intensity of cattle traction use.

Paleopathology is an attractive alternative because it provides a direct and abundant source of evidence regarding the life histories of animals. Cattle did not evolve to pull ploughs and carts; the biomechanical strain resulting from such activities can precipitate adaptive remodeling of skeletal tissues when it repeatedly exceeds optimal loading (e.g. Currey, 1984; Goodship et al., 1979; Lanyon and Rubin, 1985) and can therefore be identified archaeologically. The most secure way that traction animals can be identified is when they are buried in the position in which they would have worked during life and their bones exhibit pathological and/or sub-pathological changes consistent with traction use, such as the example from the Eneolithic settlement of Svodín in south-western Slovakia (Fabiš et al., 2005). Such discoveries are rare, however, and it is disarticulated, fragmentary animal bones that are encountered routinely on archaeological sites. In such specimens, the identification of traction animals can be achieved through the recognition of joint disease in isolated bones. For example, Baker (1984) suggested that osteoarthritis in the acetabulum of cattle can occur following repeated over-rotation of the femoral head, which might result from pulling a plough on heavy soil. There are three problems with this approach, however: 1) no individual pathologies are pathognomonic of traction, multiple causes need to be considered in a differential diagnosis (indeed, pelvic osteoarthritis was not observed in the Svodín individuals); 2) the frequency of such lesions is typically low and dependent on the preservation of those body parts; 3) reported cases are often restricted to those exhibiting advanced remodeling, with little consideration of prevalence and biological context making it difficult to track spatial and diachronic change.

In 1997, Bartosiewicz et al. pioneered a systematic, quantitative method to record adaptive remodeling in the lower limbs of cattle (the autopodia), to facilitate the identification of draught cattle in the archaeological record. Metapodials and phalanges are amongst the most useful bones for this purpose for three reasons: 1) they are susceptible to remodeling 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 method was developed following a comparative analysis of the autopodia of 18 draught oxen and seven fattened bulls from Romania. It involved scoring the severity of a suite of pathological and sub-pathological osseous characters (Table 1) following visual comparison against published reference sequences (Bartosiewicz et al., 1997: Figs. 19–40). Most characters 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. Other characters are recorded on a scale of one to three (e.g. palmar depressions on metapodials) or on a presence/absence basis (e.g. ankylosis of the second and third metacarpal) (Table 1).

A Pathological Index (PI) is calculated for each skeletal element when all characteristics are present by entering the total score into a formula (Bartosiewicz et al., 1997: 20):

PI = (sum of scores – number of variables)/(maximum score – number of variables).

For complete individuals, it is possible to calculate the Individual Pathological Index (IPI) as follows:

IPI = (sum of the PI of the skeletal elements present)/(number of skeletal elements considered).

Table 1
Name, description and scoring of the osseous characters captured by the recording protocol developed by Bartosiewicz et al. (1997: 33–53).

Original variable descriptor	Bones affected (scoring)	Change described
Proximal exostosis (pex)	Metacarpal (1–4); Metatarsal (1–4); Proximal phalanx (1–4); Medial phalanx (1–4); Distal phalanx (1–4)	New bone formation near the proximal articulation. This encompasses entheseal as well as osteophytic changes.
Proximal lipping (plip)	Metacarpal (1–4); Metatarsal (1–4); Proximal phalanx (1–4); Medial phalanx (1–4); Distal phalanx (1–4)	Functional extension of the proximal articular surface due to new bone formation.
Distal exostosis (dex)	Metacarpal (1–4); Metatarsal (1–4); Proximal phalanx (1–4); Medial phalanx (1–4)	New bone formation near the distal articulation. This encompasses entheseal as well as osteophytic changes.
Broadening of the distal epiphysis (brd)	Metacarpal (1–4); Metatarsal (1–4)	Broadening of the distal (primarily medial) condyle of the metapodial, likely as an adaptation to loading.
Palmar/plantar depressions (depr)	Metacarpal (1–3); Metatarsal (1–3)	Depressions on the palmar/plantar surface of the distal shaft of metapodials, corresponding to the location where the *bursae articularis* of the metapodials and proximal phalanges overlap.
Proximal eburnation (peb)	Metacarpal (1–2); Metatarsal (1–2); Proximal phalanx (1–2); Medial phalanx (1–2); Distal phalanx (1–2)	Eburnation on the proximal articular surface, pathognomonic of osteoarthritis.
Distal eburnation (deb)	Metacarpal (1–2); Metatarsal (1–2); Proximal phalanx (1–2); Medial phalanx (1–2)	Eburnation on the distal articular surface, pathognomonic of osteoarthritis.
Transverse striations (str)	Metatarsal (1–2)	Transverse striations on the medio-proximal surface of metatarsals near the attachment site for the *musculus extensor digitorum brevis.*
Fusion of second metacarpal (fus)	Metacarpal (1–2)	Ankylosis of the vestigial second metacarpal with the medial side of the third metacarpal.
Striated facet on the metacarpal (facet)	Metacarpal (1–2)	Striations on the triangular facet for the attachment of the *ligamentum accessorium.*

Application of these formulae to the original samples studied yielded mean pathological index values of 0.325 for the sample of older draught cattle and 0.014 for the young meat bulls (Bartosiewicz et al., 1997). These were considered to provide useful benchmarks for comparison with archaeological datasets, to determine if there was evidence for draught use in the past.

The application of normative criteria to categorize continuous data can be difficult when specimens present intermediate or slight levels of change (Bartosiewicz et al., 1997: 53–55; Johannsen, 2005: 41). Nevertheless, follow-up studies have demonstrated the benefit of applying this system to prehistoric and historic period assemblages in the Old and New World, providing useful insights into the origin and changing intensity of cattle use for traction (de Cupere et al., 2000; Dietmeier, 2018; Johannsen, 2005, 2006; Gaastra et al., 2018; Lin et al., 2016; Marković and Bulatović, 2013; Telldahl, 2005, 2012; Thomas, 2008a; Vann, 2008).

Pathology such as enthesophytes and extension of articular surfaces are skeletal responses to physiological needs to improve joint stability and cope with biomechanical stress (Craig et al. 2016, 137–138). As such, there is a wide range of both internal and external factors that can precipitate skeletal changes in the lower limb. These include factors related to the welfare of the animals, such as the frequency and intensity of traction use, recovery time, stalling systems, and nutritional balance (e.g. Maton, 1987; Mgasa, 1991; Murphy et al., 1987; Somers et al., 2003; Vaarst et al., 1998). However, it also includes biological variables such as age, sex, body weight and genetic predisposition (e.g. Craig et al. 2016, 137; Nigam and Singh, 1980; Petersen, 1988; Thomson, 1969; Vaughan, 1960). An added layer of complication is the fact that many of these factors are interdependent. For example, 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.

Acknowledged problems with the two samples studied by Bartosiewicz et al. (1997) were the absence of cows and the limited age distribution: the draught oxen were aged 6–19 years, while the young bulls destined for the meat market were less than two years old. This made it difficult to evaluate comprehensively the combined influence of age and sex on skeletal changes. Follow-up studies of 295 aurochs (*Bos primigenius* Bojanus, 1827) autopodia brought this matter into focus by revealing that some of the characters– notably distal exostoses of the proximal phalanx – exhibited late stage changes in a population never used for traction (Johannsen, 2005, 2006). This research revealed the necessity for further control data from domestic cattle with known life histories, to disentangle the links between adaptive remodeling of the autopodia and biological variables. Failure to recognize the causes of sub-pathological changes in the lower limb bones of cattle, risks generating pathological indices that reveal more about the biological composition of the assemblage (e.g. age profile), than the use of cattle in the past. The issue with many modern specimens is that they are slaughtered early and bred to grow rapidly for slaughter: they are not

Fig. 1. location of Chillingham Park.

ideal comparanda for the past. A suitable control group has been identified amongst the semi-feral cattle from Chillingham Park, Northumberland. The aims of our study are fourfold:

1 apply the method of Bartosiewicz et al. (1997) to a sample of cattle from Chillingham Park;
2 explore correlations between the expression of pathological/sub-pathological changes and age, sex and body size;
3 establish whether adjustments are required to the formula developed by Bartosiewicz et al. (1997) i.e., disregarding scores for pathological/sub-pathological changes strongly correlated with biological variables; this is necessary to ensure that the pathological index provides a proxy for the use of cattle for traction in the past, rather than a reflection of assemblage composition in terms of biological variables (i.e., age, sex and body size);
4 apply the formula to archaeological datasets to: i) evaluate the impact of any adjustments to the method through comparison with the original formula; and ii) demonstrate the value of the method for charting the changing exploitation of cattle for traction through time. If the method is successful, we expect higher pathological index values in periods where there is corroborating documentary or archaeological evidence for increased traction use.

2. Materials and methods

The semi-feral herd of white cattle at Chillingham Park, Northumberland (Fig. 1), are documented as being ‘wild’ from at least CE 1645 and may represent a medieval relict population (Hall, 2006, 2007). The size of the herd is, and probably always has been, relatively small (currently *c.*100 head) and the animals are permitted to range freely across a gently-rolling 135-hectare (wood pasture) park. The animals receive limited veterinary intervention, although they are given supplementary feed (hay) during harsh winters. The herd remain healthy despite their genetic isolation and small population size (Visscher et al., 2001). The fact that these animals are genetically ‘unimproved’, are allowed to feed, grow and age naturally, and inhabit an environment free from biologically ‘unnatural’ features and intervention that can have a significant impact on lower limb bone health, such as stalling (Maton, 1987; Murphy et al., 1987; Somers et al., 2003; Vaarst et al., 1998) and inhibited mobility (Gustafson, 1993; Regula et al., 2004), make them a preferable analogue for the study of domestic cattle in the past (see also Thomas et al., 2018).

This study comprised the analysis of 15 individuals: nine aged between 7–10 months and 14 years, curated at the Natural History Museum in London; three adults collected from Chillingham Park in 2011, curated at the University of Leicester Bone Laboratory and the Birmingham Zooarchaeology Laboratory; and autopodia from three heifers donated from a reserve herd in an undisclosed location in Scotland in 2018, kept under similar free-ranging conditions, curated at the University of Leicester Bone Laboratory (Table 2). Not all individuals were complete (Table S1).

For some of the specimens curated at the Natural History Museum, age and sex data were available. In their absence, individuals were sexed on pelvis morphology using the methods of Greenfield (2006) and aged according to tooth eruption and wear and epiphyseal fusion following Grant (1982), Halstead (1985), Jones and Sadler (2012) and Silver (1969). A discrepancy in age based on mandibular age stage and epiphyseal fusion was noted for two individuals (1953.4.22.1 and 1953.4.22.2), but the anterior cusps of the second molar had only just begun to wear, placing them closer to age stage C (5–18 months) (Jones and Sadler, 2012: 22).

Proximal and medial phalanges were identified as deriving from the forelimb or hindlimb using the criteria of Dottrens (1946); no attempt was made to distinguish the distal phalanges in the same way, due to the unreliability of published criteria. Metapodials were sided and measured using the guidelines of von den Driesch (1976).

The pathological index values from the Chillingham cattle were compared with values from fused, complete cattle autopodia from nine archaeological sites in England dating from the Iron Age to the mid-18th century (Table 3). This provides the first comparison of pathological index values from the same geographical location over a 2000-year period.

The statistical significance of differences in pathological index values was tested using the non-parametric Mann-Whitney U test, in recognition of the fact that sample sizes were unequal and the data for some phases were not normally distributed. The strength of correlations between pathological index values and biological variables was tested using the Pearson’s correlation coefficient. All statistical analyses were conducted using PAST (PAlaeontological STatistics) (Hammer et al., 2001).

3. Results

Most pathological/sub-pathological characters in the Chillingham Park cattle were scored at stage 1 (i.e. the bones appeared ‘normal’). No examples of the following changes were observed (Table S1): eburnation on either proximal or distal articular surface, palmar/plantar depressions on the metapodials, ankylosis of the second and third metacarpal and transverse striations on the medio-proximal surface of the metatarsal. The IPI ranged from 0.000 to 0.190, with a mean value of

Table 2
Breakdown of the Chillingham cattle sample analyzed in this study.

Accession Code	Location	Sex	Age	Tooth wear stage (Grant, 1982)					Age stage (Halstead 1985; Jones and Sadler, 2012)
				dP_4	P_4	M_1	M_2	M_3	
1953.4.22.4	NHM	Female	24–26 months	k		h	f	E	D (16–28 months)
1953.4.22.5	NHM	Male	3–5 years		f	k	k	j	G (40 months - 6.5 years)
1953.4.22.6	NHM	Male	3–5 years		f	k	k	k	G (40 months - 6.5 years)
1953.4.22.2	NHM	Indeterminate	7–10 months**	j		h	b		D (16–28 months)
1953.4.22.1	NHM	Indeterminate	7–10 months**	j		h	b		D (16–28 months)
1981.985	NHM	Female	5 years		E	k	j	g	G (40 months - 6.5 years)
1981.984	NHM	Female	14 years		f	m	m	m	K (14–20 years +)
1981.989	NHM	Female	10 years		f	k	k	k	J (8–16 years)
1981.986	NHM	Female	14 years		ABS	l	k	k	J (8–16 years)
BZL491	BZL	Male*			f	k	k	h	G (40 months - 6.5 years)
R625	UoL	Male*			f	k	k	k	J (8–16 years)
R670	UoL	Male			f	m	l	l	J (8–16 years)
R671	Uol	Female	3.5 years						
R672	Uol	Female	3.5 years						
R673	Uol	Female	3.5 years						

Key: * - sexed using the methods of Greenfield (2006); ** - aged based on the fusion of the acetabulum (Silver, 1969); ABS – tooth lost post-mortem; blank cells indicate absent data.

Table 3
Archaeological assemblages from England that form a comparative dataset in this study.

Site name	Site type	Dates	Sample size	References
Burrough Hill, Leicestershire	Hillfort	Iron Age	11	Unpublished
Alchester, Oxfordshire	Legionary fort and later town	Roman	84	Unpublished
Colchester, Essex	Town	Roman	50	Vann (2008)
Hallaton, Leicestershire	Shrine	Roman	11	Unpublished
Ashton, Northamptonshire	Small town	Roman	57	Mahoney (2015)
Worcester Cathedral, Worcestershire	Ecclesiastical	Anglo-Saxon	31	Unpublished
Wigmore Castle, Herefordshire	Castle	Medieval-early modern (12th-17th century	110	Thomas and Vann (2015)
Dudley Castle, West Midlands	Castle	Medieval-early modern (12th-mid-18th century	762	Thomas (2008a,b)
Chester, Cheshire	Town	Medieval-early modern (12th-13th and 16th century	86	Gordon (2015)

0.072 (Table 4). Only two individuals (1981.989 and R670) – a ten-year old cow and an 8−16-year-old bull - exhibited stage 3 scores (in characters that score out of four). The average IPI was higher for males (0.105) than females (0.069), although this difference was not statistically-significant ($U = 13$; $P = 0.341$).

Pathological index values were not evenly distributed across the lower limb bones examined (Fig. 2). When averaged by individual, the scores for the distal phalanx (forelimb and hindlimb combined) were much higher than for other bones. Metacarpals and anterior proximal and medial phalanges exhibited higher values than their hindlimb counterparts.

IPI values of zero (i.e., no adaptive remodeling in any bone) were observed in all cattle under 12 months. Thereafter, IPI values increased with age, albeit with individual variation (Fig. 3). For example, two bulls aged 3−5 years with almost identical tooth wear patterns (1953.4.22.6 and 1953.4.22.5) had IPIs of 0.018 and 0.087. Similarly, a 14-year old female (1981.986) had a score of 0.102, while a 10-year old cow (1981.989) generated a score of 0.158. It was notable that the highest IPI value of the three heifers from the reserve herd (R672) exhibited a lateral curvature of the inter-metatarsal groove, suggesting that atypical conformation of the lower limb can influence adaptive remodeling. The correlation between age and IPI was statistically significant: $r = 0.766$; $p = 0.000$.

Not all characters increased in severity with age to the same extent: broadening of the distal metacarpal, distal exostoses of the metatarsal and proximal phalanx, and proximal exostoses and lipping of the distal phalanx all exhibited statistically-significant positive correlations with age (Table 5). For some bone-lesion combinations the effect was striking. All cattle over ten years exhibited stage 2 or 3 lipping and exostoses of the proximal articulation of the distal phalanx, whilst frequencies of 44 % and 33 % were observed in cattle aged 3−5 years respectively. Stage 2 distal exostoses of the proximal phalanx were also observed with increased frequency with age: 0% in cattle under three years; 19 % in cattle aged 3−5 years; and 69 % in cattle over ten.

A positive correlation was identified between metapodial length and breadth measurements and individual pathological index values (Fig. 4). This correlation was statistically significant for length measurements (metacarpal GL: $r = 0.728$; $p = 0.005$; metatarsal GL: $r = 0.717$; $p = 0.006$) but not for breadths (metacarpal Bp: $r = 0.477$; $p = 0.099$; metatarsal Bp: $r = 0.525$; $p = 0.065$). Visually, this correlation appears to be most strongly influenced by sex in the metacarpal breadth.

Table 4
Pathological index values for the Chillingham cattle based on the original method of Bartosiewicz et al. (1997).

Specimen No.	Sex	Age	IPI
1953.4.22.2	?	7−10 months	0.000
1953.4.22.1	?	7−10 months	0.000
1953.4.22.4	f	24−26 months	0.053
R671	f	3.5 years	0.025
R672	f	3.5 years	0.028
R673	f	3.5 years	0.043
1953.4.22.5	m	3−5 years	0.087
1953.4.22.6	m	3−5 years	0.018
1981.985	f	5 years	0.071
BZL491	m	40 months - 6.5 years	0.085
1981.989	f	10 years	0.158
1981.984	f	14 years	0.074
1981.986	f	14 years	0.102
R625	m	8−16 years	0.190
R670	m	8−16 years	0.146

Together, the data from Chillingham indicate that adjustments are required to the pathological index formulae developed by Bartosiewicz et al. (1997: 20), since some of the sub-pathological characters that contribute to the calculations are strongly correlated with biological variables. In particular, the proximal and distal exostoses of the metatarsal, broadening of the distal metacarpus, proximal lipping and exostoses of the distal phalanx and distal exostoses of the proximal phalanx are strongly correlated with age (Table 5). Continuing to include these variables risks generating pathological index values that may partially reflect the demographic characteristics of the assemblage rather than the exploitation of cattle for draught use. To remedy this, modified formulae are suggested for each element to exclude age-dependent characters as set out in Table 6.

To understand the impact of the modified formulae, the original mean PI values and the modified PI values from nine archaeological sites (Table 3) are compared (Fig. 5). The mean pathological index values by site are generally lower using the modified formulae. However, there were four sites at which the modified formulae yield higher average scores – the shared characteristic of these sites is that they had relatively small sample sizes with no, or few distal phalanges. Despite these differences in absolute values, the general temporal trends are consistent across both datasets (Fig. 5). This suggests that the age profiles of the cattle herds at each site did not strongly influence the underlying data.

4. Discussion

The distribution and frequency of pathological/sub-pathological changes in the autopodia of the Chillingham cattle consolidates previous knowledge drawn from modern and archaeological assemblages. The low overall incidence of adaptive remodelling in this sample compares with the results obtained in other studies of cattle that were not used for traction (Bartosiewicz et al., 1997: 62; Johannsen, 2005, 2006).

The absence of remodeling in four characters is consistent with observations drawn by Bartosiewicz et al. (1997: 43–50). Osteoarthritis was observed in the metatarsals of two draught oxen from Romania and the hindlimb phalanges of another. Meanwhile, palmar/plantar depressions, ankylosis of the second metacarpal and transverse striations on the surface of the metatarsal, were absent in the young bulls that had not been used for ploughing.

The higher pathological index values in the forelimb compared with the hindlimb in the Chillingham cattle (Fig. 2) was also observed in draught oxen (Bartosiewicz et al., 1997: 61) and aurochs (Johannsen, 2006: 37), and likely reflects differences in weight distribution: the thoracic extremity accommodates up to two thirds of the entire weight of cattle, placing additional loading stress on these elements. By contrast, Johannsen (2006) observed that the anterior/posterior distribution was more equal in a large sample of Neolithic cattle that in all

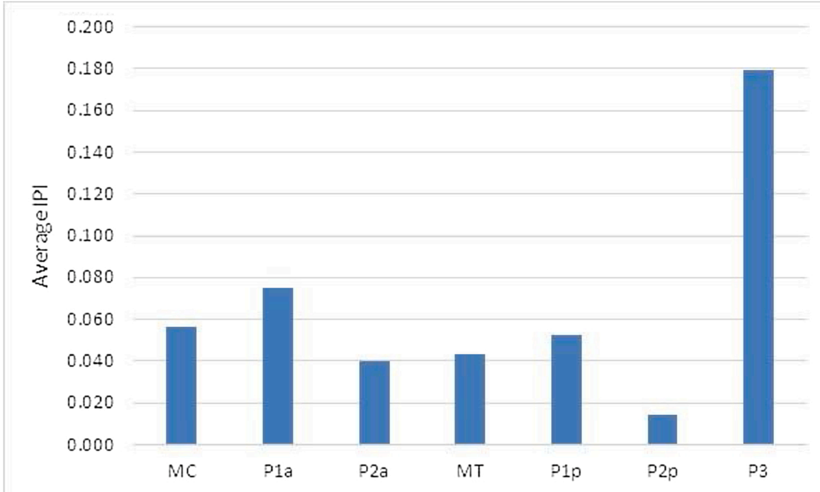

Fig. 2. Average IPI values by anatomical element. Key: MC – metacarpal; P1a – proximal phalanx (forelimb); P2a – medial phalanx (forelimb); MT – metatarsal; P1p – proximal phalanx (hindlimb); P2p – medial phalanx (hindlimb); P3 – distal phalanx (forelimb and hindlimb combined).

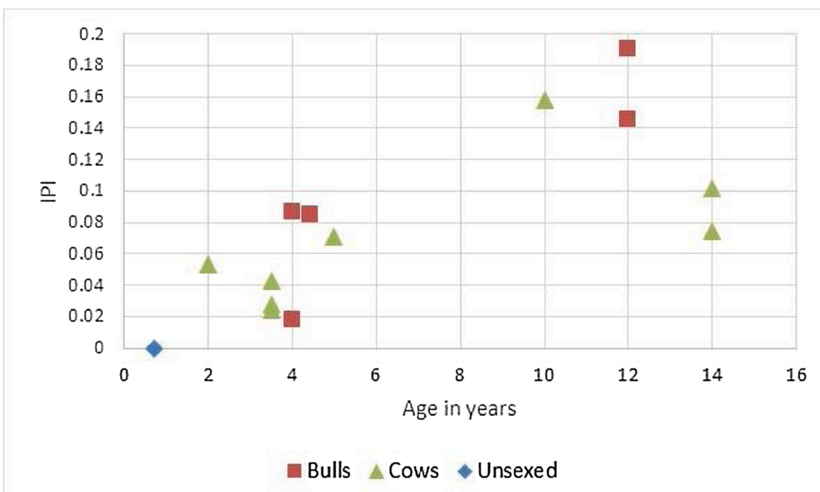

Fig. 3. Correlation between IPI and age for the Chillingham cattle. Cattle with documented age ranges have been plotted at their mid-point. Specimens without documented ages have been plotted at the mid-point of the age stage (after Jones and Sadler 2012, Table 1).

likelihood included draught animals. Similarly, at Dudley Castle (Thomas, 2008a), the mean pathological index values for the posterior elements were consistently higher than the anterior elements in a period (AD 1321–1397) when cattle appear to have been used intensively for traction (see below). This probably reflects the fact that the hind limbs produce most of the propulsion during locomotion (Phillips 2002, 180; Skerritt and McLelland 1984, 224) and draught work requires significantly increased retrorse thrust (Johannsen 2006, 40). Repeated, increased loading on the hind limbs can result in functional adaptation to strengthen and stabilize joints – initially in terms of soft tissue structures (muscles, tendons and ligaments), but eventually bone tissue (e.g., Crockett et al., 2002). Ultimately, these changes become manifest in the characters recorded in the system developed by Bartosiewicz et al. (1997) and reduce or even reverse the anterior/posterior distribution gap in samples that include a significant proportion of draught animals. Unfortunately, despite long-standing recognition of this phenomenon, it remains the case that some studies of sub-pathological changes in cattle do not present separate scores for anterior and posterior phalanges (e.g., Dietmeier, 2018; Gaastra et al., 2018).

The fact that IPI values were higher in bulls than cows in the Chillingham sample is consistent with findings from clinical literature in cattle and other mammals (e.g., Nigam and Singh, 1980; Petersen, 1988: 461; Thomson, 1969; Vaughan, 1960). This, in part, reflects the inter-related link between adaptive remodelling and body mass: heavier animals experience greater biomechanical stress to joints and associated connective tissues. This phenomenon was identified by Bartosiewicz et al. (1997: 68), who demonstrated a strong positive correlation between IPI and live weight in modern draught oxen from Romania and has been reflected in subsequent archaeological studies (Telldahl, 2012: 214). Within the Chillingham cattle sample it is evidenced further by the positive correlation between IPI and metapodial length (Fig. 4).

The strong positive correlation between age and IPI observed in the Chillingham cattle (Fig. 3) is a notable point of departure from the study by Bartosiewicz et al. (1997: 68), where the correlation coefficient in draught oxen aged 6–19 years was only 0.090. While genetic, environmental and behavioral differences between the two populations may have influenced this outcome, it more likely reflects the inclusion of younger-aged cattle in the Chillingham sample, which returned very low IPIs. Indeed, the correlation co-efficient for older age cattle at Chillingham (10–14 years), was closer to the Romanian sample at 0.142. The association between age and joint disease is well founded in clinical studies of cattle and other mammals (e.g., Craig et al. 2016, 137; Nigam

Table 5
Pearson's correlation coefficients and *p*-values for age and average scores for characters consistently exhibiting adaptive remodelling. Statistically-significant differences are highlighted by filled cells.

Bone	Character	R	*P*
Metacarpal	Pex	0.499	0.058
	Plip	0.354	0.195
	Dex	0.331	0.229
	Brd	0.922	0.027
Metatarsal	Pex	0.631	0.012
	Plip	0.485	0.067
	Dex	0.571	0.026
	Brd	0.250	0.369
Proximal phalanx	Pex	0.491	0.063
	Plip	0.801	0.071
	Dex	0.616	0.014
Medial phalanx	Pex	0.787	0.076
	Plip	0.229	0.331
	Dex	0.229	0.331
Distal phalanx	Pex	0.784	0.001
	Plip	0.700	0.004

Pex = proximal exostosis, Plip = proximal lipping, Dex = distal extostosis, Brd = broadening of distal epiphysis.

and Singh, 1980; Petersen, 1988; Thomson, 1969). Bone remodeling increases with age in response to cumulative microtrauma to bone and associated connective tissue, increasing joint laxity and degeneration of articular cartilage. Since body mass increases with age, this is also a contributory factor. If all recorded characters were affected equally by age, this could be identified and accommodated in archaeological studies through comparison of pathological index values against slaughter profiles. However, this study shows that some characters are more susceptible to age-related effects, notably proximal and distal exostoses of the metatarsal, broadening of the distal metacarpus, proximal lipping and exostoses of the distal phalanx and distal exostoses of the proximal phalanx (Table 5). The latter was also identified by Johannsen (2005, 2006) in aurochs. This finding has implications for archaeological interpretation: if all elements are used in the calculation of the mean pathological index, then samples with more distal phalanges will look more 'pathological' and could be mis-interpreted as more intensive exploitation for traction.

Considering this evidence, we suggest that inter- and intra-site comparisons of mean pathological index values should exclude distal phalanges and that the formulae for other bones (Bartosiewicz et al., 1997: 20) should be adjusted as set out above to exclude characters that are strongly correlated with age as set out in Table 6.

The data presented in Fig. 5 reveal that no archaeological sites yield pathological index values as high as those observed in the Romanian draught oxen studied by Bartosiewicz et al. (1997). This difference is unsurprising, given the fact that the archaeological assemblages would include a more representative sample of cattle populations, many of which would not have been used for traction. By contrast, in the Romanian sample all the cattle had been used for the pulling carts and ploughs or for hauling timber.

In the Iron Age and early Roman period, the intensity of cattle use for traction appears to have resulted in little adaptive remodeling of the lower limb bones. At the Roman site of Alchester, Oxfordshire, there is a notable increase in the pathological index values in the late 1st or early 2nd century AD (Fig. 5). This coincides with an increase in the size of cattle (Thomas, 2008b), which may have contributed to higher pathological index values, given the connections observed in Fig. 4. These changes correspond to a period of increasing relative abundance of cattle throughout England (e.g., King, 1991) and growing investment in selective breeding (e.g., Albarella et al., 2008) and may reflect increased cereal production enabled through agricultural extensification (introducing production to previously uncultivated areas) (Allen et al., 2017). Indeed, Fowler (2002: 283) has postulated that a "widespread, state-led agricultural revolution … occurred during the second half of the first century AD, concentrating on making existing arable more efficient and breaking in more land to increase the area under cultivation". This 'revolution' is evidenced by the ploughing of marginal lands, wetland drainage, the emergence of new field systems and was driven by the

Table 6
Modified pathological index formulae.

Element	Original formula	Characters excluded	Modified formula
Metacarpal	(sum of scores – 9)/17	broadening of the distal epiphysis	(sum of scores – 8)/14
Metatarsal	(sum of scores – 8)/16	proximal exostosis, distal exostosis	(sum of scores – 6)/10
Proximal phalanx	(sum of scores – 5)/11	distal exostosis	(sum of scores – 4)/8
Medial phalanx	(sum of scores – 5)/11	n/a	(sum of scores – 5)/11
Distal phalanx	(sum of scores – 3)/7	proximal lipping, proximal exostosis, proximal eburnation	excluded

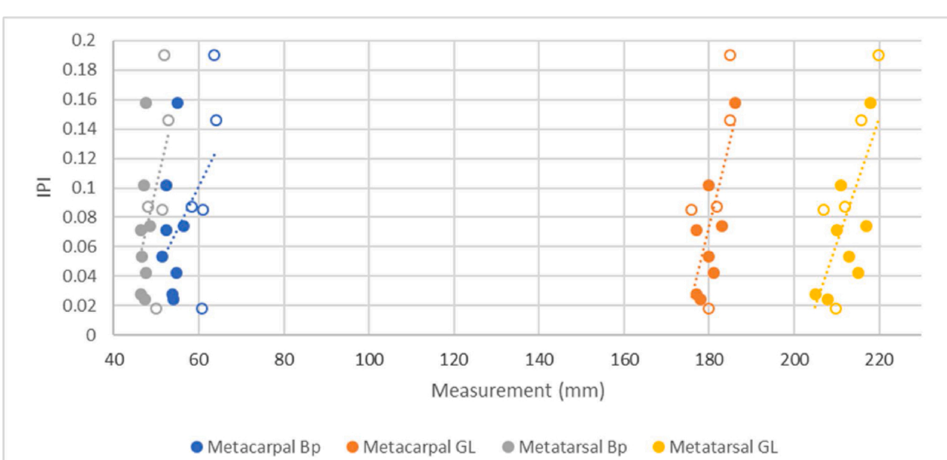

Fig. 4. Correlation between IPI and metapodial size in the Chillingham cattle. Cows are represented by filled symbols; bulls are represented by open symbols. Dashed lines indicate the line of best fit.

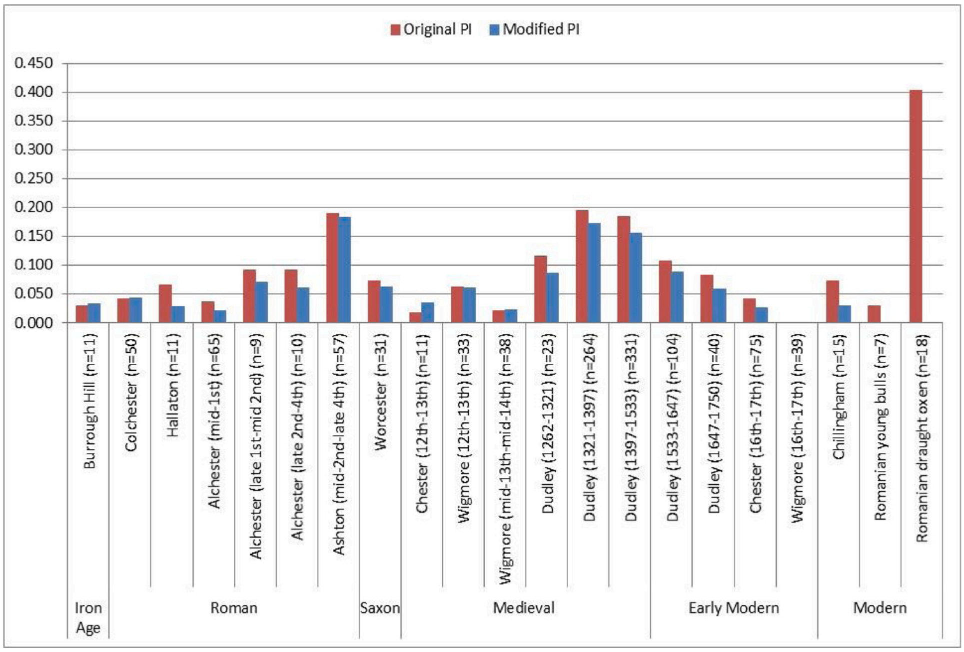

Fig. 5. Comparison of average PI and modified PI values in three modern samples with archaeological datasets from nine sites in England (Table 3); sample sizes are provided in parentheses.

need to feed the occupying army, the growth of towns and the construction of roads (Fowler, 2002: 283). There is no extant evidence for a change in plough technology in this period, with the ard continuing in use (Fowler, 2002: 198), but these changes would have still necessitated a rise in the numbers of cattle required for ploughing and carting or at least increased intensity of exploitation (Van der Veen and O'Connor, 1998: 132–133). While the limited paleopathological evidence supports this narrative, it also hints at some regional variation since the pathological index values from late Roman Alchester are somewhat lower than they are from contemporary Ashton.

It is difficult to say much about the impact of the withdrawal of the Roman army from Britain on cattle use for traction. The only Anglo-Saxon site with available data – Worcester – indicates a return to low intensity exploitation for traction, which is consistent with the reduced population and the collapse of urban infrastructure and markets in the 5th-6th centuries (Holmes, 2014). The mouldboard plough was introduced by at least the 7th century (Thomas et al., 2016), but the impact of this heavier technology on the lower limb bones of cattle remains to be demonstrated, and is the focus of a current project (Hamerow et al., 2019, 2020).

Pathological index values were higher in the later medieval period, although the only site with a complete temporal sequence is Dudley Castle, West Midlands. The fact that the pathological index values at Dudley Castle are higher than contemporary assemblages from Wigmore Castle and Chester, suggests regional variation, although this remains to be tested. The dramatic rise in the pathological index values at Dudley Castle, West Midlands, in the later 14th century has been described elsewhere (Thomas, 2008a). A coincidental increase in the size of the cattle (Thomas, 2005a, 2005b) is likely to have been partly responsible. However, there is also historical evidence, not discussed by Thomas (2008a), for either an increase in the intensity of use of traction animals or an increase in the proportion of cattle used for traction, which had the net effect of inflating the severity of pathology to the lower limb bones. Between 1319 and 1322, a panzootic in cattle (probably rinderpest) spread into Britain from mainland Europe. The scale of mortality was astonishing: drawing upon manorial accounts Slavin (2012) has calculated that, on average, 62 % of cattle died of pestilence in England and Wales between 1319 and 1320 and that it may have taken decades to restock, especially on manors where the losses were total. The "loss of 55 per cent of oxen meant massive losses of draught animals, both as 'tractors' and 'haulers'" (Slavin, 2012: 1255). Furthermore, Slavin (2012) has estimated that by 1350 - some thirty years later - 13.5 % of manors never recovered their oxen stocks to pre-pestilence levels. Some of this work may have been taken up with the use of the horse; however, it seems likely that surviving cattle and their immediate descendants may have to work far more intensely than their predecessors, and this could partly explain the increased pathological index values.

By the early modern period, pathological index values decrease. This is consistent with the historical evidence for the declining use of cattle as traction animals from the later medieval period, with horses becoming increasingly preferred (Langdon, 1986, 1997), and the concomitant rise of the dairy and veal industries. Indeed, this is often cited as the principal reason for the widespread decline in cattle slaughter age at this time (e.g., Albarella, 1997: 22).

Overall, therefore, it can be observed that higher pathological index values occur in periods where there is corroborating evidence for the increased or more intensive use of cattle for traction, confirming the validity of the approach. As noted above, however, factors other than traction use are known to predispose domestic livestock to heightened vulnerability to lower limb bone disorders, such as genetic predisposition, stalling conditions, levels of exercise and nutrition; however, these remain to be investigated from an archaeological and historical perspective.

5. Conclusions

The sample from Chillingham Park consolidates previous research of adaptive remodeling in the lower limb bones of cattle. The low pathological index scores demonstrate that changes to the autopodia are slight in a free-ranging population of cattle, supporting the view that more pronounced changes can provide useful identifiers of traction use. The absence of some pathological and sub-pathological characters - eburnation on either proximal or distal articular surface, palmar/plantar depressions on the metapodials, ankylosis of the second and third metacarpal and transverse striations on the medio-proximal surface of the metatarsal - suggests they might be particularly profitable markers of traction use. Correlations between pathological index values and biological variables - sex, body size and age - were identified, conforming to clinical studies. Modification to the formulae developed by Bartosiewicz et al. (1997) have been suggested in recognition of the fact that adaptive remodeling of some aspects of the autopodia are strongly age related. Once these characters were excluded, comparison of average pathological index values at nine sites in England over the past 2000 years demonstrated that intensive use of cattle for traction was only identifiable in the Roman and late medieval periods. These correspond to historically-recognised periods of increased use of cattle for ploughing. However, greater regional and temporal coverage is required to explore these trends further.

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Contributions

RT and LB performed the data collection and analysis, with comparative archaeological data provided by RG, MH, NNJ and MM. DS assisted in the collection of samples from Chillingham Park. All authors contributed to the final version and approved the manuscript.

Ethical concern

None.

Declaration of Competing Interest

The authors report no declarations of interest.

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Appendix A. Supplementary data

Supplementary material related to this article can be found, in the online version, at doi:https://doi.org/10.1016/j.ijpp.2021.02.003.

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