# THE ORIGINS OF ANIMAL TRACTION IN BRITAIN




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*“The struggle of man against power is the struggle of memory against forgetting.”*
— Milan Kundera

# Declaration

I, the author, confirm that the Thesis is my own work. I am aware of the University's Guidance on the Use of Unfair Means (`www.sheffield.ac.uk/ssid/unfair-means`). This work has not been previously been presented for an award at this, or any other, university.

All photographs, plates, and figures included in this thesis were taken or produced by the author, except for Plates 2.1 and 2.2.

# Publications

- Liu, P., Salvagno, L., Wimmer, B., Albarella, U. (2025). "In search of draught cattle: An identification method". *Journal of Archaeological Science*, 179:106229. DOI: 10.1016/j.jas.2025.106229
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# Abstract

Animal traction is a key technological advancement that drove socio-economic transformations in prehistoric societies. However, its emergence in Britain has remained poorly understood, primarily due to the limited preservation of physical evidence and the absence of iconography associated with animal traction. While previous research has identified biometric differences between modern draught and non-draught cattle, these findings have yet to be systematically applied to archaeological assemblages. This thesis investigates the origins of animal traction in Britain in two stages. The first stage establishes a new biometric method for identifying draught cattle from archaeological sites by analysing over 150 modern non-draught cattle alongside a comparative sample of draught cattle, focusing on metapodials, first and second phalanges. The second stage implements a large-scale analysis integrating four osteological methods: biometry, Pathological Index, entheseal changes, and kill-off pattern in 22 British archaeological sites. The convergent results from all methodological approaches indicate that the earliest substantial evidence for cattle traction in Britain emerged during the Middle to Late Bronze Age. This timing coincides with a period of profound social transformation marked by agricultural intensification and the development of more complex hierarchical social structures during the latter half of the second millennium BC. Animal traction was, however, not universally adopted, but a strategic technological adaptation initially limited to specific communities. The adoption of animal traction not only enhanced agricultural productivity by enabling the cultivation of larger areas but also likely accelerated social stratification by creating unequal access to productive resources and agricultural surplus. Animal traction represents a pivotal technological development in British Later Bronze Age societies, reshaping agricultural practices and economic structures.

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# 1 INTRODUCTION

## Contents


**1.1 Aims and research questions . . . . . 3**
**1.2 Defining the chronology . . . . . 3**


Cattle, once domesticated, made their most revolutionary contribution not only by providing primary products but also through their traction power—a technological innovation that dramatically changed agricultural and economic systems. The Secondary Products Revolution posited by Sherratt (1981) suggests that the exploitation of secondary products, including milk, wool, and draught power, was the key to significant socioeconomic transformations across the Near East and Europe during the fourth and third millennia BC. Recent research reveals that these secondary products did not emerge simultaneously (Chapter 2). For example, archaeological evidence suggests that dairy production may have begun shortly after domestication of cattle in the Near East (Evershed et al., 2008). The emergence of animal traction, however, remains comparatively unclear.

The main challenge in understanding the early use of animal traction stems from the absence of physical products that leave straightforward archaeological evidence. Early studies have primarily relied on indirect lines of evidence such as plough remains, ard/plough[1] marks, and iconographic representations to

[1]Strictly speaking, an ard is a more primitive tillage tool without a mouldboard, while a plough is an implement with a mouldboard to turn the soil (Glob, 1951: 109; Fowler, 1983: 166; Rees, 1981: 73). In this thesis, the terms ard and plough are used synonymously due to inconsistency in their usage within the literature. The term preferred in the original publication is followed to maintain alignment with the source material.

infer the use of draught animals in prehistoric contexts. Nonetheless, as will be discussed in Chapter 3, the interpretation of these lines of evidence for animal traction is often problematic. Studying animal traction in prehistoric Britain is particularly challenging. Minimal wooden artefacts related to animal traction have been discovered, and there is a complete absence of prehistoric rock art depicting ploughing scenes. The current understanding of the origins of animal traction in Britain remains nebulous, with speculation for decades being anchored to patchy evidence—principally the plough marks in South Street Long Barrow (Mercer, 1981: x) and the pathological cattle bones from Etton (Armour-Chelu and Clutton-Brock, 1985). Consequently, the osteological approach is the most promising methodological avenue for investigating the development of animal traction. Prior works on the Pathological Index and biometric analyses have demonstrated the potential of skeletal remains to provide further insights into the draught use of cattle (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; R. Thomas, 2008; Vann, 2008; Gaastra et al., 2018; Lin et al., 2018; Holmes et al., 2021a,b; Kamjan et al., 2022; Lin, 2022; Pigière and Smyth, 2023; Crabbé et al., 2025). However, pathological and morphological changes are multi-factorial processes that could be attributed to numerous factors such as age, sex, breed, and body size. This requires the analysis of modern animals with known life histories to clarify interpretations before applying methods to archaeological materials. Furthermore, although previous works have shown the biometric difference between modern draught and non-draught cattle (Bartosiewicz et al., 1993; Lin et al., 2016), a systematic application to archaeological specimens has yet to be proposed.

Animal traction marked a significant transition in human-animal relationships, reflecting a new dynamic in which animals are more actively involved in human activities. Unlike passive extraction of resources such as milk and wool, which primarily requires humans to manage and harvest from animals, animal traction involves a cooperative partnership. Cattle are not just resources

but active participants, working with humans to perform labour-intensive tasks such as ploughing and transportation. This cooperation required intensive training, advancing a relationship where animals directly contributed to human productivity and societal advancement.

## 1.1 Aims and research questions

This thesis investigates the origins of animal traction in Britain through a two-part approach. The first part (Chapter 5) uses modern data to develop a biometric method for identifying draught cattle. By developing a systematic osteological method grounded in modern comparative data, the study moves beyond speculative interpretations to provide empirical evidence of animal traction. The second part (Chapter 6) presents the first systematic analysis of osteological evidence to address the central research aims. Within the broad aim, four questions will be answered:

1. How can draught animals be identified in archaeological assemblages?
2. When did animal traction begin in Britain?
3. What motivated the use of animal traction in later prehistoric Britain?
4. What social and economic changes did this technology bring to prehistoric societies in Britain?

## 1.2 Defining the chronology

Table 1.1 presents the sub-division of each period from England, following Albarella (2019). The Orcadian Neolithic is generally divided into the Early and Late phases, where the transition is suggested around 3000 cal. BC (Card, 2005: 47). The Later Bronze Age is often defined as the period between 1500–700 cal. BC (Yates, 2007: 1), encompassing the Middle to Late Bronze Age.

It should be noted that the sub-division of the periods may vary between publications, and related issues will be discussed for the specific sites in Chapter 6. Although this study focuses primarily on Neolithic and Bronze Age sites, Chapter 6 incorporates comparative sites from later periods.

Table 1.1: Chronology used in this thesis (following Albarella, 2019).

| **Time period** | **Sub-division** | **Chronology** |
|---|---|---|
| Neolithic | Early | 4000 – 3200 cal. BC |
| | Middle | 3200 – 2800 cal. BC |
| | Late | 2800 – 2300 cal. BC |
| Bronze Age | Early | 2400 – 1600 cal. BC |
| | Middle | 1600 – 1150 cal. BC |
| | Late | 1150 – 700 cal. BC |
| Iron Age | - | 700 cal. BC – AD 43 |
| Roman | - | AD 1$^{st}$ – 4$^{th}$ century |
| Saxon-Norman | - | c. AD 950 – 1150 |
| Medieval | Early | c. AD 1150 – 1250 |
| | High | c. AD 1250 – 1400 |
| | Late | c. AD 1400 – 1500 |
| Post-Medieval | - | 16$^{th}$ - 20$^{th}$ century |

# 2

# ANIMAL TRACTION IN PREHISTORIC SOCIETIES

## Contents


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## 2.1 Introduction

The first objective of Chapter 2 is to establish the background associated with the origins of animal traction in Britain. It reviews the debate surrounding the Secondary Products Revolution, a model that initiated major discourse on the first use of draught animals in Europe. The second objective is to provide a chronological framework for the emergence of traction animals in archaeological contexts, including the probable origins of animal traction and early evidence from the European mainland. The review of the development of animal traction in continental Europe helps shape the understanding of this innovation in Britain, as it is possible that this innovation was introduced from the Continent. The third objective is to synthesise current evidence and interpretations of draught animals in prehistoric Britain. The last section reviews various aspects that influence the

use of draught cattle, such as team size and harnessing systems.

Unlike milk and wool, no actual product is produced through animal traction. Identifying draught cattle in archaeological contexts conventionally relies on indirect evidence, such as plough marks and wooden remains of agricultural implements. Since this chapter focuses on the chronological framework, the validity and limitations of the evidence and methods used to identify draught cattle are discussed later in Chapter 3.

## 2.2 Secondary Products Revolution

Childe (1936: 69) viewed the use of harnessed animals for ploughing and carrying loads as an adaptation that paved the way for the second revolution in human economy following the beginning of farming. Later, Sherratt (1981, 1983) developed the Secondary Products Revolution (SPR) 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 the Near East and Europe. The shifting emphasis from largely primary products to secondary products first appeared in restricted areas in West Asia before diffusing to Central Europe at the mid-fourth to the beginning of the third millennium BC (Bökönyi, 1974: 42; Sherratt, 1983; Greenfield, 1988, 2010).

Animal traction can be further separated into two aspects: agricultural use for hauling ploughs and transportation usage to pull carts or wagons (Sherratt, 1981: 159). The traction plough is believed to have been invented in Upper Mesopotamia or North Syria before the fifth millennium BC (C. W. Bishop, 1936). The plough beam was probably later converted into the pole in wheeled vehicles (Littauer and Crouwel, 1979: 10). Nonetheless, the capability of large domestic animals to drag sledges and logs is often overlooked as a component of animal traction (Greenfield, 2010). This neglect of other potential usages of draught cattle

may stem from the limitations of earlier studies that primarily concentrated on deducing the use of draught cattle based on evidence from artefacts remains.

While the SPR model has been important in investigating the intensification and spread of secondary products in prehistoric societies, several arguments have arisen regarding various aspects of its initial conception. One such area of debate concerns the origins and intensification of using secondary products. An alternative hypothesis proposes that animals were exploited for secondary products shortly after domestication (Bogucki, 1988) and that the exploitation of renewable resources may have been the primary motivation for domestication (Vigne and Helmer, 2007; Shipman, 2014: 50).

However, it becomes clear that generalising the situation is problematic. For example, wool-bearing sheep appeared long after the initial domestication of sheep, indicating that wool could not have been a primary motivation for their domestication. Sheep were first domesticated in Southwest Asia during approximately 10000 to 8000 BC (Zeder, 2008). Analysis of textile fibres suggests that wool was used in Mesopotamia during the third millennium BC and became more widespread in the Mediterranean and Aegean by the second millennium BC (Sabatini et al., 2022). This supports the view that wool production developed significantly later than the initial domestication.

In contrast, evidence indicates that dairy products were already used in the Near East by the seventh millennium BC (Evershed et al., 2008) and in Eastern Europe by the sixth millennium BC (Craig et al., 2005; Salque et al., 2013; Casanova et al., 2022). This evidence does not conclusively support or disprove the alternative view that the exploitation of secondary products was a motivation for domestication. However, these findings suggest that some secondary products, such as dairy, may have been exploited shortly after the initial domestication.

The difference in the timing of the emergence of various secondary products, as demonstrated by more recent studies, has called into question the SPR model's claim that innovations involving these products were interrelated and transmitted as a package from West Asia during the mid to late fourth millennium BC (Sherratt,

1981: 183–6). Instead, some components may have developed earlier than others and with discrete origins, suggesting that these innovations did not necessarily spread simultaneously (Greenfield, 2010: 46, 2014: 8; Shipman, 2014: 41; Leppek, 2017: 99). The exploitation of animals for draught use is complex, requiring the development of tools such as harnessing equipment and plough beams. Moreover, draught use involves the active participation of animals that require long-term training. As a result, animal traction may not have developed immediately after domestication.

Lastly, critiques are raised towards the imbalanced use of evidence. Sherratt (1981, 1983, 2006) heavily emphasised the artefactual and iconographic evidence, whereas zooarchaeological data are almost neglected (see Chapman, 1982; Marciniak, 2011). Particularly, the representation of ploughs and wheeled vehicles is the crucial component in the model for discussing the earliest use of draught animals (Sherratt, 1981, 1983). Given the lack of physical evidence of ploughs in Europe prior to the fourth millennium BC, coupled with the presence of models and rock art depicting draught cattle from the later period, it proposed that the introduction of plough technology diffused around 3500 BC to Europe (Sherratt, 1983: 92). It is nevertheless possible that animal traction was employed before the invention of the cart or plough, such as by dragging trees for field clearance, or pulling loads with simple padding (Bogucki, 1988: 176; Leppek, 2017: 101). Although yokes provide unambiguous evidence of animal traction in the past, these wooden implements are rarely preserved. However, exceptions have primarily been found in bog environments, such as the Dostrup and Donnerupland ards from Denmark. Zooarchaeological evidence, including kill-off patterns and pathological studies, is an important area that can offer insights into the early use of draught animals but was largely ignored by Sherratt.

## 2.3 The origins of animal traction

As hypothesised by Sherratt (1981, 2006), the earliest development of traction occurred in West Asia around the fifth millennium BC. This section provides

a brief overview of the earliest evidence of animal traction and the regions in which it occurred. Most of the earliest evidence comes from Mesopotamia and is closely connected to the invention of the plough and wheeled vehicles. Regarding agricultural use, the traction plough is believed to have been invented in in Upper Mesopotamia or North Syria about 6000 to 4000 BC (C. W. Bishop, 1936). Plough marks were found at a site in Khuzestan, Iran, dating back to 5000 BC (T. Wright et al., 1980: 275). These traces are commonly assumed to be the result of animal traction. However, caution should be taken, as trace marks do not necessarily reflect the use of draught cattle since parallel grooves from ridged cultivation can also be created without animal assistance (Curwen, 1927; Sherratt, 1997) (further discussion see Section 3.1.1). A similar depiction was found later in an Akkadian cylinder seal in Mesopotamia, dated around 2300 BC (Sherratt, 1981: 165).

Clay tablets depicting wheeled vehicles were discovered at Uruk and dated to the end of the fourth millennium BC (Sherratt, 1981: 160), but do not indicate animal traction *per se*. Before the invention of wheeled vehicles, sledges were used to carry loads on the dry grass of steppes; iconography from a similar period of Mesopotamia presents oxen drawing a sledge (Piggott, 1992: 16). Cylinder seals from the late Uruk period (3500-3100 cal. BC) were discovered at Arslantepe, Turkey, illustrating cattle dragging a sledge with one person seated (Rosenstock, 2022: 49). Although the earliest pictorial representations of using animal traction are dated around the fourth millennium BC, the practice could be older, dating back to the fifth millennium BC or even earlier (C. W. Bishop, 1936). This claim is supported by recent zooarchaeological research, indicating that cattle could have been exploited for power earlier than previously suggested. Based on pathological deformations observed on the first phalanx, analyses suggest that cattle could have been used for heavy-duty tasks at Tell Aswad in Syria and Cafer Höyük in Turkey as early as 8200 to 7500 cal. BC in West Asia (Helmer et al., 2018). Similarly, pathological results from Neolithic Çatalhöyük from the East and West Mounds in Central Anatolia reveal the earliest use of animal traction could be traced to

the sixth millennium BC (Kamjan et al., 2022). However, as discussed further in Chapter3, interpreting osteological evidence is not straightforward.

## 2.4 Animal traction in prehistoric Europe

It has been long assumed that the use of secondary products in Europe was not an indigenous development but was introduced from West Asia. Childe (1930: 40, 1936: 51) suggested that although the Neolithic communities had acquired oxen, exploiting harnessed animals for ploughing or carting was a later adaptation, as there was no clear evidence of animal-drawn ploughs before the Bronze Age. Later, Sherratt (1981, 1983, 1997) reinforced this claim by arguing that there was a lack of equivalent proof of using draught cattle in Europe before the fourth millennium BC. Hence, he suggested that the inventions of ploughs and wheeled vehicles originated in Mesopotamia and arrived in Northwest Europe around 3500 BC, concurrent with the significant transformation of settlement patterns.

However, alternative hypotheses propose that animal traction may have emerged autonomously as a polycentric phenomenon (see Leppek, 2017: 98). For instance, the attachment of cattle to a digging stick could have been independently attempted in different regions (Halstead, 2014: 58). While it remains uncertain whether this innovation was introduced or developed independently, recent studies suggest that animal traction might have been in use as early as the seventh or sixth millennium BC in several parts of continental Europe, as will be discussed below.




Figure 2.1: Map showing the regions mentioned in this section

### 2.4.1 The Mediterranean

The earliest evidence of draught cattle use in the Mediterranean may potentially date even to the beginning of the Neolithic. Wooden pieces discovered in the late sixth millennium BC context from La Draga (Catalonia) have been interpreted as yoke remains (Tarrús et al., 2006: 26), although this interpretation has been considered inconclusive and ambiguous (Sherratt, 2006). Nonetheless, osteological analyses from the same site revealed the presence of castrated cattle and phalanx deformations, possibly related to draught use, suggesting the potential use of

draught animals during 5430-4796 cal. BC (Helmer et al., 2018). Cattle skulls showing evidence of cranial perforation were initially interpreted as deriving from animals used for traction purposes (Tarrús et al., 2006; Llado et al., 2008; Helmer et al., 2018). However, the association between cranial perforation and draught use has been disproved (see Section 3.2.1).

Artefactual evidence of the use of traction cattle in Greece is provided by figurines of a pair of yoked oxen from an Early Bronze Age village in Nemea (Pullen, 1992). The Lavagnone ard remains, found in Lake Garda of northern Italy date back to the Early Bronze Age (c. 2048-2010 BC) based on their stratigraphic position, resembling the rock carvings (Barker, 1985: 130–1; Marzatico, 2006).

Zooarchaeological studies show that the increasing survivorship of male cattle in Thessaly (Greece) during the third millennium BC was likely due to the use of oxen for traction (Halstead, 1987: 80). Additionally, the high frequency of pathological skeletal elements from the sixth millennium BC at Knossos (Crete), combined with the mortality patterns showing a high proportion of adult deaths and sex ratio, may reflect the small-scale exploitation of cattle power (Isaakidou, 2006, 2008).

### 2.4.2 The Balkans

The Balkans have been a critical crossroads for trade and cultural exchange that bridged Western Europe with West Asia. Greenfield (1988, 2005) focused on a range of Neolithic sites in the Central Balkans to test whether the use of secondary products was introduced into Europe from West Asia. He suggested that the shifting patterns of slaughter age from the Neolithic to the Post-Neolithic reflect the changing strategy in emphasising both primary and secondary products starting at the end of the Neolithic (Greenfield, 2005).

Evidence of early ploughing activities in the Balkan-Danubian region is thought to have been demonstrated by a piece of deer antler with a rectangular hole measuring 3.5 x 2.3 cm from Late Neolithic Căscioarele (Romania), associated with the Gumelnița culture (c. 4700-4000 BC). Dumitrescu and Banateanu (1965)

interpreted this antler piece as a primitive ploughshare which, however, may equally be associated with human and animal traction.

Skeletal modifications identified in cattle remains from the Vădastra sites in the Lower Danube, specifically the development of spiky processes on the vertebrae, suggest that cattle were possibly used for traction during the fifth millennium BC (Mateescu, 1975). This observation aligns with a later microscopic analysis of flint traces found at Neolithic sites (c. 4500-4300 BC) in Bulgaria. It indicates that the flints were part of a threshing sledge and that it was probably pulled by cattle (Anderson, 2003: 425). A recent study of stress-related lesions in cattle from the Western Balkans region suggests that they were likely used for non-specialised light traction from the Early Neolithic period onwards (c. 6100-4500 cal. BC) (Gaastra et al., 2018). Similar analyses in Romania indicate possible use of draught cattle at the Poduri site, dating back to around 4450-4150 cal. BC (Balasescu et al., 2006).

### 2.4.3 Western Europe

The oldest wooden ard remains in Europe were discovered in Schwebsingen (Luxembourg) and were dated to 3295-2780 cal. BC (Tegtmeier, 1993: 20). Severe osteoarthritis on cattle phalanges was recorded at two Late Neolithic sites (c. 3200-2300 BC) in western Languedoc (France), in conjunction with probable steers and a high proportion of advanced-age cattle (Lignereux et al., 2006). These results concur with later pathological studies of the final Neolithic sites in Languedoc and Provence; they thus may imply the use of draught cattle in the region (Helmer et al., 2018). Wooden travois and a double horn yoke were discovered at Lake Chalain in Jura (France), alongside a kill-off pattern indicating an increase in the number of adult and old individuals at the same site (see Section 3.2.4 for discussion of kill-off patterns). It appears cattle were likely used for their traction power but at a low-intensity during the late 4th millennium BC (Arbogast et al., 2003).

### 2.4.4 Central and Eastern Europe

Central and Eastern Europe provide vast evidence related to animal traction use. An oak ard was found in Asterlagen (Germany), with a radiocarbon date of 2855-2465 BC (Drenth and Lanting, 1997: 54). Another was discovered in Ukraine, dating back to a much later period around 1700 cal. BC (Lerche and Steensberg, 1980: 85; Piggott, 1981: 58). Plough marks were found in Germany, Czechia, Slovakia and Poland, dating from the mid-fourth millennium BC onwards (e.g. Chapman, 1982: 122; Thrane, 1989; Nobles, 2014).

One of the earliest traces of plough furrows in Europe came from Sarnowo (Poland) and is attributed to the mid-fifth millennium cal. BC (Bakker et al., 1969; Niesioowska-Śreniowska, 1999). However, the interpretation of these strips as plough traces was later challenged (see Section 3.1.1 for discussion). The earliest dated German plough traces came from Lower Saxony, indicating that the use of ploughs may have started with the Funnel Beaker culture and continued into the Early Bronze Age (Tegtmeier, 1993; Kramer et al., 2014).

Potential cart tracks were discovered beneath a Neolithic long barrow at Flintbek, north Germany (Bakker et al., 1999). Recently, the Bayesian analysis has provided a more precise date range of 3420 to 3385 cal. BC for the site (Mischka, 2011). If these tracks were correctly associated with wheeled vehicles, it would imply the earliest use of wheeled transport in Europe, suggesting a similar timeline for the use of ploughs. This interpretation is further supported by a Funnel Beaker vessel found in a 3450-3100 BC phase from Bronocice (Poland). It depicts wagons and represents the earliest known use of wheeled vehicles in prehistoric Europe in the fourth millennium BC (Piggott, 1983: 41). Cattle bones from the same pit fill as the vessel were later radiocarbon dated to c. 3637-3373 cal. BC. This evidence indicates that wheeled vehicles appeared in Central and Eastern Europe at least from the mid-fourth millennium BC (Bakker et al., 1999).

A cattle horn core with a predominant depression was found at Bronocice phase (2900-2600 BC). Milisauskas and Kruk (1991) attributed this depression

to using a horn yoke with reins tied to the horns. Using this evidence in combination with the presence of 25% castrated males from the same occupation, they suggested that oxen were likely exploited for traction to provide greater power during the Middle to Late Neolithic. In addition, a rock carving illustrating wheeled vehicles with cattle was found at Lohne (Germany), later in the early third millennium BC (Piggott, 1983: 43). Although the connection between horn core depression and yoking cattle remains uncertain, other lines of evidence, including plough and cart traces, suggest that cattle were possibly used for traction in Central and Eastern Europe during the mid-fourth millennium BC.

The castration of bulls predates the late six-millennium cal. BC in some German sites, suggesting that docile but strong animals were required (Piggott, 1981: 58, Müller, 1964; 1998, as cited in Bogaard, 2004: 46, Drenth and Lanting, 1997: 63). Yet, it should be noted that castration may also have been used to accelerate the growth of calves to optimal meat weight (Bogucki, 1988: 87); therefore, not necessarily for traction purposes. The combination of limb pathologies in cattle and the discovery of several fragments of disc-shaped wheels at the Seekirch-Achwiesen site may suggest that cattle were used for drawing wheeled vehicles during the final Neolithic period (c. 2900 BC) in southern Germany (Schlichtherle, 2006; Steppan, 2006).

Double cattle burials are frequently unearthed in Central and Eastern European Neolithic sites from 3500 BC onwards, such as in Hungary, southwest Germany, Poland, and Ukraine (Piggott, 1969, 1983: 47, 1992: 20; Pare, 1992; Pollex, 1999; Bartosiewicz et al., 1997b: 9). This kind of burial has been associated with using a pair of cattle for traction, particularly for driving wheeled vehicles. Although no actual remains of a wagon have been discovered in the burials, two clay wagon cups found together with two oxen skeletons in Budakalász (Hungary) may verify the claim (Foltiny, 1959; Piggott, 1969: 46). Furthermore, Piggott (1969, 1983: 47) suggested that the Budakalász pit, as well as similar graves in Germany and Poland, had enough space to accommodate an unpreserved wooden vehicle. These skeletons may, therefore, potentially represent a plough team. In addition,

a Chalcolithic burial containing two cattle skeletons with spinal arthritis and vertebral abnormality was noted in Slovakia; these animals were likely to have been used as a pair for pulling carts or ploughs (Fabiš, 2005).

### 2.4.5 The Caucasus

The steppe environment and pastoralist cultures of prehistoric communities in the Caucasus region made ploughing unlikely, as the mobility associated with pastoralism often limited investment in permanent agricultural practices such as ploughing systems. The evidence of animal traction in this region is, therefore, mainly related to transportation. Wagon burials are commonly associated with cultures that emerged in the late fourth millennium BC. The related burials were frequently found in this region, indicating the use of wheeled vehicles during this period (Reinhold et al., 2017). This is supported by the discovery of isolated clay discs in the southern Caucasus dating back to the second half of the fourth millennium BC (Sagona, 2018: 361). At late Maikop sites in the north Caucasus dating to a similar period, cattle skulls were often discovered alongside looped nose rings, which are assumed to have been used to control the direction of the cattle (Reinhold et al., 2017). Additionally, graves containing four-wheeled wagons dating back to 3356-3033 cal. BC, from the early Yamnaya culture, were discovered at Sharakhalsun in Russia (Tucker et al., 2017).

### 2.4.6 The Alps

Wooden yoke pieces dating back to the early third millennium BC were found at Lake Biel (Switzerland) (Tschumi, 1949). Subsequently, an incomplete wooden artefact was discovered at Arbon-Bleiche on the southern shore of Lake Constance. This is dated to around 3400 cal. BC and is considered a double yoke for harnessing medium-sized animals (Deschler-Erb et al., 2006).

Like neighbouring regions, plough traces were exposed in Switzerland and attributed to the late fourth or third millennium BC (Thrane, 1989; Tegtmeier, 1993). The most recent study discovered plough traces at the Anicens Aresnaux site

(Switzerland), dating to the beginning of the fifth millennium BC (Van Willigen et al., 2024). This new evidence represents the earliest known plough marks in Europe. Iconographies of pairs of yoked oxen pulling travois or wheeled vehicles were identified at Mont Bégo in the southwestern Alps. Several of the figures of yoked cattle without terminal parts were attributed to c. 4000 BC (Huet, 2017). Similarly, rock carvings in Val Camonica (Italy) display a pair of oxen pulling a four-wheeled vehicle, together with another team driving a plough from the late third millennium BC (Anati, 1961: 114; Piggott, 1983: 53).

Pathological studies conducted on the Arbon-Bleiche material and other Neolithic sites in Switzerland revealed lesions on the limb bones and vertebrae of cattle, indicating that animal traction could have been practised from 3400 BC onwards (Plogmann, 2002, as cited in Johannsen, 2006: 45; Deschler-Erb et al., 2006). This interpretation is supported by the discovery of possible yokes in the same area and from the same period, which together suggest that draught cattle were likely in use by the middle of the third millennium BC.

### 2.4.7 Northern Europe

The waterlogged environment in Northern Europe has preserved much of the physical evidence of ploughing practices. The oldest evidence of these practices in Northern Europe was demonstrated by the plough remains from Danish peat bogs, dated to the Bronze Age (Glob, 1951; Payne, 1957). The Walle ard, found in East Frisia, was initially proposed to have originated from c. 4000–3000 BC. However, this chronology has since been revised as pollen analysis from the finding spot suggests that the ard cannot have been deposited prior to the Early Bronze Age (Glob, 1951: 111; Payne, 1957). Meanwhile, the Hvorslev ard discovered in Jutland was radiocarbon dated to 1490 cal. BC, which is the oldest of its kind found in this region (Lerche and Steensberg, 1980: 83; Payne, 1957). Two of the most well-known finds, the Dostrup and Donnerupland ards were classified by Glob (1951: 114) as being the type of ard called a bow ard. The former was discovered in Jutland (Denmark), dating to 810 cal. BC (Lerche and

Steensberg, 1980: 82), while the Donnerupland ard was possibly from a similar period (Glob, 1951: 114–5). Probable plough marks have been found in Denmark, the Netherlands, Sweden, and Norway dating to the mid-fourth millennium BC or later (Sherratt, 1983; Thrane, 1989; Prøsch-Danielsen, 1993; Louwe Kooijmans, 2006: 201; Nobles, 2014; Johannsen, 2017; Ivanova, 2017: 45).

Pictorial evidence of ploughing scenes featuring two yoked oxen was found in Sweden and is dated to a similar period (Glob, 1951: 112–3, 116). Wooden disc wheels from wagons or carts discovered in Denmark and the Netherlands were from the early third millennium BC (Piggott, 1992: 18; Johannsen, 2017). A yoke was discovered in Jutland providing unambiguous proof of the use of animal traction. It is, however, much later, having been dated to 330 cal. BC (Fenton, 1973: 73).

The utilisation of draught cattle in Northern Europe appears to have begun later than in other regions of continental Europe, as further confirmed by osteological studies. Previous works focusing on the Neolithic sites in south Scandinavia indicate the use of draught cattle may have preceded the mid-fourth millennium BC based on the kill-off patterns and the occurrence of morphological changes in limb bones related to traction stress, whilst the exploitation became intensified around the 3300 BC (Johannsen, 2005, 2006, 2017). It is suggested that the adoption of animal traction occurred in parallel to with the invention of wheeled vehicles, facilitating the construction of large structures during the fourth millennium BC (Johannsen, 2017: 130).

### 2.4.8 Ireland

Plough marks were found at both Ballygalley in Antrim and Céide Fields in Mayo, while stone ard shares were found at Céide Fields within the same context of the plough marks, originally attributed to the Early Neolithic (O'Connell and Molloy, 2002). Nonetheless, recent research claims that Céide Fields may, in fact, date to the Bronze Age (Whitefield, 2017).

Sixteen intact yokes were recovered from Ireland, most of which were suggested to be from the Early Medieval period (Stanley et al., 2003). The Toberdaly yoke from Ballybeg Bog, dated 889-543 cal. BC presents the Irish earliest surviving material evidence for animal traction (Stanley et al., 2003). Recent pathological analyses of a faunal assemblage from Kilshane in Dublin, indicate the exploitation of draught oxen from the later fourth millennium BC (c. 3600 cal. BC) (Pigière and Smyth, 2023).

### 2.4.9 Further considerations on the Secondary Products Revolution

In a subsequent discussion, Sherratt (2006) revised the original model and posited that the draught animals were adopted gradually from 8000 to 4000 BC, starting with non-specialised use. However, he remains doubtful about the accuracy of the dating and the interpretation of the evidence, especially the osteological data related to paired animal traction in Europe before 3500 BC. Particularly, Sherratt highlighted the lack of advanced harnessing systems in Europe before the mid-fourth millennium BC, limiting the usage of animal traction to possibly only a single animal for treading grain or ad hoc use (Sherratt, 2006). This claim, however, has been criticised for potentially underestimating the capability of early farmers and drawing weak assumptions based on the absence of material evidence (Halstead and Isaakidou, 2011). Chapman (1982) argued that contemporary plough traces in Central and Southeast Europe make it hard to doubt that plough cultivation in Europe was already in place as early as the late fifth millennium BC. Furthermore, plough scenes with a single animal have been depicted in Mesopotamia cylinders (Ward, 1910: 132, Fig. 369, 371–2), whereas a single animal can draw wagons (Pollex, 1999). Adding to this, Halstead (2014: 59) stressed that the significant maintenance costs may have limited the use of draught cattle rather than being a result of technological constraints. Therefore, the advanced harnessing system for paired animals may not be a prerequisite to specialised use.

As discussed in the previous section, the non-osteological evidence from Europe comes mainly from the period when Sherratt proposed the SPR model, supporting the argument that the draught use of cattle likely emerged after the fourth millennium BC. Despite the more recent discovery of potential wooden yoke fragments from the late sixth millennium BC in La Draga and plough traces from the beginning of the fifth millennium BC in Switzerland, there is not yet conclusive evidence of draught animal use before the fourth millennium BC in Europe based on artefactual remains. The hypothesis of early animal traction is primarily supported by pathological or biometric analyses of cattle bones, suggesting that the use of this innovation could have begun as early as the sixth or even seventh millennium BC in the Mediterranean, Balkans, and Central and Eastern Europe. However, as will be further discussed in Section 3.2, the correlation between pathologies and draught use is not straightforward, as skeletal modifications could also be related to the age of the animals or environmental conditions. This in no way rejects the possibility that draught cattle were used before the fourth millennium in continental Europe. Nonetheless, the osteological evidence, particularly biometry, requires further systematic analysis.

## 2.5 Animal traction in prehistoric Britain: Current understanding

Evidence of the use of animal traction in prehistoric Britain is relatively scarce compared to continental Europe. As Fowler (1983: 14) noted, 'why graphics of, for example, ard-scenes do not occur amongst the various rock-carvings of later prehistoric Britain is another curiosity of the insular evidence.' No wheeled vehicles were discovered in the early British prehistoric period (Serjeantson, 2011: 20), nor have the wooden remains of ards been found in Britain before the later centuries BC (Fowler, 1983: 171). Additionally, depictions of ploughing scenes are only dated from the Roman period onwards.

Indirect evidence, such as plough tracks or remnants of plough implements, has been the key source of information for previous studies investigating the

early use of animal traction. The primary indications of plough use in prehistoric Britain are the working tips of the ards, which were made of stone, hardwood, or possibly bone (Rees, 1981: 73). Both ard tips and wooden parts of the plough were mostly found in Scotland, with only sporadic discoveries in southern Britain. The stone ard shares from Shetland and Orkney that originate from the early to mid-second millennium BC and the ard head and slit from Milton Loch in Dumfries and Galloway dated to 450 cal. BC all suggest similarities with the Danish Donnerupland or Dostrup ard (Payne, 1957: 73; Lerche and Steensberg, 1980: 84; Piggott, 1981: 57; Rees, 1979, 1981: 73, 1983; Fowler, 1983: 171–2). A large number of stone ard points discovered from Orkney and Shetland are suggested to be largely limited to the Northern Isles as comparable finds are sporadic in other parts of Britain (Rees, 1979: 6). These stone tips are suggested to have been attached to the ard used in the third to second millennium BC (Fowler, 1983: 172). A probable wooden plough ard-share was excavated at Dundarg Castle in Aberdeenshire, again resembling the Donnerupland ard (Rees, 1983). Radiocarbon dating of this ard-share is unavailable due to the bog environment; nonetheless, Rees (1983) speculated it could be from the Iron Age at the earliest. However, the ard-shares might not be related to the use of draught animals.

More explicit evidence of using traction animals is suggested by a complete 2.5 m plough beam from 55 cal. BC (Lerche and Steensberg, 1980: 83), found in a peat bog at Lochmaben in southwest Scotland, which was equipped with a 5.8 cm x 2.3 cm rectangular opening, possibly for attaching yoked oxen (Payne, 1957; Rees, 1979: 43, 1981: 73). This beam looked similar to the Danish bow ards portrayed in Scandinavian and North Italian rock arts (Rees, 1979: 71). It was believed to have also been used in Southern Europe and the Mediterranean region (Payne, 1957). The remnants of ploughing tools provide support to Curwen's (1927) early speculation that the ox-drawn plough was introduced into Britain in the Late Bronze Age or Early Iron Age. This can be consistent with Clark's (1962: 37, 1966: 185) assertion that cross-cultivation by ards was brought to southern England by the Beaker people in the Late Bronze Age.

Prehistoric plough traces have been uncovered at several British sites, although it remains unclear whether animal traction was involved. English sites include Carrawburgh in Northumberland, Rudgeway in Gloucestershire, and Gwithian in Cornwall (Fowler and Evans, 1967; Fowler, 1983: 113; Rees, 1981: 77). Similar traces have been identified both on the Scottish mainland and the islands, including Carn Dubh in Perth (Rideout, 1995), Achany Glen in Sutherland (Carter, 1998: 158–9), Wellhill and Cranberry in Perth and Kinross (Brophy and D. Wright, 2021), Rossinish, Benbecula, and Sumburgh in Shetland (Halliday et al., 1981: 55; Downes and Lamb, 2000: 8), as well as Skaill and Links of Noltland in Orkney (Rees, 1981: 77; Clarke and Sharples, 1985: 73–4). The earliest evidence of ploughing in Britain was initially believed to come from the Early Neolithic Fussell's Lodge Long Barrow in Wiltshire; however, this interpretation was later rejected (Ashbee, 1966).

It is widely accepted that the earliest criss-crossing plough marks in Britain were uncovered beneath the South Street long barrow in north Wiltshire, which is dated to the Early Neolithic. These plough traces must have been created before the construction of the barrow. A recent study has provided a more accurate chronology of the South Street long barrow, estimating that its initial construction occurred between 3565 and 3105 cal. BC (Whittle et al., 2011: 105). It is suggested that the preservation of ard marks results from burial mounds covering them; consequently, most ard marks were found beneath mounds, although they also occur in other contexts (Fowler and Evans, 1967; Rowley-Conwy, 1987; Thrane, 1989). Since it is rare to have mounds before the period of causewayed enclosures (later part of the Early Neolithic), it is expected that plough traces are unlikely to be preserved in the earliest Neolithic (Rowley-Conwy et al., 2020: 410).

The longest furrow in South Street was 140 cm, with an average width of 5-10 cm, crossed at right angles to one another around 30 cm apart (Ashbee et al., 1979; Fowler and Evans, 1967; Piggott, 1981: 54; Fowler, 1983: 112). In addition, these marks penetrated the solid chalk subsoil up to a depth of 15 cm and cut into the buried soil up to 30 cm, which appeared to be deeper than typical practices

(Piggott, 1981: 55; Fowler and Evans, 1967). According to Fowler and Evans (1967), the plough marks were likely caused by either animal or human traction, while Mercer (1981: x) pointed out that they were produced by the use of a 'rip ard', which required cattle to pull the ard to create the marks on the chalk bedrock. The 'rip ard' is a hypothetical tool proposed by Reynolds (1981: 102–3), which could potentially produce deeper traces than the typical bow ards used to convert woodland or scrub into arable land. This tool may have been responsible for the deep furrows found at South Street. Although no remains of a 'rip ard' have ever been found (Tegtmeier, 1993: 122), Reynolds (1981: 102) believes that this is the type of ard that is represented on the rock carving at Aspeberg (Sweden), which was previously classified by Glob (1951: 45) as a bow ard.

Barker (1985: 202) similarly argued that the prehistoric light ards discovered in Europe could not have generated the deep furrows at South Street; however, the reasoning behind this assertion is not clearly explained. Nonetheless, experimental studies using replicas of prehistoric ards support Barker's view, showing that bow ards, including the Donneruplund ard, are unlikely to produce furrows deeper than 15 cm (Reynolds, 1967: 122, Tab. 23).

Given the unusual depth of the South Street traces, Barker and Webley (1978) proposed that these marks were more likely associated with turf-cutting for two possible purposes: first, turf-cutting using spades, which is suggested as a typical method for constructing Neolithic monuments to dig into the soft soil; second, Neolithic farmers might have removed grass and roots by hand. This process, involving spades or a simple plough, could create noticeable patterns of furrows in the soil (Barker and Webley, 1978). Despite this suggestion, most of the plough marks uncovered in England, including those at South Street, Earl's Farm Down, and others from later periods, present a remarkably consistent distance of approximately 30 cm between each furrow (Fowler and Evans, 1967). This uniform spacing could have prevented the ard from slipping to the back and was assumed to be a traditional practice associated with arable cultivation without using a plough with a mouldboard (Fowler and Evans, 1967; Rees, 1979: 83). Nonetheless,

the interpretation of parallel grooves as plough marks has long been debated (see Section 3.1.1). If the marks were indeed produced by ploughing, South Street could represent the earliest instance of plough cultivation in Britain. But even if these are plough marks, they alone cannot conclusively indicate that animal traction were used as an ard or plough could have also been pulled by humans.

Remains of wooden yokes are the most direct indications of the adoption of animal traction, but they are rarely found. According to Rees (1979: 72), 15 yokes were discovered in Scotland and Ireland, of which seven are likely prehistoric; however, no direct dating was available at the time of Ress' writing. Later, a dating program suggested that the double yoke remains from White Moss in Orkney and Loch Nell in Argyll, both in Scotland, date to 1516-1253 cal. BC and 1950-1525 cal. BC, respectively (Hedges et al., 1995). Additionally, a complete Iron Age wooden yoke for paired animals has been reported from the Ulster region in northern Ireland, though the exact location remains unknown (Piggott, 1949).

Subsequent excavations in England have uncovered several more wooden objects that may be interpreted as yokes. At the Late Bronze Age site of Flag Fen (Cambridgeshire), a wooden object (A2405) has been identified as a yoke (Pryor et al., 1986: 15). More recently, excavations at Must Farm, also in Cambridgeshire, revealed two wooden objects (WD5683 and WD7332) that have been suggested as potential single yokes for harnessing a small animal (Bamforth, 2024: 682). Bamforth (2024: 682) pointed out that WD5683 is compatible with A2405 from Flag Fen in terms of size and structure, providing greater certainty that it is likely a yoke, while WD7332 may be too lightweight for harnessing an animal. Although no direct dating is provided for the wooden objects from Must Farm, the site is dated to the mid-9$^{th}$ century cal. BC (Tyers et al., 2024: 1280).

Archaeological evidence of wheeled vehicles in prehistoric Britain is relatively rare. The oldest known example comes from the wooden disc fragments found at Flag Fen in Cambridgeshire, dated to the Bronze Age (c.1300 BC) (Taylor, 2001: 213–4). Similar wooden discs were also recovered from the peat at Blair

Drummond in Perthshire, dating between 1220-800 cal. BC (Piggott, 1959; Sheridan, 2002). Tripartite wheel fragments have been identified at Lingwood Fen (Cambridgeshire) (Taylor, 2001: 213–4), and the recent excavation at Must Farm (Cambridgeshire) uncovered the most intact British disc wheel, dating to around 865-825 cal. BC (Bamforth, 2024: 652).

Osteological evidence from Etton in Cambridgeshire provides another frequently mentioned indication of using animal traction in Neolithic Britain. Osteoarthritis was noticed on cattle scapulae and acetabula, mostly in females (Armour-Chelu and Clutton-Brock, 1985: 300–1). Due to the majority of cattle being killed before six to seven years old and unusual lesions on scapulae, it is assumed they were exploited for traction (Armour-Chelu and Clutton-Brock, 1985). However, using osteoarthritis as an indicator of draught cattle is questionable (see Section 3.2.1). Lesions on scapulae are rare even in Roman and Medieval sites in Central Europe, where cattle were extensively used for tillage (Bartosiewicz and Gál, 2013: 315, Fig. 129), indicating they might have other aetiology unrelated to traction.

Skeletal pathologies and modifications that are possibly related to traction stress, including cranial perforation, osteoarthritis, and asymmetrical metapodials, have been identified in prehistoric sites such as Late Neolithic Links of Noltland (Fraser, 2015: 205), Early Bronze Age Down Farm (Serjeantson, 2011: 22), and Early Bronze Age West Row Fen (Olsen, 1994: 144). These findings suggest that draught cattle may have been used at these sites but the evidence, as will be discussed in Chapter 3, is problematic. Although, as discussed in the previous section, castration was not exclusively associated with draught animals, the presence of steers has also been noted at two Early-Middle Neolithic sites, Windmill Hill and Fussell's Lodge (Serjeantson, 2011: 22), as well as at several Late Neolithic sites, including Skara Brae and Durrington Walls (Watson, 1931: 199; Piggott, 1981: 50).

Speculations based on plough remains originally proposed that the use of cattle-drawn ploughs in Britain did not occur until the Bronze Age or Early Iron

Age (Curwen, 1927; C. W. Bishop, 1936: 274). While it has also been suggested that draught cattle may have been utilised in the construction of Stonehenge, this has never been conclusively verified (Serjeantson, 2011: 20). Various types of evidence potentially related to animal traction have been reviewed in this section; however, as will be further illustrated in Chapter 3, plough marks, plough remains, and pathologies do not directly indicate the use of animals for draught purposes. Consequently, the earliest unambiguous evidence for animal traction in Britain comes from the rare yoke remains found at Loch Nell in Scotland, dated to 1950-1525 cal. BC. Overall, evidence for the emergence of animal traction in prehistoric Britain is scarce and patchy, leaving unanswered questions about when and how it first appeared.

As previously noted, animal traction distinguishes itself from other secondary products by significantly expanding human capability. Studying the origins and diffusion of this innovation in prehistoric communities is more complex than for other components, such as milk and wool, due to the absence of actual products produced by draught use. Given the scarcity of material evidence in the British prehistoric context, the analysis of kill-off patterns and skeletal modifications offers the most promising approach to investigating the development of animal traction despite its limitations.

## 2.6 Cereal cultivation in prehistoric Britain

Undoubtedly, cattle could be used for various traction tasks; however, ploughing was the most significant function, particularly prior to the invention of the wheel. Ploughing is essential for arable cultivation. Although it has been discussed in the previous section that manually drawn ploughs were also likely, the extent of cereal cultivation may offer indirect evidence of the use of draught cattle.

Despite the long debates on the importance of cereal cultivation in Early Neolithic Britain, it is widely agreed that cereal cultivation began in the fourth millennium BC. The earliest dates of cultivation from charred cereals are suggested to be around 3950 cal. BC (Brown, 2007). Bogaard (2005b) suggested that

garden cultivation, which involves relatively high labour per unit, was adopted in early farming in Central and Southeastern Europe. It is later argued that the same farming regime was also embraced in Early Neolithic Britain, as woodland clearings were mainly restricted to small areas, indicating small-scale but intensive farming units (G. Jones and Bogaard, 2017; Rowley-Conwy et al., 2020). There is a possibility that if using cattle for draught ploughing was practised on the Continent, the farmers would have brought their skills with them when they settled in Britain. Nonetheless, ox-ard cultivation is associated with the extensification of the scale of cultivation (Halstead, 1995: 14; Bogaard, 2011: 267). Therefore, while cereal cultivation was a key component in Neolithic Britain (e.g. G. Jones and Bogaard, 2017; G. Jones and Rowley-Conwy, 2007; Rowley-Conwy et al., 2020), the small-scale farming may not have required the involvement of draught cattle for ploughing.

Cultivation was later significantly reduced during the Middle to Late Neolithic in Britain (Brown, 2007; Stevens and Fuller, 2012). This claim is supported by evidence from southern England (De Vareilles et al., 2023). However, the abandonment of cultivation appears to have been a regional phenomenon, as arable agriculture remained important in the Late Neolithic in Scotland (R. R. Bishop, 2015). A resurgence in arable agriculture emerged in the Middle Bronze Age, coinciding with the appearance of visible field systems, primarily in southern England (Fowler, 1983: 95; Yates, 1999; Bradley and Yates, 2007). The division of land into rectilinear blocks of field systems is suggested to be associated with intensification in mixed farming (Barrett, 1980: 88; Pryor et al., 1986; Yates, 1999, 2007: 120; Champion, 1999: 103). However, more recent studies argue that the development of field systems reflects broader social changes and a shifting relationship between people and the landscape (Brück, 2019; Carey et al., 2024). Regardless of the association between field systems and the intensification of farming, the increase in cereal cultivation during the Middle Bronze Age is clearly demonstrated by Stevens and Fuller (2012). This change in agricultural practice was associated with large-scale but less intensive cultivation (De Vareilles et al.,

2023; Stevens and Fuller, 2012; Yates, 2001). It is estimated that a farmer can produce 7 to 10 kg·m/s (kilogram-metre per second) (equivalent to moving 7–10 kg over one metre in one second) of work on average, whereas a cow can generate 35 kg·m/s and oxen up to 56 kg·m/s (Hopfen, 1981: 4, 10). Animal traction reduces labour input per unit area by an average of $30 - 40\%$ (Bogucki, 1993, 2000: 228). This enhancement in efficiency likely contributed to the expansion of arable farming during the Bronze Age.

## 2.7 Draught cattle

Draught exploitation of cattle is a diverse practice, determined by various factors such as team size, as well as the sex, and age of the draught cattle. These factors are important in interpreting osteological evidence for indicating possible draught cattle. This section focuses on past practices by reviewing archaeological records and considering ethnographic observations from prior studies in Europe.

### 2.7.1 Team size

Most prehistoric iconographies in Europe depict two animals yoked side by side as the most typical method of traction. This is evident from the rock carvings found in Val Camonica (Anati, 1961: 114–6), Fontanalba (France) (Bicknell, 1913: 40), and Sweden (Glob, 1951: 112–3), which depict a pair of yoked cattle pulling a plough. Nonetheless, prehistoric iconography sometimes presents various forms of teams. For example, three Assyrian cylinders (Ward, 1910: 132) and a vase by Nikosthenes from Greece (C. W. Bishop, 1936: 273) illustrate ploughing scenes with a single animal, while Bronze Age rock arts in the Maritime Alps of Italy show groups of three or four animals yoked together for ploughing (Bicknell, 1913: 33). Despite the absence of clear evidence indicating the use of a single animal for traction power in Europe, such practice was prevalent in Eastern Asia, such as China and Japan (Bray, 1978; Hopfen, 1981: 11; Lin, 2022: 85).

Likewise, wheeled vehicles were also commonly pulled by a pair of animals, as illustrated in iconographies from Lobne (Germany) (Piggott, 1983: 43), Syunik (Armenia) (Piggott, 1969: 80), Val Camonica (Italy) (Anati, 1961: 114), and Mont Bégo in the southwestern Alps (Huet, 2017). Ox burials in Central and Eastern Europe and the Caucasus regions from the mid-third millennium BC containing two animals have been interpreted as a symbol of the cattle pair that would drive wagons or carts (Piggott, 1969, 1983), in agreement with the pictorial representations.

There is no direct evidence from the British prehistoric context; however, a pair of cattle was likely the norm. The 2.5 meters long plough beam from Lochmaben is suggested to be long enough to accommodate one pair of oxen (Rees, 1979: 71). The common use of one or two animals for traction may indicate that farmers either could not afford more animals or did not require more than two at a time (Bartosiewicz et al., 1997b: 32).

### 2.7.2 Sex of the draught cattle

Castrated oxen are preferred for traction activities due to their strength and docility. As mentioned in Section 2.4.4, castration has been associated with draught cattle to produce strong but manageable animals (Bökönyi, 1974). It is further supported by osteological studies conducted at prehistoric sites such as Cafer Höyük in Turkey (Helmer et al., 2018), Le Mourral in France (Lignereux et al., 2006) and Kilshane in Ireland (Pigière and Smyth, 2023), where probable oxen exhibited lesions related to traction stress.

The exploitation of draught cows was not uncommon in past communities. Extensive osteoarthritis was found in the pelves of adult female animals at Knossos (late sixth millennium BC), suggesting they were the primary source of traction power while males were more for meat production (Isaakidou, 2006). Similar findings are known from Neolithic sites in the French Jura (Arbogast et al., 2003), the Western Balkans (Gaastra et al., 2018) and Etton in Britain (Armour-Chelu and Clutton-Brock, 1985), indicating the use of cows for traction

power. We must, however, consider that the pulling power of draught animals is directly proportional to their weight, making cows less effective for traction than specialised draught oxen due to their lighter build, which limits their ability to plough heavy soil (Hopfen, 1981: 9; Johannsen, 2011: 15; Halstead, 2014: 16).

On average, oxen can produce up to 0.75 horsepower, while cows can produce only 0.45 horsepower and operate at a slower working speed (Hopfen, 1981: 10, Tab. 2). Specialised draught oxen for ploughing reduced human labour significantly by performing 2-15 times faster than manual cultivation; however, they involve long-term training and management with higher costs (Barker, 1985: 258; Halstead, 1995; Bogaard, 2004: 32). Conversely, multi-purpose cows were used for milk and calf production but also valued for their power in light traction tasks for small-scale cultivation which is still more efficient than manual ploughing (Johannsen, 2011: 15; Isaakidou, 2011: 101; Halstead, 2014: 59). Draught cows were probably used in Neolithic Europe, but they may have not significantly increased the scale of cultivation (Bogaard, 2005b; Halstead, 2014: 59–60).

Whilst it is unclear whether using bulls for traction was a typical practice, it is noteworthy that they were possibly used in some regions. Pathological analyses conducted on cattle metapodials in Spain and Ireland revealed that bulls were likely used for this purpose during the prehistoric period (Galindo-Pellicena et al., 2017; Pigière and Smyth, 2023). Rock engravings from Lisleby (Sweden) may have depicted draught bulls in plough scenes. Yet, there is uncertainty as to whether this was a regular practice (Johannsen, 2011: 16). Similarly, a Greek red-figure bell-krater from around 430-420 BC illustrates a pair of bulls (one possibly a cow) pulling a plough (D. M. Robinson, 1931). However, it has been pointed out that ancient Greek farmers would not use intact bulls for traction because they were difficult to control; the depiction of bulls in ploughing scenes may have merely represented an artistic device (Ekroth, 2014).

As Bartosiewicz et al. (1997b: 17) observed, a young bull less than a year old was used for draught work in contemporary Romania. Comparable practices are also reported in modern-day Chad and Mexico (Starkey and Mudamburi, 2022: 14).

Despite the possibility that young bulls may be used occasionally, fully sexually mature bulls are rarely adopted in modern farming practices (Johannsen, 2011: 16), due to their aggressive behaviour. Further, the assumption that asymmetry on one bull metacarpal is a consequence of traction (Galindo-Pellicena et al., 2017) is questionable. Asymmetrical metapodials are common, even in non-working animals, because the medial portion supports more weight, resulting in a pronounced broadening on the medial side, particularly in metacarpals (Bartosiewicz et al., 1993).

### 2.7.3 Age of the draught cattle

A significant number of fully grown adult cattle in archaeological assemblages is often interpreted as evidence of their use as draught animals. At a Neolithic Irish site, most cattle were slaughtered for meat production between 34-43 months of age, whereas a small number were kept beyond 40 months, likely for draught work (Pigière and Smyth, 2023). At Neolithic Knossos, $35 - 55\%$ of animals were not killed before their fifth years, suggesting they may have been used for non-specialised milk production or traction (Isaakidou, 2006: 104).

Ethnographic studies further support this age pattern. For instance, the traction team in Romania was composed of cattle aged between 6 and 19 years (Bartosiewicz et al., 1997a: 18). Typically, animals are put to work between the ages of two and three years old, although the exact age may vary depending on their breed and the environment, with some animals beginning as early as one year old, and others as late as five (Johannsen, 2011: 16). It should be noted, however, that while the aforementioned animals are adapted for specialised draught work, early prehistoric communities were not likely to have used cattle extensively for such a purpose.

### 2.7.4 Harnessing style

Various forms of harnessing were used to attach cattle during traction, allowing them to transmit their force to ploughs or vehicles. The earliest method of

harnessing cattle likely involved fastening a rope around their horns without a yoke or pole (C. W. Bishop, 1936: 265). This primitive harness may be illustrated by Assyrian cylinders as a form of attachment for ploughing with one animal (Ward, 1910: 132), which also appeared in the later Dynastic ritual traction scenes in Egypt (C. W. Bishop, 1936: 268).

Yokes represent a later invention of harnessing systems by adopting the pole-and-yoke harness, which allows paired animals to be attached in traction activities (C. W. Bishop, 1936; Littauer and Crouwel, 1979: 14). It can be divided into two broad types: the head or horn yokes (Plate 2.1), where the yoke is placed in front of or behind the horns, and the withers yokes which lie around the neck or shoulder of the draught cattle (Fenton, 1973: 69; Rees, 1979: 72). Iconographies from Europe have yet to indicate which types of yokes were adopted. Nevertheless, the head yokes were assumed to be the earliest device to accommodate animals for traction purposes, with comparable remains discovered in Switzerland dating to around 2000 BC and a Scottish yoke from Argyll dated to 1950-1525 cal. BC (Fenton, 1973: 70–2; Hedges et al., 1995). The depression on the horncore found at a Neolithic site in Poland has led to the hypothesis that a horn yoke was in use (Milisauskas and Kruk, 1991). However, this association with draught use is questionable, as discussed later in Section 3.2.1.

Withers yokes (Plate 2.2) appear to have been a later development. The first clear representation of applying this yoke form on cattle comes from a second millennium BC tomb engraving in Egypt (Bartosiewicz et al., 1997b: 25). Similarly, a potential withers yoke from Oldenburg, Germany, is dated around 2000-1700 BC, suggesting there is a possibility that the withers yoke was used as early as the head yoke in some regions (Fenton, 1973: 72). Although both forms of yokes can be applied to a single animal, single yokes were uncommon (Starkey, 1989: 28). Using only a single animal for traction power is more common in East Asia. It is unclear whether single yokes were used in prehistoric Europe or Britain, as the rare finds from Scotland, Ireland, and Denmark all indicate double yokes (Fenton, 1973; Rees, 1979: 72). Nonetheless, one wooden object from a recent

excavation at Must Farm (Cambridgeshire) is suggested to be a potential single yoke (Bamforth, 2024: 682).

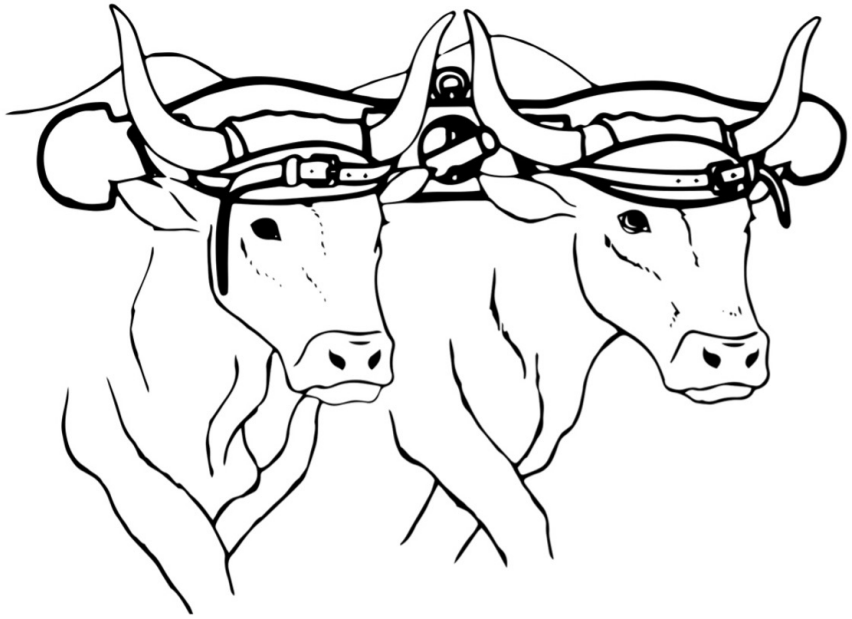


Plate 2.1: The head yoke. Illustration courtesy of Staatliche Schlösser und Gärten Hessen.

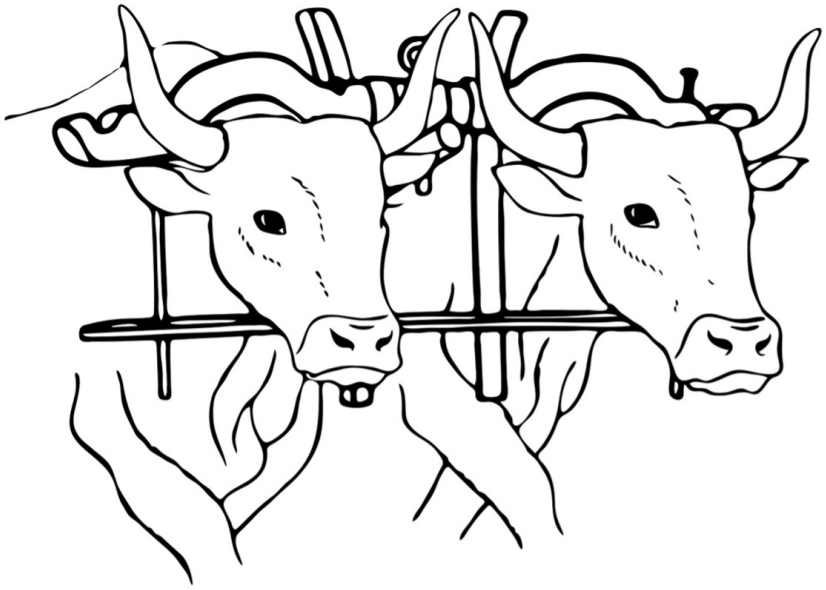


Plate 2.2: The withers yoke. Illustration courtesy of Staatliche Schlösser und Gärten Hessen.

# 3

# PRIOR METHODS TO IDENTIFY DRAUGHT CATTLE IN ARCHAEOLOGICAL RECORDS

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## 3.1 Non-osteological approaches

Most of the evidence from Europe has already been presented in Chapter 2. This chapter, however, focuses on interpreting non-osteological evidence to infer the use of animal traction rather than the timing of its introduction. In early studies, iconography, and artefacts played critical roles in facilitating analyses of the exploitation of animal power. The Secondary Products Revolution model developed by Sherratt (1981, 1983) emphasises mainly non-osteological data suggesting the first appearance of draught cattle can be dated from the early fourth millennium BC in Mesopotamia and then spread across Europe.

### 3.1.1 Plough marks

Plough marks may be detected as grooves on the ancient soil surface, consisting of V-shaped furrows that form parallel lines, typically spaced 30 cm apart and scratching into the subsoil (Fowler, 1983: 113). The oldest known example of

these grooves in Europe dates back to the early fifth millennium BC Anciens Arsenaux site of Switzerland (Van Willigen et al., 2024). Many other cases have been identified throughout the mid-fourth millennium BC and later in Europe (Glob, 1951; Thrane, 1989; Fowler and Evans, 1967; Niesioowska-Śreniowska, 1999; Tegtmeier, 1993; Mischka, 2011; Nobles, 2014). However, the interpretation of plough marks to infer the timing of cultivation activities has been questioned. Difficulties in accurately dating plough traces have been highlighted by Thrane (1989: 113) and Tegtmeier (1993: 28), who emphasised the uncertainty surrounding the time elapsed between the initial ploughing and the subsequent construction of the protective mound.

Moreover, it is uncertain if these furrows are related to ploughing activities. Reynolds (1981: 101) argued that such traces are unlikely to be preserved under repeated ploughing, where self-cancelling could occur. Since these marks are mainly found beneath round or long barrows, Rowley-Conwy (1987) suggested that they may represent preparation for rituals rather than cultivation activities. The criss-crossed regular dark strips from the fifth millennium BC in Sarnowo (Poland) were initially hypothesised to be plough marks. However, this interpretation was later modified to suggest that they represent burnt traces of a wooden structure since they appear alongside burnt clay and charcoal (Niesioowska-Śreniowska, 1999; Sherratt, 2006). Despite this, plough marks in England are claimed to be unrelated to ritual activities due to the striking consistency in the distances between furrows (Fowler and Evans, 1967).

Even when the soil marks are attributed to the cultivation process, it does not necessarily point to animal labour, as human-drawn ploughs are also a possibility. Midgley (1992: 389) pointed out that 'it is by no means clear whether all the identified ard-marks are the result of a draught-pulled plough.' A distance between each furrow of 30 cm is suggested to prevent the crook-ard from slipping to the back (Rees, 1979: 83). Glob (1951: 101) defined the crook ard as the most primitive type of ploughing tool; it had a substantial side branch in the main trunk and has been found in Denmark, northern Germany, and Poland. However,

examples from Sarnowo in Poland show an average distance of 13 cm between furrows, and some Danish examples have a distance of 10 cm, leading Midgley (1992: 389) to argue that these furrows may have been made by hoes instead of an ox-drawn plough. This claim is, nevertheless, doubted as the narrow distances between furrows could be attributed to multiple ploughing (Drenth and Lanting, 1997: 63). Further, the primitive foot-plough, allowing farmers to drive furrows with human power, was suppressed after the adoption of animal labour in Western Europe and Britain, yet this instrument did not vanish from some areas until the first century BC (Curwen, 1927).

The depth of the furrows is suggested to indicate whether they are related to draught animals. Marks produced by human-drawn ploughs would have been shallower than those made by animal-drawn ploughs, as draught cattle can generate greater power (Drenth and Lanting, 1997: 63). In a ploughing experiment with a replica of the Donnerupland ard, Reynolds (1967) demonstrated that 12-15 cm deep furrows can be created by four-person power. This result is similar to his subsequent experimental work ploughing with two cattle, which also showed an average depth of 15 cm (Reynolds, 1981). Analyses have also been conducted with a replica of the Walle ard, classified as a crook ard, which differs from the Donnerupland ard (Glob, 1951: 111). The furrows created by the Walle ard range from 6 cm to 12 cm (Tegtmeier, 1993: 122, Tab. 23). The depth is, therefore, more likely to reflect the type of plough used rather than the agent that drew the plough.

### 3.1.2 Artefact remains

#### 3.1.2.1 Plough and yoke

Timber remains are only preserved under specific natural conditions, such as waterlogged deposits. Some of the best examples of plough remain in North-West Europe are from Danish peat bogs, dated to the Late Bronze Age or Early Iron Age (Payne, 1957). The Donnerupland ard from Denmark comprises four parts, beam, stilt, ploughshare, and fore-share (Payne, 1957). It is believed that a similar type of light wooden framed implement was also commonly used in later prehistoric

Britain (Fowler, 1983: 168). The Donnerupland ard was classified as a bow ard type, a more advanced farming implement capable of ploughing more efficiently than the crook ard (Glob, 1951: 113). Despite their differences, both bow ard and crook ard types had a rectangular or circular hole on the beam that is believed to have been used for securing the ox-yoke to the animal (Glob, 1951: 111, 114). An equivalent tool was discovered in Lochmaben in southwest Scotland, where the ard beam showed a 5.8 cm x 2.3 cm rectangular opening, which may have been designed for attaching cattle (Payne, 1957; Rees, 1981: 73).

A yoke is a device used to harness cattle to a plough or cart. Head yokes are attached to the horns, while withers yokes are attached to the shoulders (Rees, 1981: 74). Yoke fragments have been discovered in various Late Chalcolithic and Early Bronze Age Europe sites, such as in Switzerland and Italy (Tschumi, 1949; Bartosiewicz et al., 1997b: 9; Anthony, 2007). More recently, possible yoke remains were found at the Early Neolithic site of La Draga, Catalonia, along with perforations in four cattle skulls, which has led to the hypothesis of draught exploitation (Llado et al., 2008). Nonetheless, cranial perforations should no longer be considered traction-related because identical lesions have been identified in wild animals (Manaseryan et al., 1999; Baxter, 2002) (see Section 3.2.1).

#### 3.1.2.2 Cart and wagon

Apart from ploughing, draught cattle were exploited to transport goods. The two-wheeled cart and four-wheeled wagon were likely to represent a later development of technology, where the earliest surviving wooden disc wheels in Europe were found in the Netherlands and Denmark, dating from the third millennium BC (Piggott, 1981: 59, 1992: 18). Nonetheless, two approximately 60mm wide traces which dated around 3420 to 3385 cal. BC in Flintbek (northern Germany) were interpreted as cart tracks since they were spaced 1.10m apart, corresponding to the axial spacing of Neolithic wheel discs discovered later (Mischka, 2011).

Additionally, burials from the late fourth to the early third millennium BC with pairs of cattle discovered in Central and Northern Europe have been regarded as

symbolic of a traction team (Piggott, 1969, 1981: 59; Bartosiewicz et al., 1997b: 9). A grave with paired oxen skeletons buried along with two clay wagon cup models was uncovered in Budakalász, Hungary (Foltiny, 1959; Pollex, 1999), whereas Piggott (1992: 20) suggested that a wooden vehicle was once buried in the same place, but no physical evidence was preserved. The idea of buried cattle being used for traction has been challenged due to the mixture of cows, bulls, oxen, and calves found in the graves, which does not align with the expectation of a specialised plough ox (Bóna, 1960; Pollex, 1999). This claim was countered by the idea that they may symbolise a working team to avoid killing valuable draught oxen for funerary practices (Sherratt, 1981; Piggott, 1983: 48). The association has been put forward by a more recent analysis of a paired oxen burial from a Baden culture (second half of the fourth millennium BC) settlement in Slovakia, showing several lesions on the vertebrate and limb bones which may reflect that these animals could have been a plough team (Fabiš, 2005).

It is worth mentioning that ox goads can also infer the use of animal traction, although none were found before the Iron Age. A goad is a tool for the ox driver to guide the animals (Payne, 1947: 99). In earlier prehistory, it could take the shape of a simple pointed stick, or a sharpened bone attached to a wooden rod, and only became more distinctive when its use became more specialised during the Iron Age and Roman period (Rees, 1979: 75).

### 3.1.3 Iconography

Prehistoric ploughing scenes with draught cattle were seldom depicted on cylinders from Western Asia and rock carvings in Europe. Rock carvings of ploughing scenes of an individual with two oxen were discovered at Aspeberget, Finntorp and Litsleby (Sweden), possibly dating to the Late Bronze Age (Glob, 1951: 112–3, 116). Comparable figures from the late third millennium BC appear in Val Camonica (Italy), presenting pairs of cattle drawing ploughs and wagons (Anati, 1961: 114; Piggott, 1983: 53). These pictorial representations provide significant insight into

the size of the draught cattle teams that were used in past communities (see Section 2.7.1). However, similar art carvings have not yet been discovered in Britain.

Despite the valuable evidence provided by material remains, they are uncommon and restricted to specific areas. Besides, the non-osteological indicators do not necessarily reflect an exact chronology of the actual use of draught cattle (Johannsen, 2005: 40). As illustrated in the previous chapter, the absence of material evidence may not be conclusive of the absence of the practice. The lack of animal traction evidence from non-osteological data does not disprove the zooarchaeological indications of an earlier use of animal traction in Europe (Halstead and Isaakidou, 2011: 70).

## 3.2 Osteological approaches

As discussed in the previous chapter, non-osteological evidence is crucial for understanding the past use of animal traction, but neither the dating of evidence such as plough marks and iconography can be precise, nor do these types of evidence necessarily indicate the actual use of draught animals. Morphological and pathological approaches to skeletal remains provide valuable insight into the historical exploitation of cattle labour, with osteological evidence typically more abundant than other sources.

### 3.2.1 Pathology

#### 3.2.1.1 General pathology

Certain lesions, such as eburnation and exostoses on the articular surfaces of the autopodia, deformations on hip joints, ring depression on horncores, cranial perforations, and spavin, are traditionally viewed as possibly 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). It is, however, suggested by recent studies that some pathologies are strongly related to age, trauma, nutrition, and genetic

factors rather than artificial loading. The four most commonly described 'traction pathologies' are discussed below.

**Osteoarthritis**

Osteoarthritis is a degenerative disease that mainly affects weight-bearing synovial joints. When the articular cartilage erodes, an inflammatory response triggers new bone formation around the joint margins and other changes. In order to diagnose this pathology in archaeological materials, Baker and Brothwell (1980: 115) suggest that at least three of the following four criteria should be observed on the same bone:

- Grooving on the articular surface
- Eburnation (a polished area on the articulating surface)
- Lipping
- Exostoses

Osteoarthritis on the acetabulum can also result from heavy draught work, causing the hip joints to over-rotate repeatedly (Baker, 1984: 254). This lesion has been frequently observed in archaeological assemblages and is hypothesised to be a consequence of traction activity (e.g. Mateescu, 1975; Armour-Chelu and Clutton-Brock, 1985).

However, although mechanical effects cannot be excluded, ageing is a significant risk factor for cartilage degeneration. Veterinary studies point out that degenerative joint diseases are commonly found in cattle over six years old (Thomson, 1969), though young animals aged between one and three years are also susceptible to the lesion (Barbosa et al., 2014). Likewise, eburnation on acetabula and femora has been observed in a recent analysis of modern non-working cattle aged between four and eight (Rassadnikov, 2021). It is, therefore, simplistic to assume that osteoarthritis is necessarily a consequence of exploitation, as it may also reflect a normal ageing process.

### Horn core depression

In an early study, Milisauskas and Kruk (1991) described a cord impression on horn cores from a Late Neolithic site in southeastern Poland and interpreted it as evidence of using horn yokes or yokes attached to the neck where the reins were tied to the horn. A similar assumption was also made by Müller (1992) by noticing ring-like depressions near the base of several cattle horn cores from Medieval sites in Central Europe. More recent studies on feral domestic cattle (R. Thomas et al., 2018), sheep (Albarella, 1995), and steppe bison (Kierdorf et al., 2016) have, however, challenged the relationship between ring depression and yoking. Rather than associated with mechanical pressure, this pathology is more likely to reflect trauma, metabolic disorders, or anatomical variant (R. Thomas et al., 2018). Although the aetiology of this condition is yet to be conclusive, it should no longer be considered a consequence of yoking.

### Cranial perforation

Smoothed margin holes are a common finding on cattle skulls in archaeological contexts (e.g. Ryder, 1970; Dobney et al., 1996; Llado et al., 2008; Johnstone and Albarella, 2015; Onar et al., 2015). Perforation can occur with single or multiple holes on the frontal, parietal and occipital area; it was hypothesised to have associations with external pressure caused by head yokes (Brothwell et al., 1996). Nonetheless, this assumption has been called into question after an identical lesion was found on European wisent (Manaseryan et al., 1999) and aurochs (Baxter, 2002). Recent research has further argued that developmental disorder is the most probable reason for this condition (Fabiš and R. Thomas, 2011).

### Spavin

The pathological fusion of metapodials to carpals or tarsals is known as spavin; this condition is most frequently described in horses, though cattle, sheep, and deer can also be affected (Baker and Brothwell, 1980: 117; Albarella et al., 1997; Bulatović et al., 2016; Albarella, 2019: 245). Ankylosis of limb joints is attributed to multiple factors, which are likely interrelated (Baker and Brothwell, 1980: 118). This assumption is demonstrated by the occurrence of spavin on sheep, indicating

that traction is not the sole aetiology leading to this condition. Furthermore, while it is suggested that mechanical stress is the primary cause of spavin in modern draught oxen, the effects of age and weight are inseparable (Bartosiewicz et al., 1997a: 117).

#### 3.2.1.2 Pathological Index

Most lesions regarded as 'traction pathologies' present multiple aetiologies; therefore, it is unwise to interpret them simply as consequences of draught exploitation. Additionally, reporting on the presence or absence of a particular pathology alone is insufficient for effective comparisons, as the severity of the condition should also be considered.

In 1997b, Bartosiewicz et al. established a systematic method that scored the severity of eight osseous modifications on metapodials, and phalanges based on the observation of 18 Romanian draught oxen and seven non-draught young bulls from the same crossbreed. A Pathological Index (PI) was then calculated on each complete element by a suggested formula (Bartosiewicz et al., 1997b: 20). Results highlight that the working group experienced greater PI values than the non-working group; in particular, pronounced exostoses and lipping were observed in the traction herds. It also offers cut-off values for comparisons in archaeological assemblages. This quantifying method has been widely applied to facilitate the study of the earliest use of draught cattle and the changing intensity of such exploitation (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; R. Thomas, 2008; Vann, 2008; Gaastra et al., 2018; Lin et al., 2018; Holmes et al., 2021a,b; Kamjan et al., 2022; Lin, 2022; Pigière and Smyth, 2023; Crabbé et al., 2025). Later, Carlson Dietmeier (2018) proposed a modified PI for recording fragmentary metapodials that assess proximal and distal portions separately, which is more suitable for archaeological material.

The main limitation of the Bartosiewicz et al. (1997b) study is the uneven age of the two samples; the unworked samples were less than two years old, while

the draught oxen were aged beyond six. Additional analyses have been done on mature aurochs autopodia (Johannsen, 2005, 2006), yet modern comparative data are limited. R. Thomas et al. (2021) addressed this issue by investigating a set of non-working Chillingham cattle specimens with known life histories. This study demonstrated several traits from the original method, including exostoses on the proximal and distal metatarsal, distal metacarpals broadening, lipping and exostoses on third phalanges, and exostoses on the distal end of the first phalanges should be excluded as they are significantly related to non-traction-related factors. Nevertheless, it is acknowledged that a relatively small sample size of 15 individuals may lead to inconclusive results. Further study on modern samples is needed before applying this method to archaeological materials to reduce the effect of confounding factors and provide a baseline for comparison.

### 3.2.2 Biometry

Measurements are taken to investigate deformation on metapodials that are potentially associated with the long-term impact of draught works. The premise for this hypothesis is based on theoretical principles associated with bone properties; a detailed discussion is provided in Chapter 4. Various approaches have been applied; Bartosiewicz et al. (1997b) included the measurement of the breadth between the medial and lateral articular crest, medial articular crest and medial trochlea, and the length between the lateral articular crest and the lateral trochlea in the study of Romanian cattle. Allometric equations were calculated based on the measurement of the fused third and fourth metapodials to assess growth rate differences between different herds. The results revealed that the asymmetrical distal condyles in the non-working cows and bulls are more prominent in the forelimb than the hindlimb, whereas draught oxen exhibit a more pronounced asymmetry on metatarsals, which could be attributed to the artificial loads added (Bartosiewicz et al., 1997b: 95).

Likewise, Johnstone and Albarella (2015: 20) measured the widths of individual condyles and the widths at the fusion points of the distal metapodials from an

archaeological site in Essex. The results show that some of the metapodials exhibit pronounced distal splaying, along with other pathologies, indicating that some animals were likely to have been used for draught work. The authors, however, also suggest that there is no single or straightforward method to analyse asymmetry on metapodials. In the most recent study, Lin et al. (2016) identified that measurements of distal breath, greatest breadth from medial condyle ridge to medial articulation edge (e) and antero-posterior diameter of the external trochlea of the medial condyle (1) (see Plates 5.1-5.3 for the location of the measurements) on metapodials yield the most promising result in separating draught cattle from non-working groups. An e/1 shape ratio of 0.75 has been adopted as the benchmark point for indicating draught cattle from archaeological materials (Gaastra et al., 2018; Pigière and Smyth, 2023). However, the rationale behind adopting the value of 0.75 remains unclear.

Apart from metapodials, Helmer et al. (2018) employed the principal component analysis on metric data by measuring the first phalanges of modern draught oxen, non-working bulls, and aurochs. The results indicate distinct clusters between the bulls and oxen, where the latter show higher allometric variations because of phalangal deformations.

Compared to the PI method, biometry could show lower interobserver variability, as the scoring stages on pathological conditions can be subjective. The original study indicates that the scorings of some deformations appear to have low consistency between the three observers Bartosiewicz et al. (1997b: 55–61). Although osteometric approaches provided satisfactory results in detecting working animals, Lin et al. (2016) emphasised that this method may fail to identify cattle used for light traction since measurable alterations do not necessarily occur under light work. Gaastra et al. (2018) later adopted this biometric approach in combination with the PI to examine materials from Western Balkans Neolithic sites; despite Lin et al.'s (2016) warning, they concluded that cattle were exploited for light traction for ad hoc usage.

### 3.2.3 Entheseal Change

#### 3.2.3.1 Enthesis properties

Entheses are areas where muscles, ligaments, tendons, or joint capsules attach to the periosteal surface of bone, functioning as an anchor for connecting tissue to transmit contractile force and provide joint stability during musculoskeletal motions (Benjamin and McGonagle, 2007; Shaw and Benjamin, 2007; Apostolakos et al., 2019). Different terminologies are used in early research to describe modifications of entheses, including enthesopathy (Dutour, 1986), muscle crests (Angel et al., 1987), musculoskeletal stress markers (Hawkey and Merbs, 1995) and markers of occupational stress (Kennedy, 1998). Jurmain and Villotte (2010), however, propose a more neutral term - entheseal changes.

Based on anatomical characteristics, entheses are divided into two categories: the fibrocartilaginous entheses are found in long bone epiphyses or short bones, which are indirectly attached onto the bone surface through a layer of fibrocartilage (Benjamin et al., 2006; Villotte and Knüsel, 2013); and the fibrous entheses, typically attached to the long bone diaphysis or metaphysis (Weiss, 2015). The latter type is subclassified as bone or periosteal attachment, depending on whether the fibrous entheses connect directly to the bone or indirectly via the periosteum (Benjamin et al., 2006). Even though this form of enthesis is associated with the strongest and largest muscle, it is less understood compared to fibrocartilaginous entheses, as irregularities may occur within normal attachment surfaces (Benjamin et al., 2002).

Similar to the biometry approach, the correlation between entheseal change and activity patterns is built on assumptions associated with bone functional adaptation. When repetitive mechanical loading occurs during physical activities, blood flow is increased to the periosteum in response to the stresses, thus, encouraging osteon activity which leads to hypertrophy of bones and alters entheseal morphology (Zumwalt, 2006; Jurmain et al., 2012; Foster et al., 2014). Despite the structural differences between the types of entheses, two forms of observable modifications - osteoblastic and osteolytic can be measured on the

bone cortex to identify activity patterns. The former includes bone formation and increased surface complexity, while erosion, porosity and cavitations are defined as osteolytic characters (Foster et al., 2014; Henderson et al., 2016).

#### 3.2.3.2 Entheseal changes in human remains

Reconstruction activities based on the morphological variations of entheses have been widely adopted in archaeological human remains to reveal occupation (e.g. Eshed et al., 2004; Mateescu, 1975; A. Thomas, 2014), habitual activities (e.g. Dutour, 1986; Lieverse et al., 2009; Karakostis et al., 2018), gender divisions of labour (e.g. Hawkey and Merbs, 1995; Mazza, 2019), handedness (e.g. Wilczak, 1998; al-Oumaoui et al., 2004; Foster et al., 2014), and social hierarchy (e.g. Havelková et al., 2011; Yonemoto, 2016; Refai, 2019). Some promising results have been obtained. For example, a study of ancient Egyptians has revealed variations between workers and high-status officials, in which the former presented more pronounced entheseal changes as they were constantly involved in building constructions, hence receiving more biomechanical stress (Refai, 2019).

Nonetheless, the validity of using enthesis changes as a proxy of past activity is often questioned, as it is a multifactorial process (e.g. Godde et al., 2018; Weiss, 2015). Later studies are, therefore, more concentrated on investigations of documented skeletal collections, attempting to understand the relations between biological factors and variations on entheses. In general, the results indicate that age, sex, body size, genetics, and trauma are all confounding factors to morphological changes (Benjamin et al., 2002; Weiss, 2004; Weiss et al., 2012; Weiss, 2015; Cardoso and Henderson, 2009; Niinimäki and Baiges Sotos, 2013; Milella et al., 2012; Schlecht, 2012). Notably, older individuals exhibit more pronounced changes than their counterparts; Niinimäki and Salmi (2021) and Milella et al. (2012) attribute this strong positive correlation to the cumulative mechanical stress over time. An alternative explanation for the impact of ageing is that osteoblast activity is reduced in older individuals, leading to cortical thinning and increased complexity on bone surfaces (Weiss et al., 2012). However,

work by Yonemoto (2016) has offered a different perspective, suggesting that morphological variations can appear in the same age groups depending on physical activities related to particular occupations.

Sex differences in entheseal changes are commonly observed, with males showing more prominent changes than females. It is argued that the divisions of labour based on gender in past societies may have contributed to the variation. The study of the ancient Eskimo population suggests that males exhibited more pronounced changes in the clavicles and humeri, likely due to their involvement in hunting with the use of a bow and arrow (Hawkey and Merbs, 1995). Nonetheless, Niinimäki (2011) regarded sex dimorphism in body size as the primary reason for pronounced modifications in males. Reverse results are, however, observed in several entheses where females manifest greater changes than males, suggesting variations occur due to activity patterns (Munson Chapman, 1997).

The effect of sex and body weight on entheseal changes is rather complex, as it appears to be tangled with other factors, such as differences in hormonal activity (Weiss et al., 2012). Although it is claimed that testosterone in males promotes greater muscle growth and strength, consequently enhancing bone remodelling (Schlecht, 2012), the direct link between hormone levels is not fully understood. Work on collections with documented history has further revealed that each enthesis reacts differently to external stress. Not only has the baseline for normal fibrous entheses yet to be established, but these features also show stronger correlations with biological factors, with ageing widely regarded as the primary cause of fibrous entheseal changes (Mariotti et al., 2007; Niinimäki, 2011).

#### 3.2.3.3 Entheseal changes in animals bones

Studies on the correlation between entheseal modifications and animal activities are limited. Pioneering research on modern and archaeological Bovinae entheseal changes was demonstrated by Higham et al. (1981), in particular, focusing on the third phalanx. Their findings indicate that the flexor process in draught cattle distal phalanges manifests more prominent changes than in

other attachment sites. This method, nonetheless, has not been adopted by further study. It is possibly due to the fact that the third phalanx is not ideal for reconstructing activity patterns as it is prone to exhibit excessive bone growth even in non-working individuals, and it is difficult to distinguish between the fore- and hindlimbs.

The first *in vivo* experimental study of sheep was attempted by Zumwalt (2006), with results showing no direct causal correlation between entheses morphology and activities. The author, however, has acknowledged that this could be due to the short exercise durations and age of the animals chosen. Analyses of entheseal changes using animal models have been undertaken in various species, such as mice (Rabey et al., 2015) and turkeys (Wallace et al., 2017), suggesting that physical activities affect the internal bone structure but not the morphology of insertion sites. Conversely, Karakostis et al. (2018) and Turcotte et al. (2022) suggested associations between repetitive muscle use and entheseal changes by observing mice in vivo after a period of exercise. These contradictions may show the limitations of experimental research, as the type, intensity and duration of exercise likely influence the outcomes, which does not reflect the real-life situation.

In more recent studies, entheseal changes have been applied to ungulate limb bones to understand past human exploitation activities, mainly focused on horses (Bendrey, 2008; Bindé et al., 2019) and reindeer (Hull et al., 2020; Niinimäki and Salmi, 2016; Niskanen and Bindé, 2021; Salmi et al., 2020). It has been revealed that several entheses differ between captive and free-ranging reindeer, which could be attributed to their distinct feeding behaviour and activity patterns (Niinimäki and Salmi, 2016). However, it should be noted that age and sex were not controlled in this study, and therefore, variations may be contributed by biological factors rather than activity level.

Bendrey (2008) investigated cranial muscle attachment sites in two groups of horses and obtained similar results to research on human skeletons, in which morphological changes of entheses are highly related to age and, to some extent, sexual dimorphism. However, the research does not offer definitive results due

to the small sample size. Moreover, the studied anatomical area may not have been ideal for analysing past activity; although the motion of the head and neck differ based on their life history, working stress has weaker impacts on their modifications compared to the limb regions. Recent research on unworked equids indicates that although older and male individuals are more prone to develop severe changes, some insertions, such as m. infraspinatus and m. flexor digitorum profundus, show no significant differences between age and sex (Bindé et al., 2019). As expected, sex variation also occurs; yet, the results cannot be attributed to divisions of labour since equids were unworked. Body weight and hormonal activities possibly play a part, though it is more likely a reflection of imbalanced age distribution as most stallions are in the older age group.

Promising outcomes are further reported by Salmi et al. (2020) in using the binary logistic regression, which correctly categorises up to $90\%$ (n = 49) of reindeer into working and non-working groups based on entheseal changes from humeri and femurs. In contrast to humans, cavitation and porosity are rare in ungulate entheses (Bindé et al., 2019; Liu, 2021), while textural changes are likely to be normal variations for animals (Niinimäki and Salmi, 2016). Varied results in animals concur with the argument proposed by Ruff et al. (2006) that reactions of bone under mechanical stress differ between species.

A peculiar sheep lesion that shows excessive enthesophytes on the distal humerus and proximal radius is known as a 'penning elbow'. This lesion is suggested to result from husbandry practices where animals were put through pens (Baker and Brothwell, 1980: 127). Holmes et al. (2021c) showed that the prevalence and severity of entheseal changes on radii peaked during the ninth to twelfth centuries, suggesting that this trend can be associated with increased age and shifting husbandry practices; however, the effects of living environments should not be dismissed. Animals living in hilly terrain need to accommodate higher stress levels from repetitive locomotion, leading to substantial changes (Bartosiewicz and Gál, 2013; Holmes et al., 2021c).

Investigations of asymmetry between the left and right sides are often performed in human skeletons. It is noted that bilateral asymmetry of entheseal expressions is more prominent in the upper limbs than the lower limbs because of the preferential use of hands; in contrast, lower limbs tend to be more symmetrical in adopting bipedal locomotion (Ruff, 2000; Drapeau, 2008; al-Oumaoui et al., 2004; Foster et al., 2014). Considering locomotion on quadrupedal ungulates, comparisons of the severity between entheses on the fore- and hindlimbs can identify traction activity as they are structurally and functionally different (further discussed in the next section). The hindlimbs of draught reindeer exhibit higher levels of entheseal modifications than the forelimbs (Niinimäki and Salmi, 2016), while reversed patterns are observed in non-working cattle and sheep (Liu, 2021). These results concur with the idea that the back legs encounter more significant physical stress during draught work to provide forward motions than the forelimbs (Bartosiewicz, 2008). Nonetheless, sample sizes in both studies are small; thus, further research on a larger modern collection is needed before drawing firm conclusions.

The inconsistency between entheseal changes and cross-sectional geometry has put further doubt on the link between entheses and activity patterns. A more recent study on modern reindeer (Niinimäki and Salmi, 2021) has, however, confirmed the association between the two characters and proved that physical work could influence, at least partially, entheses morphology. Prior research on humans and other animals has demonstrated its potential for investigating behavioural patterns, especially when non-activity factors are controlled. Although similar patterns are indicated in ungulates as in humans (i.e. larger and older individuals manifest pronounced modifications), results are not directly comparable because of the anatomical and lifespan differences between species. An additional investigation should be taken to understand the dynamic process of entheseal development in modern cattle and exclude traits strongly associated with confounding factors.

### 3.2.4 Kill-off patterns

Kill-off patterns have been the fundamental zooarchaeological approach for inferring the role of animals within the economy. The high frequency of older animals in an assemblage reflects the possibility of using cattle for draught use. For example, the increased proportion of mature cattle in Roman times compared to the Iron Age indicates the heavy dependence on draught cattle, possibly relating to shifted focus from meat to crop production (Albarella, 2019: 134–54). Similarly, the sex ratio of animals in the assemblage can also be indicative of husbandry strategies. The castration of bulls has been viewed as a way of obtaining more docile and stronger animals for traction work (Bökönyi, 1974). The increased male cattle survivorship in Thessaly, Greece, during the third millennium BC has been interpreted as the result of raising oxen for traction (Halstead, 1987).

Doubts over the mortality model have, however, been raised as it only reflects theoretical assumptions of the optimum patterns for a particular use; thus, it alone cannot validate or disprove the actual presence of traction cattle in the past directly (R. Thomas and Mainland, 2005: 1; Johannsen, 2005: 40; R. Thomas, 2008: 187). Draught cattle exploitation is a diverse phenomenon; as a result, no single fixed mortality pattern can reflect the past practices in all circumstances (R. Thomas, 2008; Johannsen, 2011: 17; R. Thomas et al., 2021). Additionally, applying mortality evidence to ascertain the use of draught animals could be particularly problematic in early prehistoric contexts. It is argued that age models are less effective in detecting non-specialised and low-intensity use of working cattle (Isaakidou, 2006: 108). A false assumption may therefore be created that cattle labour was absent in the small-scale agrarian economies in Neolithic societies by applying this approach, as herds were not dominated by working animals (Johannsen, 2005: 43).

Ageing data are, nonetheless, vital for understanding husbandry strategies, as they contribute to more robust interpretations when used alongside other osteological evidence. However, ageing alone should not be regarded as direct

evidence for the use of animals in traction. Works by Isaakidou (2006: 108, 2008: 96) at Knossos (Crete) demonstrated the benefit of employing mortality patterns along with pathological data and indicate that cattle, mainly females, were exploited for draught power from the Neolithic as most lesions appear on the pelves of adult cows. In addition, although no related pathologies were observed on sexable elements, the increased number of mature oxen in the Late Bronze Age led to the hypothesis that cattle had become more intensively employed for specialised traction use (Isaakidou, 2006: 106). These works support the view that kill-off patterns, though informative, require cautious interpretation alongside other osteological data.

The interpretations of osteological conditions as activity markers are not straightforward. Morphological changes and pathologies are most likely a consequence of mixed effects; thus, applying combinations of approaches can help to avoid misinterpretations. Additionally, previous works (e.g. Lin et al., 2016; R. Thomas et al., 2021) have demonstrated the importance of analysing modern collections with known life histories to understand the potential factors unrelated to traction stress that may impact bone modifications before applying the same methods to archaeological materials.

# 4

# MORPHOLOGICAL CHANGES IN DRAUGHT ANIMAL: THEORETICAL PRINCIPLES

## Contents


**4.1 Bone biology** . . . . . **53**
**4.2 Adaptation to mechanical stress** . . . . . **55**
**4.3 Mechanical loading and body parts** . . . . . **57**


Bone is a responsive living tissue that can accommodate dynamic mechanical environments by adjusting its internal structure and external shape. This principle is the basis for studying skeletal modifications to reconstruct past activity patterns. The following chapter provides an overview of bone biology and our current understanding of its abilities to respond to mechanical stress, and the impacts of mechanical loading on different body parts.

## 4.1 Bone biology

### 4.1.1 Bone cells

Three key types of bone cells, osteoblasts, osteoclasts, and osteocytes, are involved in the maintenance, growth and replacement of osseous tissue. Osteoblasts are responsible for producing unmineralised osteoid; the matrix is then calcified to form bone (Mays, 2021: 6). Conversely, the function of osteoclasts is to resorb and dissolve the mineralised bone matrix by secreting acid (Trammell

and Kroman, 2013: 363). Osteocytes originate from osteoblasts and are trapped in the mineralised matrix to maintain bone density (Aarden et al., 1994). This type of cell is critical to the initiation of the remodelling process, regulating the osteoblast and osteoclast activation in response to mechanical stimuli (Bonewald, 2011; Lerner, 2012; Bellido, 2014).

### 4.1.2 Bone modelling

Skeletal modelling involves the bone formation and subsequent maintenance during growth on both the periosteal and endosteal surfaces (Frost, 1982; R. B. Martin et al., 2015: 96). The goal of modelling is to produce a bone with a practical and functional shape for an adult by the independent action of osteoclasts and osteoblasts (Trammell and Kroman, 2013: 363; R. B. Martin et al., 2015: 97). The process of moving bone cells through tissue space to adjust bone morphology and mass for adaptation purposes is referred to as 'modelling drift' (Frost, 1987; Robling and Stout, 2008: 150). The formation drifts control new osteoblasts to build lamellar bone over broad bone surfaces, whereas resorption drifts regulate osteoclasts to remove bone from the surfaces (Miller, 2003).

Bone modelling not only controls the development of bone morphology during foetal life and childhood but also alters bone architecture in the changing mechanical environment (Jee, 2001: 1–25). The modelling process is turned on when strain thresholds are exceeded, increasing bone mass and strength until strain levels return to the threshold range (Frost, 1997).

### 4.1.3 Bone remodelling

Remodelling occurs over the lifespan by constant resorption and deposition of bone to protect skeletal integrity. The remodelling process involves the coordination of osteoblasts and osteoclasts to remove older bone and form secondary bone in the temporary structure-basic multicellular unit (Jee, 2001: 1–27; Robling and Stout, 2008: 151). In contrast to modelling, bone remodelling takes place in a specific location in sequential order, following the Activation–Resorption–Formation

cycle (Henriksen et al., 2009; Trammell and Kroman, 2013: 366). Secondary osteons are formed when osteoblasts deposit new bone, replacing the primary bone and repairing accumulated micro-damage in daily activities (R. B. Martin, 2003; Robling and Stout, 2008: 152). The bone remodelling process is known to be affected by intrinsic factors such as age, sex hormones, genetics, and environmental factors (e.g. Carter, 1998; Miller, 2003; Cowin, 2001; Kenkre and Bassett, 2018; Bolamperti et al., 2022).

## 4.2 Adaptation to mechanical stress

The ability of bones to adjust their structure in response to alterations in mechanical loading is a form of somatic adaptation, which involves modifications of body form without genetic changes, and is essential for survival (R. B. Martin et al., 2015: 280). Wolff (1892; translation in Wolff, 1986) proposed a mathematical rule to describe the nature of bone remodelling under stress, indicating that the internal architecture of the trabeculae bone accommodates stress from repetitive biomechanical loading, which leads to the formation of more robust structures to resist the strain. 'Wolff's Law' has been criticised for its inaccuracy due to biological misconceptions; it assumes bones to be linearly elastic, homogeneous, and isotropic materials, which is not true for cancellous bone (Cowin, 2001: 30–10). Nonetheless, the basic premise, namely, bone adapts to the changing mechanical environment through structural modifications, is accepted (Cowin, 2001: 30–2; Ruff et al., 2006; Rhode, 2013: 205). Later, it is suggested to apply 'bone functional adaptation' to describe this general concept (Ruff et al., 2006). When bones experience a sufficient level of sensible strain, osteogenic cells are activated to create four possible outcomes, including no changes due to the low intensity, modelling, resorption by osteoclasts and Haversian remodelling within the cortical bone (Pearson and Lieberman, 2004).

Metapodials of ruminants comprise the third (medial) and fourth (lateral) portions, providing two separated distal condyles. The medial condyle is slightly wider than the lateral one, whereas the lateral condyle is longer as most of

the body weight is centred on the medial half (Bartosiewicz et al., 1993, 1997b: 91; Páral et al., 2004; Nacambo et al., 2007). The mediolateral variations on distal metapodials are further reflected in bone mineral content, as the density of the third metapodials increases with body weight in cattle (Bartosiewicz et al., 1993). When comparing the measurements of metapodials between non-working bulls, cows, and draught oxen, the last group shows the most pronounced asymmetry, particularly in the metatarsals (Bartosiewicz et al., 1993, Tab. 3) . This suggests that artificial loading from traction may lead to the development of wider medial condyles.

Repetitive use of muscle through physical activities produces more strain on the bone; bone cell activities are stimulated in response to the stress, strengthening the structure to prevent breakage (Ruff et al., 2006; Weiss, 2014: 33). Some scholars attribute the correlation of enthesal changes and activities to this phenomenon. Increasing the blood flow to the periosteum due to the pull stress of muscle use, in return, encourages osteoblastic and osteolytic processes, leading to bone formation and erosions on entheses (Cashmore and Zakrzewski, 2013; Hawkey and Merbs, 1995). While it is also suggested that entheseal changes may reflect continual microtrauma induced by the overuse of muscles in habitual activities, particularly on fibrocartilaginous sites, contributing to the observable modifications on dry bones (Benjamin et al., 2002; Villotte and Knüsel, 2013; Weiss, 2015). Regardless of the mechanism of the modifications, prior studies on dry bone and in vivo animal models have confirmed a positive link between frequency of muscle use and bone remodelling, hence entheseal changes (Benjamin et al., 2002; Karakostis et al., 2019).

Although remodelling is a continuous process, its rate is reduced along with age. The most pronounced impact of mechanical loading on bone morphology occurs during the development period before maturity (Mays, 2001); thus, variations observed in mature bone may largely reflect habitual activities practised within late adolescence to early adulthood (Ruff et al., 2006; Rhode, 2013: 205). In the ethnographic study, Johannsen (2011: 16) observed that animals are commonly

involved in draught training at the age of two to three, which is also parallel to historical documentation for Britain; yet, it can be varied based on individual preferences and depending on the maturity age of the draught cattle. Modern multipurpose cows and oxen can be used for draught work beyond 15 years old (Bartosiewicz et al., 1997b); however, these data may not directly indicate situations in the past. The modifications observed on fused elements can be hypothesised as a reflection of traction use.

## 4.3 Mechanical loading and body parts

Skeletal structures with a primary role in weight-bearing are profoundly affected by mechanical use. Functional and structural differences are observed in the front and back limbs of ungulates for accommodating the quadrupedal motions, where the forelimbs bear a greater share of body weight than hindlimbs, reaching up to $65\%$ in fully grown bulls (Bartosiewicz et al., 1997b: 13). When artificial loading is added, force transmission is concentrated at the rear of the body, relying upon the hindlimbs to provide forward motion power (Bartosiewicz, 2008: 156).

Pathology studies in cattle and aurochs autopodium indicate that forelimb elements are more likely to have more severe lesions than those from the back due to unequal weight distribution (Telldahl, 2005; Johannsen, 2006; R. Thomas et al., 2021). In contrast, the PI value on the hindlimbs was higher than on the forelimbs in seventh-century England, which has been suggested to coincide with the increased proportion of males, thus a greater emphasis on power exploitation (Holmes et al., 2021a). An identical pattern is noted in the fourteenth century at Dudley Castle, by the time cattle had been exploited intensively for traction power (R. Thomas, 2008). The contradicted patterns between worked and non-working animals are also observed in entheseal studies of reindeer and cattle (Niinimäki and Salmi, 2016; Liu, 2021). The variation between two sets of limbs has yielded promising results in distinguishing possible traction animals, as it is primarily associated with the uneven distribution of loading across different body parts.

Further analysis of modern collections is, however, required to confirm this assumption since most of the previous studies focus on archaeological materials.

# 5

# DEVELOPING A NEW METHOD TO IDENTIFY DRAUGHT CATTLE BASED ON MODERN DATA

## Contents


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## 5.1 Introduction

This chapter aims to answer the first sub-question in this thesis: *How can draught animals be identified in archaeological assemblages?*

Prior osteological approaches adopted for identifying draught cattle have been discussed with their limitations in Section 3.2. The major challenge of osteological methods is that pathologies and morphological alterations are mostly multifactorial in origin. To address this problem, analysing modern cattle with known life histories enables clarification of the association between non-traction-related internal factors and skeletal modifications. Three key objectives are outlined through the study of modern materials:

- Analyse the relationship between confounding variables (i.e. age, sex, and body weight) and bone modifications.
- Develop a new biometric method to identify draught cattle. This method will be later used to classify unknown archaeological specimens.
- Understand the morphological and pathological variations between the fore- and hindlimbs.

## 5.2 Materials

### 5.2.1 Draught oxen

Biometric and pathological data of Romanian draught cattle were derived from the literature (Bartosiewicz et al., 1997b; Lin et al., 2016). This collection comprises 18 Grey and Brown oxen, ranging from six to 19 years old. The life histories of each individual are listed in Table 5.1. Unfortunately, only the metapodials and phalanges were collected, while other long bones were missing, making analysis of entheseal changes unavailable.

Table 5.1: List of modern draught oxen and their information.

| ID. | Age (year) | Weight (kg) | Sex | Breed |
|---|---|---|---|---|
| 91.107.M1 | 6 | 450 | Castrated | Romanian Grey x Brown |
| 91.107.M2 | 8 | 482 | Castrated | Romanian Grey x Brown |
| 91.107.M3 | 10 | 674 | Castrated | Romanian Grey x Brown |
| 91.107.M4 | 14 | 662 | Castrated | Romanian Grey x Brown |
| 91.107.M5 | 6 | 460 | Castrated | Romanian Grey x Brown |
| 91.107.M6 | 19 | 449 | Castrated | Romanian Grey x Brown |
| 91.107.M7 | 14 | 450 | Castrated | Romanian Grey x Brown |
| 91.107.M8 | Unknown | Unknown | Castrated | Romanian Grey x Brown |
| 91.107.M9 | 12 | 478 | Castrated | Romanian Grey x Brown |
| 91.107.M10 | 9 | 780 | Castrated | Romanian Grey x Brown |
| 91.107.M11 | 8 | 850 | Castrated | Romanian Grey x Brown |
| 91.107.M12 | 9 | 650 | Castrated | Romanian Grey x Brown |
| 91.107.M13 | 8 | 501 | Castrated | Mixed breed of Romanian Grey |
| 91.107.M14 | 10 | 515 | Castrated | Mixed breed of Romanian Grey |
| 91.107.M22 | Unknown | Unknown | Castrated | Romanian Grey x Brown |
| 91.107.M23 | Unknown | Unknown | Castrated | Romanian Grey x Brown |
| 91.107.M24 | Unknown | Unknown | Castrated | Romanian Grey x Brown |
| 91.107.M25 | Unknown | Unknown | Castrated | Romanian Grey x Brown |

### 5.2.2 Non-draught cattle

The modern non-draught cattle group used in this study is composed of 151 animals encompassing diverse species and breeds from four modern skeletal reference collections (Table 5.2) (see Appendix A for more details):

1. Bone Laboratory of the University of Leicester (UK) (5 individuals)
2. Museum für Haustierkunde Julius Kühn of the Martin Luther University of Halle-Wittenberg (Germany) (hereafter referred to as the Julius Kühn collection) (126 individuals)
3. The Natural History Museum, London (UK) (17 individuals)
4. Zooarchaeology Laboratory of the University of Sheffield (UK) (3 individuals)

As mentioned in Section 4.3, due to the substantial loading effect on the weight-bearing elements, the humerus, ulna-radius, femur, tibia, metapodials, and phalanges were recorded. For this study, only the left long bones were recorded; when absent, the right elements 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.

Separation of anterior and posterior phalanges followed Dottrens (1946) when information was not provided. All the elements analysed were fully fused. The third phalanx was omitted from this study for two reasons. First, this element is more prone than the other two phalanges to extra bone growth even in non-working cattle. Second, the lack of fusion points makes the age attribution for this element uncertain.

The age at death was known for the 77 cattle analysed in this study. For 36 of them, in the absence of direct records, age was assessed based on tooth eruption and wear for dP4, P4, and the molars. Mandibular tooth wear stages

were recorded following (Grant, 1982). Additionally, some of the tooth wear stages in the Julius Kühn collection were referenced from Wimmer (2018). Estimation of the numerical age was based on G. G. Jones and Sadler's (2012) analyses.

Sex data were not documented for five Chillingham cattle in the Natural History Museum (London). However, no attempt has been made to estimate the sex due to the absence of the pelvis. Not all cattle skeletons are complete.

All data analyses were conducted using RStudio version 2023.03.1+446 with R version 4.2.1. Non-parametric tests were applied due to the small sample size and the potential non-normal distribution of the data. These tests do not assume normality and are more appropriate when parametric test assumptions cannot be met, ensuring more reliable and valid results despite limited data.

Table 5.2: Distribution of sex and type/breed/species of the modern non-draught cattle.

| Type/Breed/Species | Castrated male | Female | Male | Unsexed | Total |
|---|---|---|---|---|---|
| American bison (*Bison bison*) | - | 1 | 1 | - | 2 |
| Angeln | - | 2 | - | - | 2 |
| Ansbach-Triesdorfer | - | 1 | - | - | 1 |
| Ayrshire | - | 1 | - | - | 1 |
| Banteng (*Bos javanicus*) | - | 1 | - | - | 1 |
| Breitenburger | - | 4 | - | - | 4 |
| Butjadinger | - | 1 | - | - | 1 |
| Charolais | - | 1 | - | - | 1 |
| Chartley | - | - | 3 | - | 3 |
| Chillingham | - | 8 | 4 | 5 | 17 |
| Devon | - | 4 | - | - | 4 |
| Devon crossbreed[1] | - | 1 | 1 | - | 2 |
| European bison (*Bison bonasus*) | - | 1 | - | - | 1 |
| Egerländer | - | 1 | - | - | 1 |
| Fjäll | - | 1 | - | - | 1 |
| Fribourgeoise | - | 1 | - | - | 1 |
| Galloway | - | 1 | 1 | - | 2 |
| Guernsey | - | 1 | - | - | 1 |
| Guernsey crossbreed[1] | - | 1 | - | - | 1 |
| Haderslebener | - | 1 | - | - | 1 |
| Harzer | - | 1 | - | - | 1 |
| Hereford | - | 1 | - | - | 1 |
| Holländer | - | 4 | 1 | - | 5 |
| Holländer crossbreed[1] | 1 | 3 | 1 | - | 5 |
| Holstein Friesian | - | 5 | - | - | 5 |
| Holstein Friesian crossbreed[1] | - | 1 | - | - | 1 |
| Hungarian Grey | 1 | - | - | - | 1 |
| Jersey | 1 | 8 | 1 | - | 10 |
| Jersey crossbreed[1] | - | - | 1 | - | 1 |
| Jeverländer | - | 1 | - | - | 1 |
| Kerry | - | 1 | 1 | - | 2 |
| Kerry crossbreed[1] | - | 2 | 1 | - | 3 |
| Longhorn | - | 3 | 1 | - | 4 |
| Murbodener | - | 1 | - | - | 1 |
| Normande | - | - | 1 | - | 1 |
| Ostpreußisches Landrind | - | 1 | - | - | 1 |
| Podolian | - | 1 | 1 | - | 2 |
| Podolian crossbreed[1] | - | 1 | 1 | - | 2 |
| Prättigauer | - | 3 | - | - | 3 |
| Schwyzer | - | 2 | - | - | 2 |
| Shorthorn | - | 4 | - | - | 4 |
| Shorthorn crossbreed[1] | - | 9 | 16 | - | 25 |
| Silesian Red | - | 1 | - | - | 1 |
| Simmental | - | 2 | - | - | 2 |
| Simmentaler crossbreed[1] | - | 1 | - | - | 1 |
| Unknown | - | 7 | 1 | - | 8 |
| Vogelsberger | - | 2 | - | - | 2 |
| Vogtländer | - | 1 | - | - | 1 |
| Watussi | - | 1 | - | - | 1 |
| Westerwälder | - | 2 | - | - | 2 |
| Wilstermarscher | - | 2 | - | - | 2 |
| Yak (*Bos grunniens*) | - | - | 1 | - | 1 |
| Zebu crossbreed[1] | - | 1 | - | - | 1 |
| Romanian Grey and Brown (non-draught)[2] | - | - | 6 | - | 6 |
| **Total** | 3 | 105 | 44 | 5 | 157 |

[1] For the crossbred cattle, only the breed of sire was documented.
[2] Data obtained from Bartosiewicz et al. (1997b).

## 5.3 Methods in modern materials

Four osteological approaches were adopted to provide comprehensive analyses and allow comparisons of effectiveness between different methods—Table 5.3 presents the recorded anatomical elements and their related methods.

Table 5.3: Anatomical elements recorded and their related methods.

| Element | Methods applied |
|---|---|
| Humerus | Entheseal changes |
| Radius-Ulna | Entheseal changes |
| Metacarpal | Pathological Index, Biometry |
| Femur | Entheseal changes |
| Tibia | Entheseal changes |
| Metatarsal | Pathological Index, Biometry, Spavin |
| Phalanx 1 and 2 | Entheseal changes, Pathological Index |

### 5.3.1 Spavin

The pathological fusion of the tarsals to the metatarsals was recorded on the basis of presence or absence.

### 5.3.2 Pathology Index (PI)

The recording of PI value followed Bartosiewicz et al. (1997b), focusing on scoring the severity of eight modifications on metapodials and phalanges (for descriptions of each trait, see Table 5.4). Most traits are graded on a four-point scale: Grade 0 refers to normal conditions without deformations, while Grade 4 indicates extreme modifications. Several features, such as proximal lipping and distal depression on metapodials, are measured with a three-point scale, whereas eburnation, striation, fusion of the second metacarpal, and striated facet are recorded on a presence or absence basis (Table 5.4). The score for an individual element can then be calculated by Equation 5.1 (Bartosiewicz et al., 1997b: 20):

$$\mathrm{PI} = \frac{\text{sum of scores} - \text{number of variables}}{\text{maximum score} - \text{number of variables}} \tag{5.1}$$

Thus, for example, the calculation of a metacarpal PI will be:

$$\text{Metacarpal PI} = \frac{\text{sum of scores} - 9}{17} \tag{5.2}$$

Table 5.4: Recording protocol of the Pathological Index (Bartosiewicz et al., 1997b).

| Code | Trait | MC | MT | PH1 | PH2 | Description |
|---|---|---|---|---|---|---|
| pex | Proximal exostosis | 1-4 | 1-4 | 1-4 | 1-4 | The formation of new, abnormal, osseous tissue on the proximal articular surface |
| plip | Proximal lipping | 1-3 | 1-3 | 1-4 | 1-4 | Functional extension of the articular surface by excess bone formation on the proximal articular surface |
| dex | Distal exostosis | 1-4 | 1-4 | 1-4 | 1-4 | The formation of new, abnormal, osseous tissue on the distal articular surface |
| brd | Distal broadening | 1-4 | 1-4 | - | - | Broadening of the distal epiphysis of metapodials |
| depr | Distal depression | 1-3 | 1-3 | - | - | Depressions on the lower third of the palmar/plantar surface of the metapodials |
| peb | Proximal eburnation | 1-2 | 1-2 | 1-2 | 1-2 | Eburnation on the proximal articular surface |
| deb | Distal eburnation | 1-2 | 1-2 | 1-2 | 1-2 | Eburnation on the distal articular surface |
| str | Striation | - | 1-2 | - | - | Transverse striations on the medio-proximal surface of metatarsals |
| fus | Fusion | 1-2 | - | - | - | Fusion of the second metacarpal to the medial side of the third metacarpal |
| facet | Proximal facet | 1-2 | - | - | - | Striations on the small triangular facet below the volar edge of the proximal surface |
| **Total minimum score** | | 9 | 8 | 5 | 5 | |
| **Total maximum score** | | 26 | 24 | 16 | 16 | |

MC = Metacarpal; MT = Metatarsal; PH1 = First phalanx; PH2 = Second phalanx.

### 5.3.3 Biometry

Measurements were taken in millimetres by callipers, with one decimal place on metapodials and phalanges, following von den Driesch (1976), S. Davis (1992) and Lin et al. (2016) (Table 5.5 and Plates 5.1–5.3). Metapodial lengths were measured in a measuring box, disregarding decimal points.

Table 5.5: Measurements taken on each element.

| Element | | Measurement | Reference |
|---|---|---|---|
| Metapodial | GL | Greatest length | von den Driesch (1976) |
| | Bd | (Greatest) breadth of the distal end | von den Driesch (1976) |
| | DD | (Smallest) depth of the diaphysis | von den Driesch (1976) |
| | Bp | (Greatest) breadth of the proximal end | von den Driesch (1976) |
| | SD | Smallest breadth of the diaphysis | von den Driesch (1976) |
| | BatF | Maximum breadth of distal fusion point | S. Davis (1992) |
| | a | Medio-lateral width of the medial condyle | S. Davis (1992) |
| | b | Medio-lateral width of the lateral condyle | S. Davis (1992) |
| | c | Greatest breadth of the medial condyle on the palmar side | Lin et al. (2016) |
| | d | Greatest breadth of the lateral condyle on the palmar side | Lin et al. (2016) |
| | e | Greatest breadth from medial condyle ridge to medial articulation edge | Lin et al. (2016) |
| | f | Greatest breadth from lateral condyle ridge to lateral articulation edge | Lin et al. (2016) |
| | 1 | Antero-posterior diameter of the external trochlea of the medial condyle | S. Davis (1992) |
| | 2 | Antero-posterior diameter of the verticillus of the medial condyle | S. Davis (1992) |
| | 3 | Antero-posterior diameter of the internal trochlea of the medial condyle | S. Davis (1992) |
| | 4 | Antero-posterior diameter of the external trochlea of the lateral condyle | S. Davis (1992) |
| | 5 | Antero-posterior diameter of the verticillus of the lateral condyle | S. Davis (1992) |
| | 6 | Antero-posterior diameter of the internal trochlea of the lateral condyle | S. Davis (1992) |
| | 7 | Depth of the most medial edge of the medial condyle | Lin et al. (2016) |
| | 8 | Depth of the most lateral edge of the medial condyle | Lin et al. (2016) |
| | 9 | Depth of the most medial edge of the lateral condyle | Lin et al. (2016) |
| | 10 | Depth of the most lateral edge of the lateral condyle | Lin et al. (2016) |
| Phalanx 1 and 2 | GL | Greatest length | von den Driesch (1976) |
| | Bd | (Greatest) breadth of the distal end | von den Driesch (1976) |
| | Bp | (Greatest) breadth of the proximal end | von den Driesch (1976) |
| | Dp[1] | Depth of the proximal end | von den Driesch (1976) |
| | SD | Smallest breadth of the diaphysis | von den Driesch (1976) |
| | GLpe[2] | Greatest length of the peripheral (abaxial) half | von den Driesch (1976) |

[1] Dp in the first and second phalanx follows von den Driesch's (1976: 99) description for equids.
[2] GLpe in the second phalanx is equivalent to the GL measurement in von den Driesch (1976: 98).

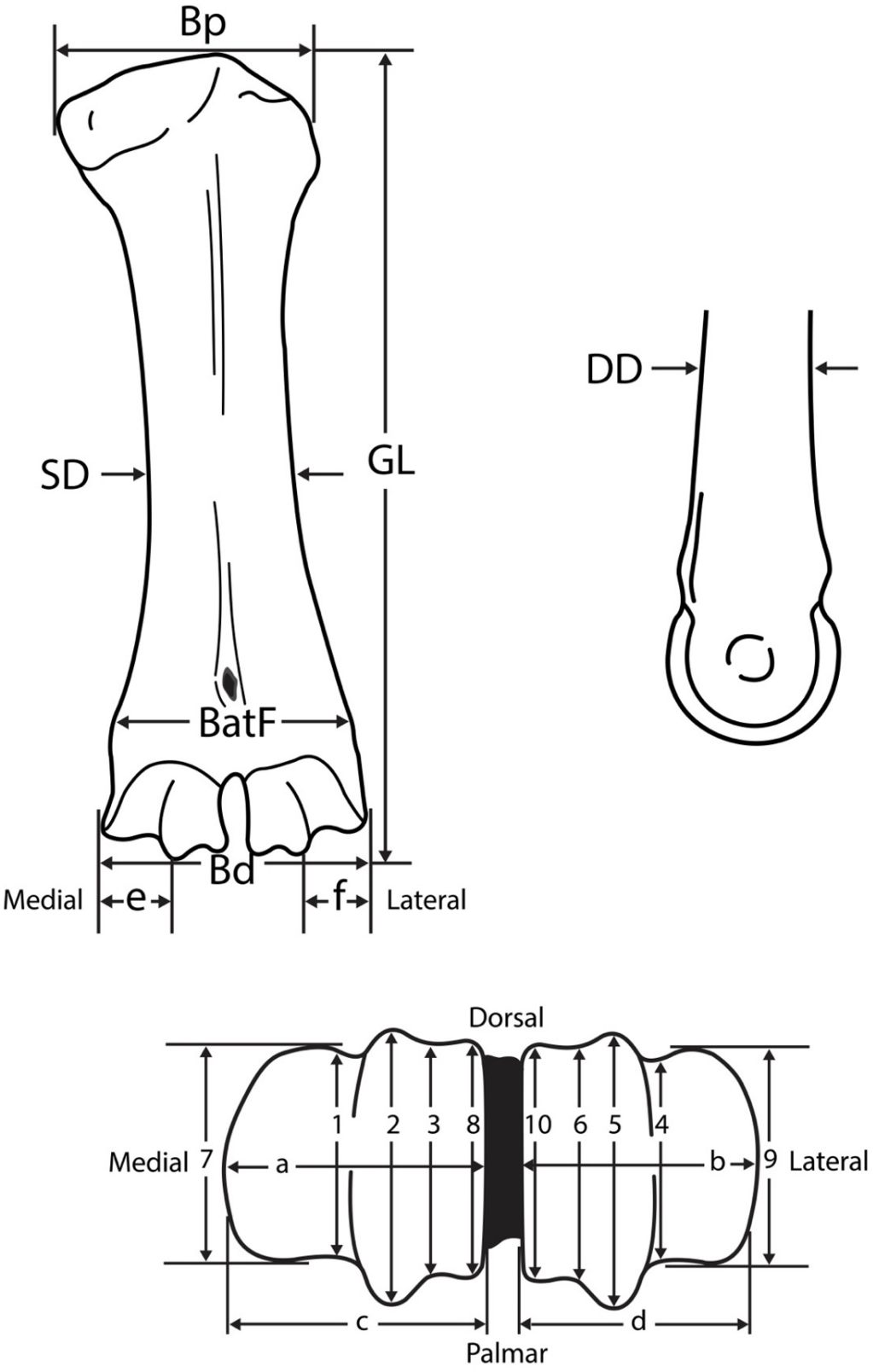



Plate 5.1: Locations of measurement taken on metapodials.

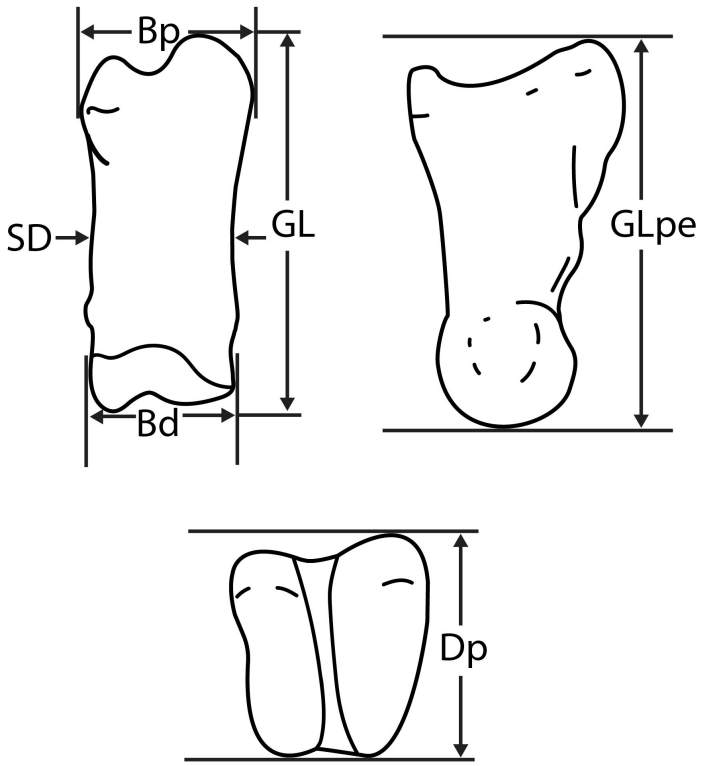



Plate 5.2: Locations of measurement taken on the first phalanx.

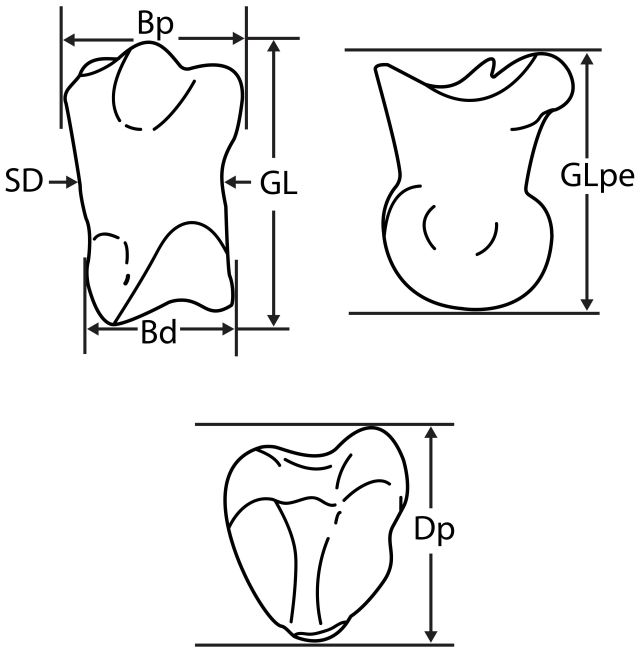



Plate 5.3: Locations of measurement taken on the second phalanx.

### 5.3.4 Entheseal changes

The recording of cattle entheseal changes was modified from methods developed for human remains (Mariotti et al., 2004; Henderson et al., 2013, 2016). Approaches introduced by Hawkey and Merbs (1995) and the Mariotti Method (Mariotti et al., 2004, 2007) are frequently adopted in the earlier research on human entheses; both involve an ordinal scale, applying to fibrous and fibrocartilaginous entheses. While anatomical structure differences between the two types of enthesis have become clearer, a scoring system that does not distinguish between enthesis types should be avoided (Benjamin et al., 2002; Villotte et al., 2009). In addition, a recent study indicates a high interobserver error rate and low reproducibility using the Hawkey and Merbs method (C. B. Davis et al., 2013).

A recently developed Coimbra method focuses only on the fibrocartilaginous entheses, dividing each site into two zones: zone 1 refers to the margin of the attachment surfaces, while zone 2 is the rest of the surfaces (Henderson et al., 2013, 2016). Nonetheless, a standard measurement of fibrous entheses has yet to be developed due to an ambiguous 'no change' baseline and insufficient anatomical descriptions (Villotte and Knüsel, 2013; Villotte et al., 2016). It is therefore suggested to retain the Mariotti method for fibrous regions and the Coimbra method for fibrocartilaginous sites, where the outcomes from the two methods are comparable (Palmer et al., 2019).

The scoring of entheseal changes is considered subjective for capturing continuous change on an ordinal scale (Zumwalt, 2006). However, further analyses of collections with known life history, which provide a detailed description of stages accompanied by photographs, have demonstrated improvement. The level of interobserver agreement reached $71.8\%$ by using the Coimbra method in human remains (Henderson et al., 2013), with higher reproducibility than other methods tested by C. B. Davis et al. (2013). A modified approach is applied to equids, showing interobserver reliability of up to $80\%$ (Bindé et al., 2019). Similarly, the Mariotti Method reveals a low intra- and interobserver error of less than $5\%$ (Mariotti et al., 2004).

Six features are measured in the Coimbra method: bone formation, erosion, textural change, fine porosity, macro-porosity and cavitation. While applying this method to ungulates, researchers noticed that textural modifications appeared to be a normal variation of attachment surfaces on horses and reindeer (Niinimäki and Salmi, 2016; Bindé et al., 2019).

As enthesis types in cattle are rarely discussed, the differentiation between fibrocartilaginous and fibrous entheses was based on human anatomy (Benjamin and McGonagle, 2001; Rhode, 2013: 204). Twenty-eight fibrocartilaginous and four fibrous attachment sites were selected as they are associated with muscles and ligaments used in locomotion (Table 5.6; Plate 5.4-5.9). In the preliminary study on cattle entheseal changes, non-specific scaling was applied to all entheses (Liu, 2021), failing to capture the variability of different insertion sites. Therefore, one of the objectives of studying the modern collection is to establish a new grading system for each enthesis independently.

Bone formation was scored for each attachment site on a three-point scale. Plate 5.10 shows the grading illustrations of teres minor (see Appendix C for the complete list of plates).

- Grade 1: No modification or slightly raised margin < 1 mm.
- Grade 2: Bone formation on less than $50\%$ of the area; distinctive ridge, raised margin < 1 mm.
- Grade 3: Bone formation on more than $50\%$ of the area; clear distinctive ridge, raised margin > 1 mm.

Table 5.6: List of entheses examined in modern cattle.

| Element | Type | Muscle/Ligament | Code | Location | Primary action |
|---|---|---|---|---|---|
| Humerus | FCE | Teres minor (I) | HTI | Proximal to the deltoid tuberosity | Shoulder flexion |
| | FCE | Infraspinatus (I) | HIE | Greater tubercle | Abduction and lateral rotation of the arm |
| | FCE | Subscapularis (I) | HSC | Crest of the lesser tubercle | Extension of the shoulder joint |
| | FCE | Extensor digitorum communis (O) | HDL | Lateral epicondyle | Digital extension and carpal extension |
| | FCE | Flexor digitorum profundus (O) | HDS | Medial epicondyle | Digital flexion and carpal flexion |
| | FE | Deltoideus (I) | HDT | Deltoid tuberosity | Shoulder flexion |
| | FE | Teres major (I) | HTM | Teres major tuberosity | Shoulder joint flexion |
| | FCE | Flexor carpi radialis (O) | HFR | Medial humeral epicondyle | Carpal extension |
| | FCE | Flexor carpi unlaris (O) | HFU | Medial humeral epicondyle | Carpal flexion |
| Radius-Ulna | FCE | Anconeus (I) | UAN | Lateral olecranon | Elbow extension |
| | FCE | Flexor digitorum profundus (O) | UDP | Medial olecranon | Digital flexion, carpal flexion and fetlock flexion |
| | FCE | Biceps brachii (I) | UBB | Radial tuberosity | Elbow flexion and shoulder extension |
| | FCE | Brachialis anticus (I) | UBA | Medial surface of the proximal end | Elbow flexion |
| Tibia | FE | Semimembranosus (I) | TSB | Medial condyle | Hip and stifle extension |
| | FE | Gracilis (I) | TSG | Medial aspect of tibial crest | Limb adduction |
| | FCE | Popliteus (I) | TPS | Caudoproximal surface | Stifle flexion |
| Femur | FCE | Gluteus profundus (I) | FGP | Greater trochanter | Hip abduction |
| | FCE | Iliopsoas (I) | FIP | Lesser trochanter | Hip joint flexion and supination |
| | FCE | Gastrocnemius caput laterale (O) | FGS | Lateral supracondylar tuberosity | Hock extension |
| | FCE | Gastrocnemius caput mediale (O) | FGM | Medial supracondylar tuberosity | Hock extension |
| First phalanx | FCE | Lateral collateral metacarpophalangeal/ metatarsophalangeal ligament | P1LC | Distal end of the lateral insertion tubercle | metacarpophalangeal/ metatarsophalangeal joint stabilisation |
| | FCE | Medial collateral metacarpophalangeal/ metatarsophalangeal ligament | P1MC | Distal end of the medial insertion tubercle | metacarpophalangeal/ metatarsophalangeal joint stabilisation |
| | FCE | Lateral collateral proximal interphalangeal ligament | P1LP | Proximal end of the lateral insertion tubercle | Interphalangeal joint stabilisation |
| | FCE | Medial collateral proximal interphalangeal ligament | P1MP | Proximal end of the medial insertion tubercle | Interphalangeal joint stabilisation |
| | FCE | Proximal digital annular ligament | P1PA | Posterior of the medial surface | Digital flexion |
| | FCE | Distal digital annular ligament | P1DA | Posterior of the lateral surface | Digital flexion |
| Second phalanx | FCE | Lateral interphalangeal proximal collateral ligament | P2LP | Distal end of the lateral insertion tubercle | Interphalangeal joint stabilisation |
| | FCE | Medial interphalangeal proximal collateral ligament | P2MP | Distal end of the medial insertion tubercle | Interphalangeal joint stabilisation |
| | FCE | Lateral interphalangeal distal collateral ligament | P2LC | Proximal end of the lateral insertion tubercle | Interphalangeal joint stabilisation |
| | FCE | Medial interphalangeal distal collateral ligament | P2MC | Proximal end of the medial insertion tubercle | Interphalangeal joint stabilisation |
| | FCE | Extensor digitorum communis (I) | P2ED | Proximal end of anterior surface | Digital and carpal extension |

FCE = fibrocartilaginous enthesis; FE = fibrous enthesis; I = insertion; O = origin.

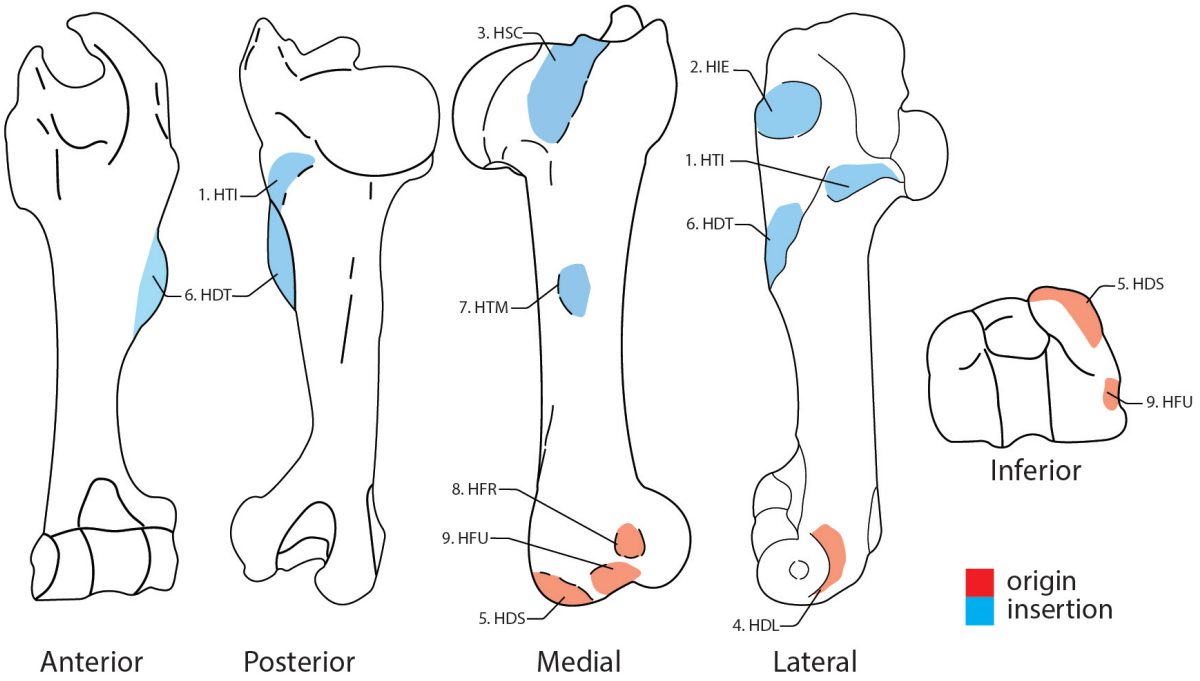



Plate 5.4: Locations of enthesis on the humerus.

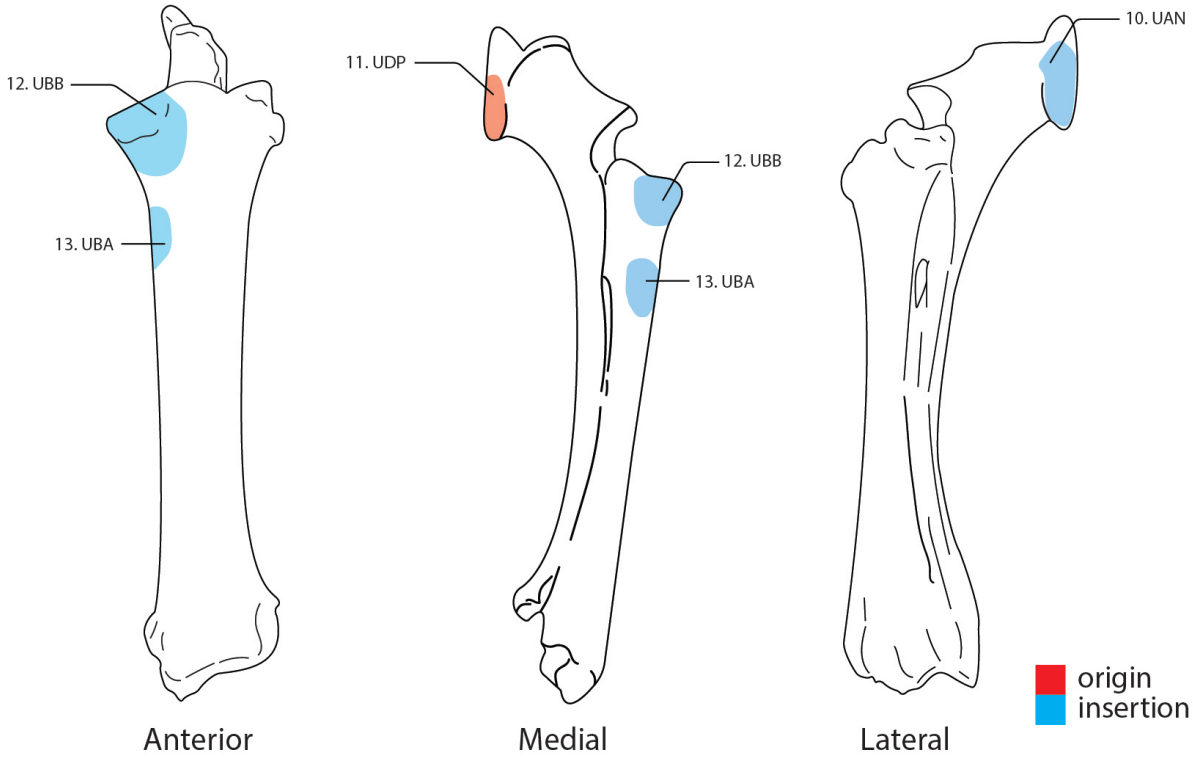



Plate 5.5: Locations of enthesis on the radius-ulna.

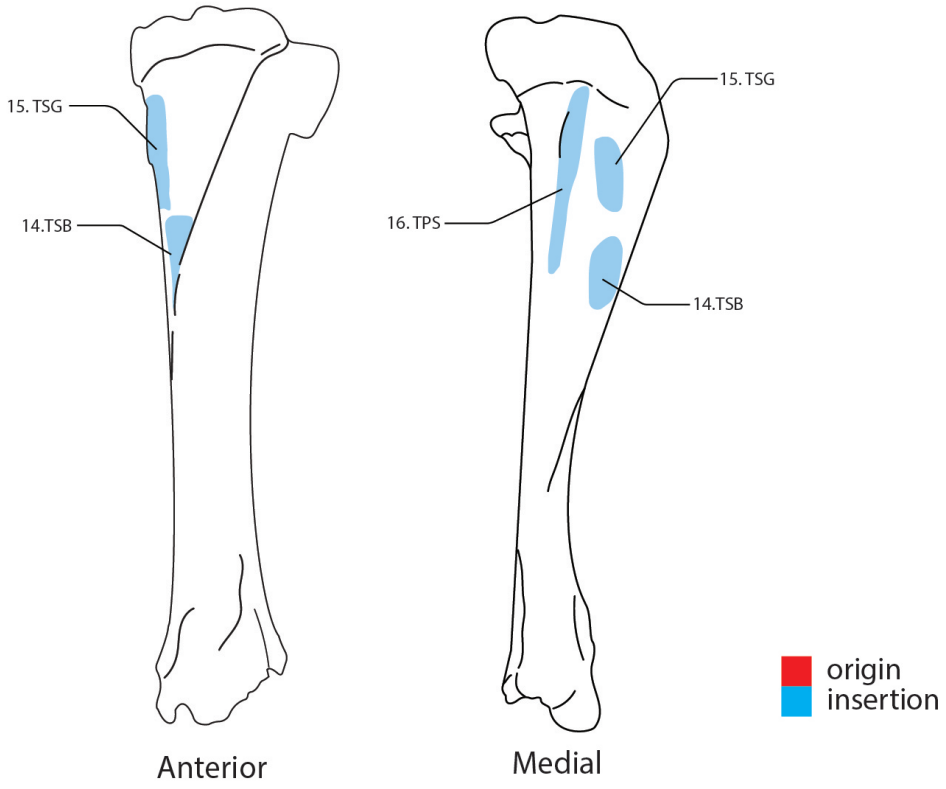



Plate 5.6: Locations of enthesis on the tibia.

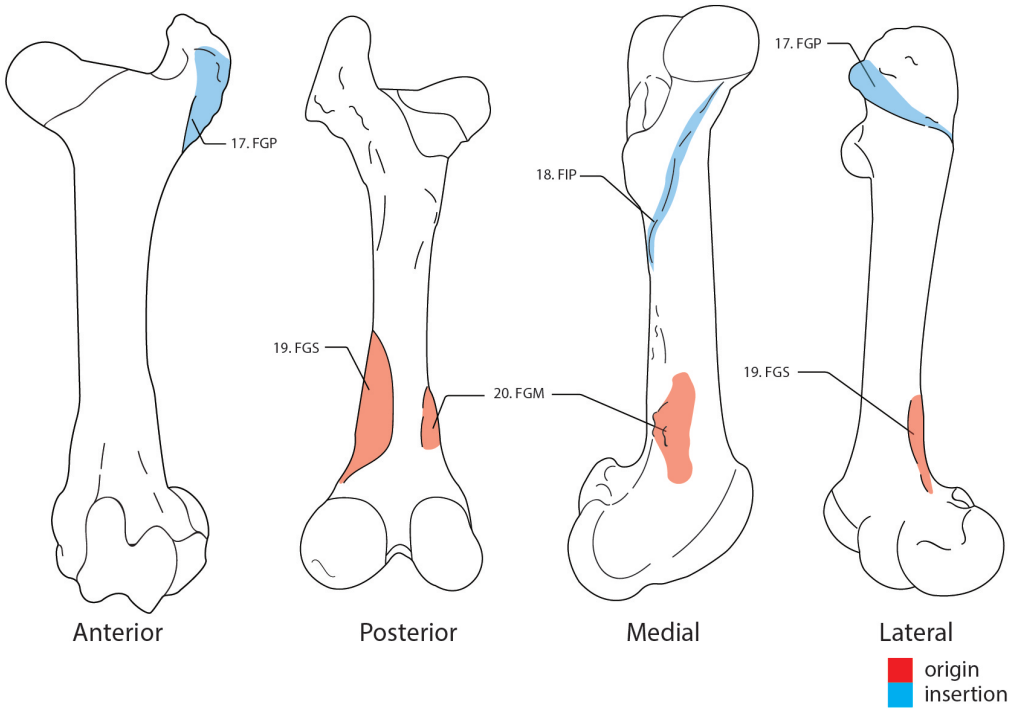



Plate 5.7: Locations of enthesis on the femur.

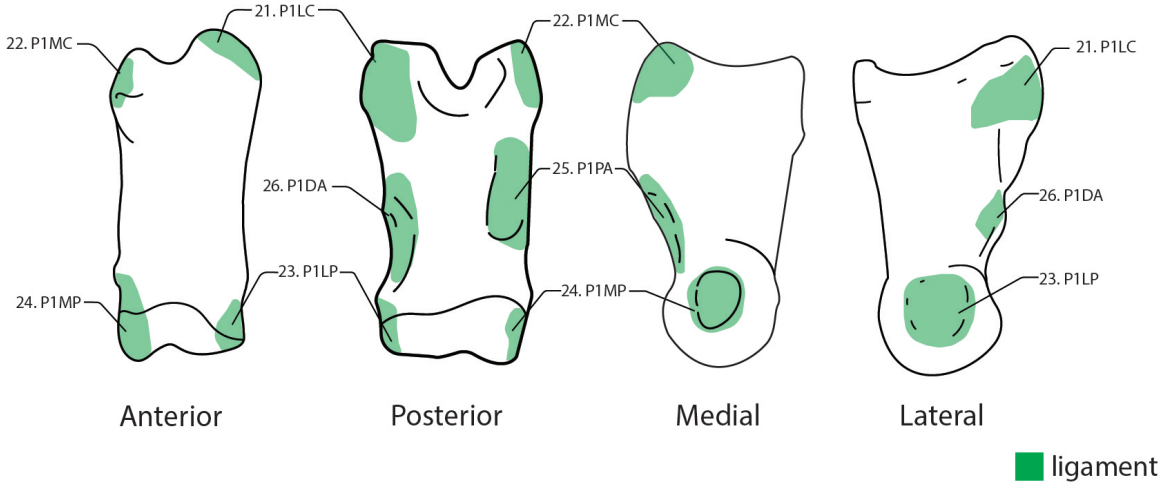



Plate 5.8: Locations of enthesis on the first phalanx.

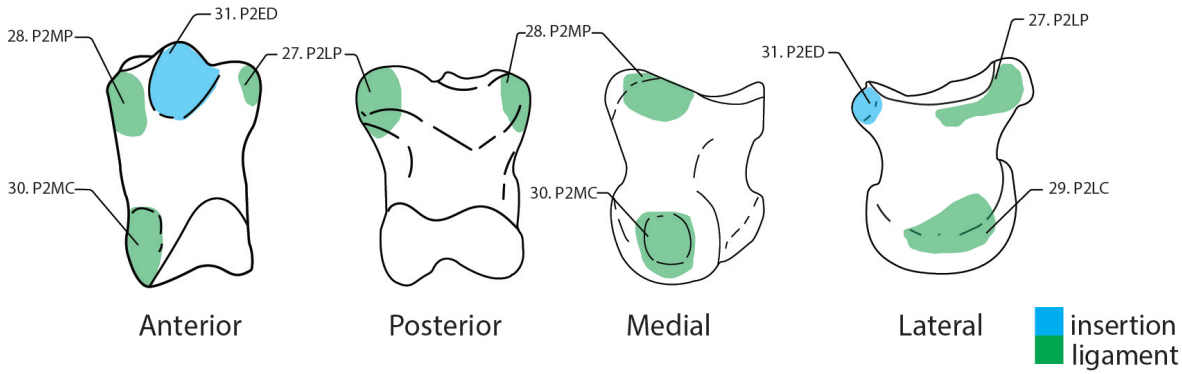



Plate 5.9: Locations of enthesis on the second phalanx.

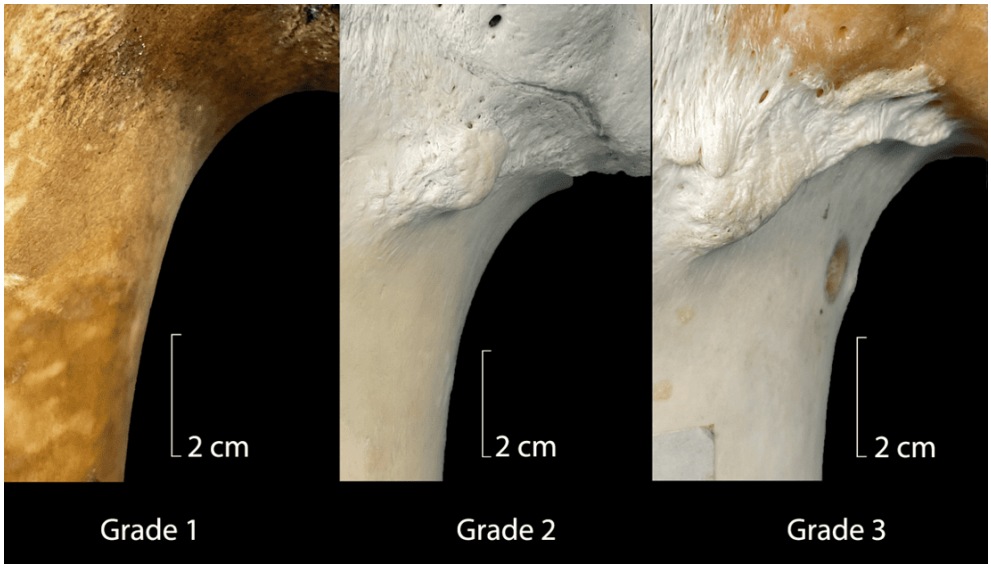



Plate 5.10: Grading illustrations for the insertion of the teres minor.

## 5.4 Spavin in modern cattle

A total of 26 cattle from the Julius Kühn collection (Table 5.7) were observed to have spavin, with 14 individuals affected on one side and the remaining individuals exhibiting spavin on both sides of their metatarsals. The prevalence of spavin in this collection is $20\%$ (n = 126). Different stages of ankylosis have been noticed (Plate 5.11). For instance, individuals 251 (Bssh4) and 322 (Bswyz4) represent an advanced stage characterised by a complete fusion of the naviculocuboid, cuneiforms and metatarsal (Plates 5.11A and B). Conversely, 289 (Bkry1) and 295 (Bkry2) are only moderately affected, with the tarsals not fully bridging with the metatarsals through the osteophytes (Plates 5.11C and D).

Table 5.7: List of modern non-draught cattle with spavin.

| ID | Age in year (Estimated age) | Type/Breed/Species | Sex | Affected side |
|---|---|---|---|---|
| 22 | 9 | Ansbach-Triesdorfer | Female | Both sides |
| 31 | Unknown | Holstein Friesian | Female | Right |
| 74 | (9.6) | Breitenburger | Female | Right |
| 83 | 17 | Butjadinger | Female | Left |
| 110 | Unknown | Yak (*Bos grunniens*) | Male | Left |
| 251 | (7.3) | Shorthorn | Female | Both sides |
| 255 | 9.5 | Hereford | Female | Left |
| 289 | (7.3) | Kerry | Female | Right |
| 294 | 13 | Podolian | Male | Both sides |
| 295 | 6.9 | Kerry | Male | Left |
| 298 | 6.8 | Shorthorn crossbreed | Male | Both sides |
| 322 | (12) | Schwyzer | Female | Left |
| 323 | Unknown | Schwyzer | Female | Right |
| 327 | Unknown | Shorthorn crossbreed | Male | Both sides |
| 328 | (7.3) | Shorthorn | Female | Both sides |
| 351 | (7.3) | Simmental | Female | Right |
| 415 | 12.2 | Kerry | Male | Right |
| 476 | 7 | Shorthorn crossbreed | Female | Both sides |
| 537 | 16.7 | Hollander crossbreed | Female | Both sides |
| 540 | 4.3 | Hollander crossbreed | Female | Left |
| 569 | 11.1 | Shorthorn crossbreed | Male | Both sides |
| 580 | 4.6 | Shorthorn crossbreed | Female | Both sides |
| 612 | 7.3 | Shorthorn crossbreed | Male | Both sides |
| 760 | 4.5 | Shorthorn crossbreed | Female | Left |
| 891 | 3.9 | Normande | Male | Left |
| 5342 | Unknown | Unknown | Female | Both sides |

Plate 5.11: Examples of spavin observed in modern non-draught cattle. [**A**] Dorsal view of both metatarsals with spavin of individual 251 (Bshh4), a Shorthorn cow with an estimated age of 11 years; [**B**] Dorsal view of the left metatarsal with spavin of individual 322 (Bswyz4), a Schwyzer cow with an estimated age of 12 years; [**C**] Dorsal view of the right metatarsal with spavin of individual 289 (Bkry1), a Kerry cow with an estimated age of 11 years; [**D**] Dorsal view of the left metatarsal with spavin of individual 295 (Bkry2), a 6.9-year-old Kerry bull.

### 5.4.1 Risk factors of spavin

Eighty per cent of the cattle with spavin were aged above five. The mean age of those with spavin was 8.8 years, whilst those without had a mean age of 7.0. To further examine the correlation between spavin and age, a point-biserial correlation was conducted on individuals with age data in the Julius Kühn collection. The test results indicate a significant positive correlation of this pathological condition with ageing (Table 5.8). Nonetheless, relatively young animals could also suffer from spavin, as demonstrated by a 3.9-year-old male Normande cattle (Table 5.7).

In terms of the effect of sex on spavin, males show a higher prevalence at $29\%$ (9/31), whereas females have a prevalence of $18\%$ (17/94). There is, however, no significant correlation between sex and the development of spavin (Table 5.9).

The living weights of these animals were not available; thus, the relative body size was estimated by the greatest breadth of the distal end (Bd) on metatarsals. It has been suggested the width measurements of bovid bones are strongly associated with body weight (Scott, 1983). A significant correlation was found between body size and spavin using a point-biserial test (Table 5.10). The results indicate that individuals with a wider distal end, namely a larger absolute body size, were more likely to develop spavin. However, there is also a possibility that a wide distal end is related to metatarsal splaying or that the animal was stocky in relation to their height.

Table 5.8: Summary of point-biserial correlation for determining the relationship between age and spavin.

| | n | Mean age (year) | Coefficient | P |
|---|---|---|---|---|
| With spavin | 26 | 8.8 | 0.27 | 0.00 ** |
| Without spavin | 28 | 7.0 | | |

** = highly significant ($P \leq 0.01$).

Table 5.9: Summary of Fisher's Exact test for the correlation between sex and spavin.

| | n | P |
|---|---|---|
| Cow with spavin | 9 | 0.21 NS |
| Bull with spavin | 17 | |

NS = non-significant ($P > 0.05$).

Table 5.10: Summary of point-biserial correlation for determining the relationship between body size proxy (metatarsal Bd) and spavin.

| | n | Coefficient | P |
|---|---|---|---|
| With spavin | 26 | 0.22 | 0.02 * |
| Without spavin | 81 | | |

* = significant ($P \leq 0.05$).

### 5.4.2 Risk factor analysis by decision tree

The results above indicate that old age and large body size are potentially associated with a higher likelihood of developing spavin. Analysing each biological variable independently, however, does not provide insights into the interrelation among these factors.

A decision tree was used to determine the important factors. This non-parametric supervised classification model measures the relevance of input factors in the decision tree to identify their importance. Three variables, namely age, sex, and body size proxy, were considered in the analysis to determine their importance in the development of spavin in cattle.

Figure 5.1A illustrates the variable importance results, highlighting the body size proxy (Bd) as the most influential risk factor, followed by age. These findings align with the analysis in the previous section, indicating that sex does not play a critical role in influencing the development of spavin. In particular, the decision tree model identified a threshold value of 66.5 mm for Bd width. Cattle with a Bd width smaller than 66.5 mm had a possibility of developing spavin of $15.3\%$, while individuals with a width greater than 66.5 mm had a higher probability of $56.2\%$ (Figure 5.1B).

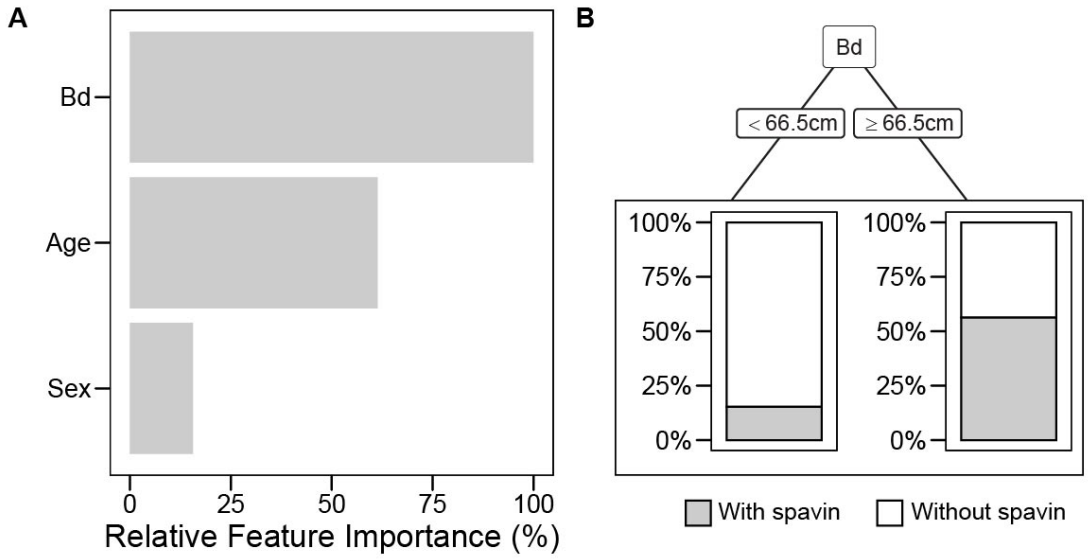



Figure 5.1: Feature importance and decision tree of spavin occurrence in modern non-draught cattle. [**A**] Feature importance plot. Relative feature importance is calculated based on Mean Decrease Accuracy. Metatarsals Bd (the greatest breadth of the distal end) is used as a body size proxy. [**B**] A top-down decision tree for classifying spavin risk based on age (n = 127).

### 5.4.3 Spavin and draught use

The final analysis of this section aims to determine whether external stress added through traction work is a significant factor that increases the possibility of developing spavin in cattle. Modern draught cattle data were adopted from Bartosiewicz et al. (1997b: 71). The prevalence rate of spavin is $28\%$ (5/18) in the draught group (Table 5.11). Despite the higher spavin prevalence in the traction animals, no significant difference occurs between draught and non-draught cattle (Table 5.12).

When considering all variables (age, sex, body size proxy, and type) in the decision tree model, age is indicated as the most influential factor in the occurrence of spavin, followed by body size proxy (Bd), with type (draught or non-draught) being the least important (Figure 5.2). This shift in significance, where age has become the most influential factor, can be attributed to the higher average age within the draught group (9.75 years in draught cattle with spavin and 8.8 years in non-draught cattle with spavin).

Table 5.11: List of modern draught cattle with spavin (data adopted from Bartosiewicz et al., 1997b: 71).

| ID | Age in year | Breed | Sex | Affected side |
|---|---|---|---|---|
| 91.107.M3 | 10 | Romanian Grey x Brown | Castrated | Both sides |
| 91.107.M9 | 12 | Romanian Grey x Brown | Castrated | Right |
| 91.107.M10 | 9 | Romanian Grey x Brown | Castrated | Right |
| 91.107.M11 | 8 | Romanian Grey x Brown | Castrated | Both sides |
| 91.107.M24 | Unknown | Romanian Grey x Brown | Castrated | Left |

Table 5.12: Summary of Fisher's Exact test for the correlation between type (draught or non-draught) and spavin.

| | n | P |
|---|---|---|
| Draught cattle with spavin | 6 | 0.36 NS |
| Non-draught cattle with spavin | 26 | |

NS = non-significant ($P > 0.05$).

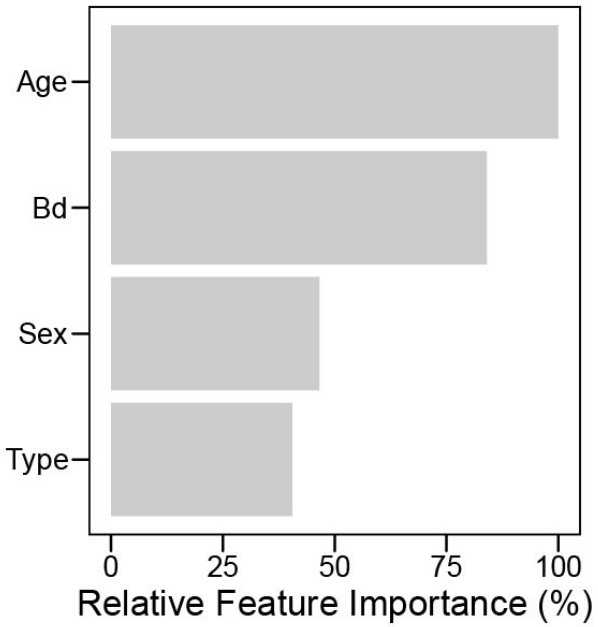



Figure 5.2: Feature importance of spavin occurrence in the decision tree model of modern draught and non-draught cattle. Relative feature importance is calculated based on Mean Decrease Accuracy. The greatest breadth of the distal end of metatarsals (Bd) is used as a body size proxy.

### 5.4.4 Discussion: Spavin in modern cattle

This section presents the analysis of spavin observed in the non-draught animals in the Julius Kühn collection and a comparison with the modern draught cattle data. The results indicated that ankylosis of tarsals to metatarsals was not uncommon in the non-draught cattle collection, with a $20\%$ (26/126) prevalence rate. The analysis also revealed positive correlations between age, body size, and the development of spavin, whilst there is no difference in prevalence between bulls and cows. Body size has been identified as the most critical factor in spavin occurrence within the non-draught group by utilising the decision tree model.

Repeated external loading on cattle, mainly when used for traction, has been suggested as a risk factor for spavin (Baker, 1984: 254; O'Connor, 2008: 177). It is, however, widely acknowledged that a complex interplay of biological factors is involved in developing this pathological condition (Bartosiewicz et al., 1997a; Baker and Brothwell, 1980: 118). No significant prevalence difference was found between the draught and non-draught groups in this study, although caution is advised due to the small sample size of the draught group. Nonetheless, while comparable studies have not been conducted in cattle, it is worth noting that in horses, where spavin is more prevalent, there is no observed association between work intensity and radiographic signs of bone spavin (Eksell et al., 1998). These findings cast doubt on the extent to which traction use contributes to the development of this condition in cattle.

The degeneration of tarsal joints is a chronic condition in which ageing exacerbates the ankylosis of the joint. The findings in this study concur with previous analyses on Swedish dairy cattle and Icelandic horses, indicating that the severity of spavin increases with age (Holmberg and Reiland, 1984; Eksell et al., 1998; Björnsdóttir et al., 2010). It should also be mentioned that a relatively young animal, a 3.9-year-old male Normande cattle from the studied collection, exhibited a sign of spavin. This observation parallels a previous study that reported radiographic changes in the tarsal joints of tied dairy cows before the age of 2, with fusion occurring when the animals reached four (Holmberg and

Reiland, 1984). The higher prevalence rate in modern draught cattle compared to their non-draught counterparts may, in part, be attributed to external stress stemming from traction; nevertheless, it cannot be regarded as the primary determinant. This is demonstrated by the strong correlation between age and the occurrence of spavin within the non-draught group, particularly noteworthy given the extended lifespan of draught cattle kept for work.

Bulls showed a slightly higher prevalence of spavin compared to cows, though no statistically significant difference was identified. Heavy bulls have been noticed to be commonly affected by tarsal degenerative joint disease (Van Pelt, 1975). Weight is, however, correlated with sex; particularly, sexual size dimorphism in mammals typically favours males, where males exhibit larger body weight than females. As the live weights of the modern non-draught cattle were not available, the distal breadth (Bd) of the metatarsal was used as a proxy for body size in the analyses. It is suggested that bone width in bovids is also associated with their living weight (Scott, 1983). The results indicated a significant correlation between Bd and the prevalence of spavin, meaning that heavier animals are more likely to develop spavin. The positive correlation indicated here, however, may also suggest that stocky animals or those with splayed metatarsals have a higher likelihood of spavin occurrence, rather than being necessarily a consequence of absolute weight. Nonetheless, the results of this study suggest that body size or weight may have a more substantial positive correlation with spavin than sex.

Restricted movement is one particular condition of the animals in the Julius Kühn collection that may exacerbate spavin. Most of these cattle were primarily kept at the institute, with exercise limited to about an hour daily in a small yard. The correlation between lack of exercise and spavin has been previously demonstrated by a study on dairy cattle, indicating that the tied herds had a higher prevalence of spavin in comparison to those with loose housing within the same age group and breed (Holmberg and Reiland, 1984).

Although a comprehensive analysis of the effect of breeds was not conducted in the present study due to the limited sample size available for each breed, it

was observed that the Kerry cattle were more likely to present signs of spavin. A previous study on living cattle reveals that the prevalence of spavin varied significantly between breeds. In particular, the Swedish Jersey cows had a higher incidence rate of $50\%$ (13/26), while the Swedish Friesian cows had an incidence rate of $20\%$ (9/44) (Holmberg and Reiland, 1984), suggesting genetic inheritance is partly responsible for this degenerative joint disease.

The effect of draught exploitation on the development of spavin cannot be disregarded; the multifactorial nature of this condition makes it difficult to use as a conclusive indicator of cattle labour. The prevalence of spavin shows no significant variation between modern draught and non-draught cattle. Most of the results accord with previous studies that age and body size are important factors that affect the development of this condition. However, no significant variation has been observed between the sexes. Additionally, the effect of breeds and restricted mobility could partly explain the high prevalence of spavin in the studied non-draught collection.

## 5.5 Pathological Index in modern cattle

### 5.5.1 Descriptive statistics of Pathological Index

The mean PI values of each trait recorded in the 121 modern non-draught cattle from the Julius Kühn collection, along with three individuals from the Zooarchaeology Laboratory of the University of Sheffield, are presented in (Table 5.13).

In general, the non-draught animals showed minimal pathological deformations in their limbs. Three traits were absent during the recording, namely eburnation on proximal or distal articular surfaces and striation on metatarsals. Exostosis in the proximal end was the most common pathology for all the anatomical elements, except for the second phalanges, which were more frequently characterised by proximal lipping.

Figure 5.3 illustrates the distribution of PI values for each trait across different anatomical elements, with a comparison to the mean values of modern draught

animals as derived from Bartosiewicz et al. (1997b: 55–9). The mean values of the non-draught cattle consistently show lower values compared to the draught animals. The mean value of proximal exostosis on metacarpals is, however, rather similar between the two groups (Fig. 5.3A). The non-draught group has a mean score of 1.51 for the proximal exostosis, while the draught group has a slightly higher mean score of 1.54. Whilst the majority of non-draught animals exhibited subtle or no pathological changes in their limbs, extensive exostoses scored as Grade 4 on metacarpals and phalanges were recorded in some cases (Plate 5.12).

Figure 5.4 displays the averaged values resulting from calculating scores for individual anatomical elements, demonstrating variations in the severity of deformation between the recorded elements. Metacarpals show the highest mean value, in contrast to the posterior first phalanges, which have the lowest value. On average, the bones of the forelimb, including metacarpals, and the anterior first and second phalanges, present higher deformation levels than those of the hindlimbs. Nonetheless, the mean scores for all elements remain below 0.09, with a maximum possible score of 1 for a single element.

Table 5.13: Mean PI values of each trait in individual anatomical elements.

| Element | Trait (scoring) | Mean |
|---|---|---|
| Metacarpal (n = 102) | Proximal exostosis (1-4) | 1.51 |
| | Proximal lipping (1-4) | 1.05 |
| | Distal exostosis (1-4) | 1.08 |
| | Distal broadening (1-4) | 1.38 |
| | Distal depression (1-3) | 1.07 |
| | Proximal eburnation (1-2) | 1 |
| | Distal eburnation (1-2) | 1 |
| | Fusion (1-2) | 1.34 |
| | Proximal facet (1-2) | 1.1 |
| Metatarsal (n = 93) | Proximal exostosis (1-4) | 1.43 |
| | Proximal lipping (1-4) | 1.38 |
| | Distal exostosis (1-4) | 1.04 |
| | Distal broadening (1-4) | 1.34 |
| | Distal depression (1-3) | 1.02 |
| | Proximal eburnation (1-2) | 1 |
| | Distal eburnation (1-2) | 1 |
| | Striation (1-2) | 1 |
| Anterior first phalanx (n = 75) | Proximal exostosis (1-4) | 1.37 |
| | Proximal lipping (1-4) | 1.11 |
| | Distal exostosis (1-4) | 1.12 |
| | Proximal eburnation (1-2) | 1 |
| | Distal eburnation (1-2) | 1 |
| Posterior first phalanx (n = 73) | Proximal exostosis (1-4) | 1.26 |
| | Proximal lipping (1-4) | 1.08 |
| | Distal exostosis (1-4) | 1.08 |
| | Proximal eburnation (1-2) | 1 |
| | Distal eburnation (1-2) | 1 |
| Anterior second phalanx (n = 77) | Proximal exostosis (1-4) | 1.18 |
| | Proximal lipping (1-4) | 1.38 |
| | Distal exostosis (1-2) | 1.21 |
| | Proximal eburnation (1-2) | 1 |
| | Distal eburnation (1-4) | 1 |
| Posterior second phalanx (n = 71) | Proximal exostosis (1-4) | 1.13 |
| | Proximal lipping (1-4) | 1.3 |
| | Distal exostosis (1-4) | 1.1 |
| | Proximal eburnation (1-2) | 1 |
| | Distal eburnation (1-2) | 1 |

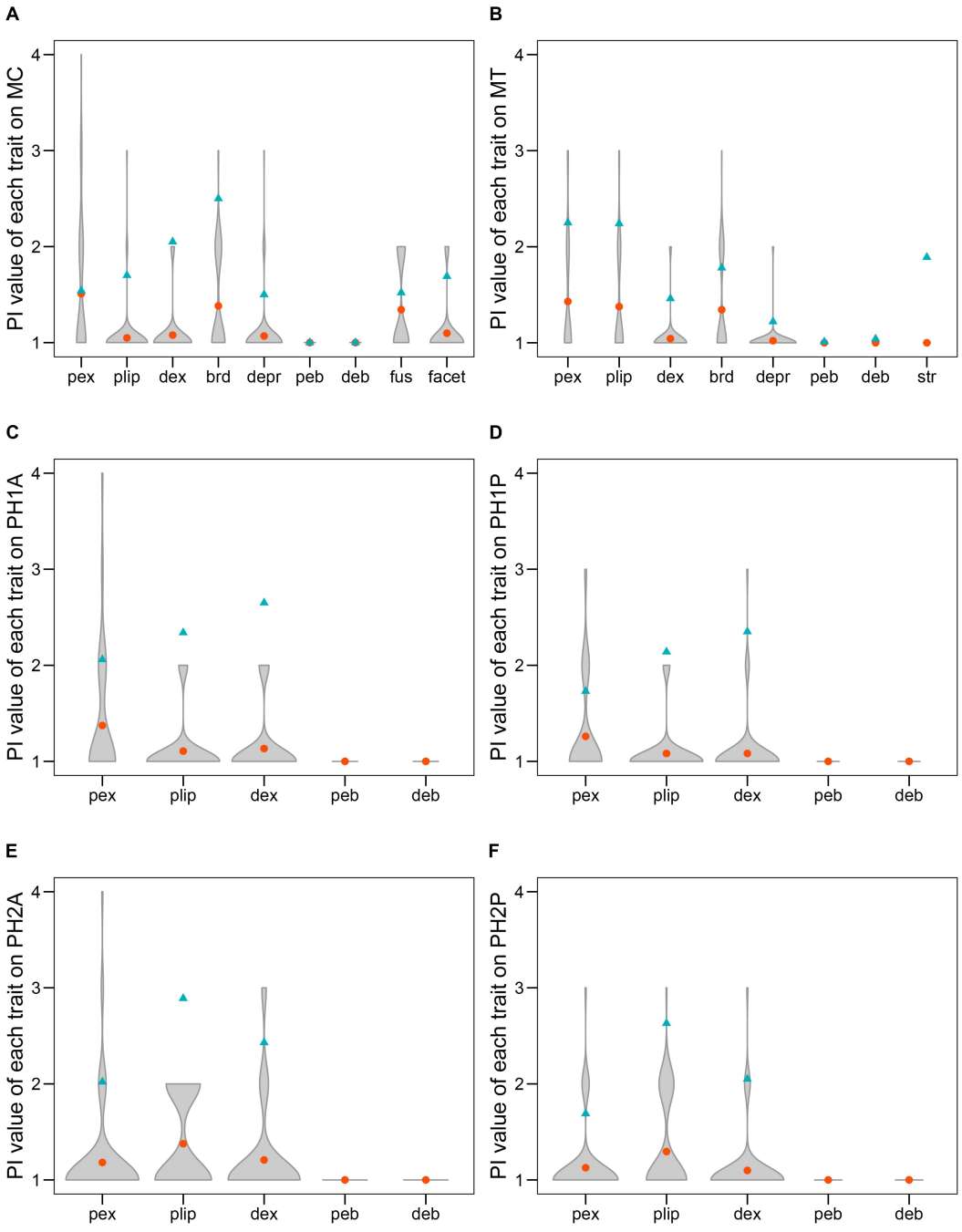



Figure 5.3: Distribution of PI values on different anatomical elements of the non-draught cattle. [**A**] Metacarpals (n = 102); [**B**] Metatarsals (n = 93); [**C**] Anterior first phalanges (n = 75); [**D**] Posterior first phalanges (n = 73); [**E**] Anterior second phalanges (n = 77); [**F**] Posterior second phalanges (n = 71). Orange dots represent the mean value of the non-draught group. Blue triangles represent the mean value of the draught group (Bartosiewicz et al. 1997: 55-9). Note that values of peb and deb from the phalanges were not provided on the original publication. pex = proximal exostosis; plip = proximal lipping; dex = distal exostosis; brd = distal broadening; depr = distal depression; peb = proximal eburnation; fus = fusion; facet = proximal facet; str = striation.




Plate 5.12: Example of stage 4 exostosis development in limb elements. [**A**] Anterior first phalanx from individual 566(Bshh8), a 6.9-year-old male Shorthorn crossbreed; [**B**] Anterior second phalanx from individual 76(Bbrtb3), a Breitenburger cow with an estimated age of 3.75 years; [**C**] Proximal metacarpal from individual 213(Bhld18), a 7.6-year-old Holländer cow.

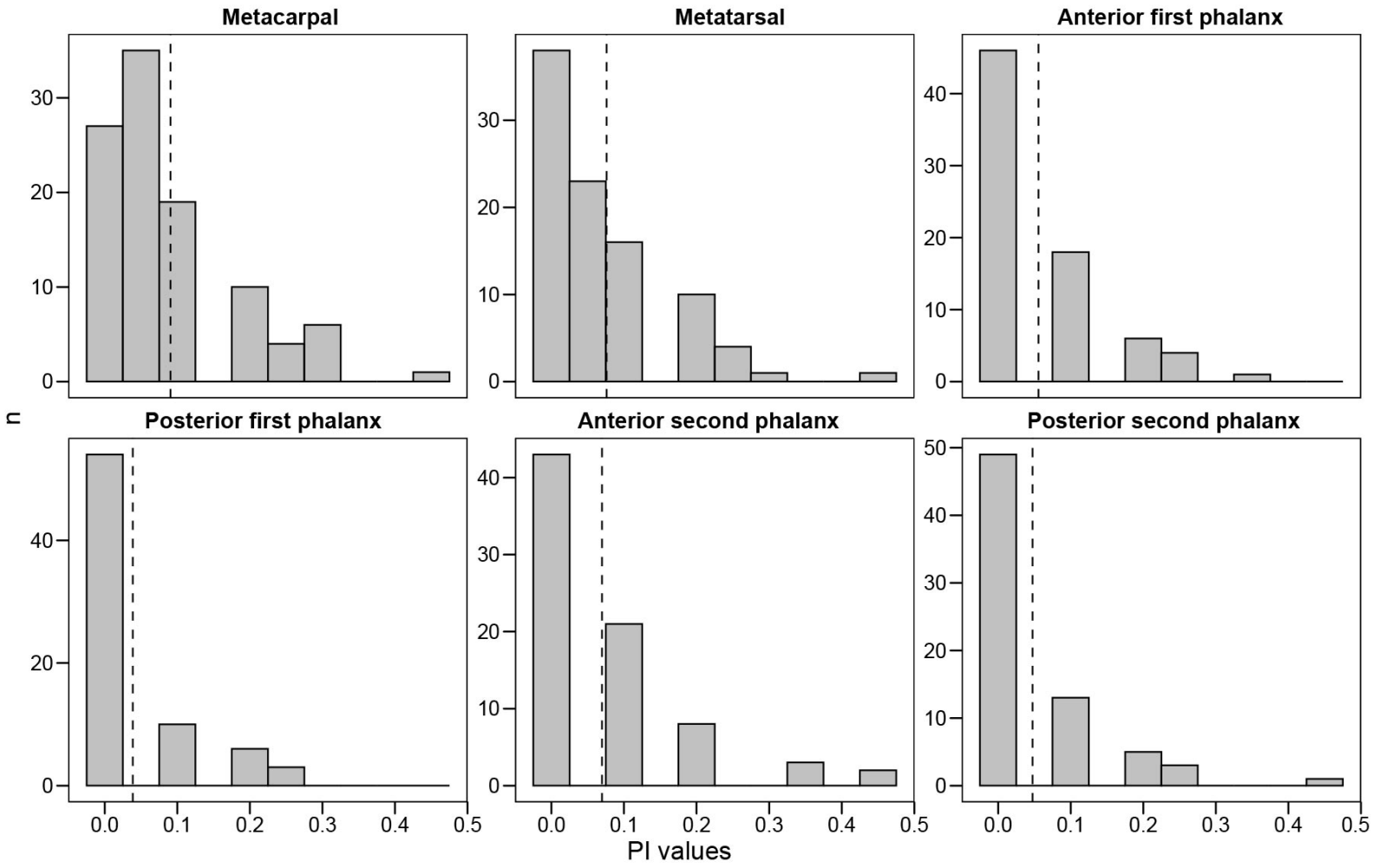



Figure 5.4: Distribution of the Pathological Index (PI) value in each anatomical element. The black lines represent the mean value of the non-draught group.

### 5.5.2 Effect of biological factors on pathological traits

#### 5.5.2.1 Effect of age on pathological traits

To examine the correlation between age and the severity of pathological conditions, Spearman's rank tests were performed for each trait on individual elements in relation to age (Table 5.14).

Not all recorded traits correlate with age; particularly proximal and distal exostosis, as well as distal broadening on metapodials, show no such association. Yet in metacarpals, three traits, including depression, fusion, and proximal facet, reveal a significant positive correlation with age, whereas proximal lipping indicates a positive result in metatarsals. Likewise, exostoses on both ends in the first and second phalanges positively correlate with ageing, while proximal lipping and distal exostoses are highly associated with old age in the anterior and posterior second phalanges, respectively.

Table 5.14: Summary of Spearman's rank correlation analysis between age and score of each trait recorded on different anatomical elements.

| Element | Trait | n | R | P |
|---|---|---|---|---|
| Metacarpal | pex | 82 | 0.18 | 0.11 NS |
| | plip | | 0.11 | 0.32 NS |
| | dex | | –0.07 | 0.56 NS |
| | brd | | –0.08 | 0.49 NS |
| | depr | | 0.29 | 0.00 ** |
| | fus | | 0.25 | 0.02 * |
| | facet | | 0.27 | 0.01 * |
| Metatarsal | pex | 75 | 0.09 | 0.44 NS |
| | plip | | 0.28 | 0.02 * |
| | dex | | –0.01 | 0.92 NS |
| | brd | | 0.08 | 0.47 NS |
| | depr | | 0.19 | 0.09 NS |
| Anterior first phalanx | pex | 59 | 0.30 | 0.02 * |
| | plip | | –0.10 | 0.45 NS |
| | dex | | 0.35 | 0.00 ** |
| Posterior first phalanx | pex | 58 | 0.28 | 0.03 * |
| | plip | | –0.06 | 0.64 NS |
| | dex | | 0.36 | 0.00 ** |
| Anterior second phalanx | pex | 59 | 0.16 | 0.21 NS |
| | plip | | 0.34 | 0.00 ** |
| | dex | | 0.29 | 0.03 * |
| Posterior second phalanx | pex | 56 | 0.33 | 0.00 ** |
| | plip | | 0.12 | 0.36 NS |
| | dex | | 0.35 | 0.00 ** |

** = highly significant ($P \leq 0.01$), * = significant ($P \leq 0.05$), NS = non-significant ($P > 0.05$). See Table 5.4 for the trait abbreviations.

#### 5.5.2.2 Effect of sex on pathological traits

A Mann-Whitney test was adopted to compare the differences in the pathological value of each trait between the sexes. It should be noted that there were only two castrated males in the sample; they were omitted from the test (Table 5.15). Except for the distal broadening of the metacarpals, none of the traits from the metatarsals and phalanges present significant differences between females and males.

Table 5.15: Summary of Mann-Whitney test on the Pathological Index value of each trait between sexes.

| Element | Trait | n. Female | n. Male | P |
|---|---|---|---|---|
| Metacarpal | pex | 71 | 29 | 0.68 NS |
| | plip | | | 0.86 NS |
| | dex | | | 0.59 NS |
| | brd | | | 0.04 * |
| | depr | | | 0.49 NS |
| | fus | | | 0.70 NS |
| | facet | | | 0.95 NS |
| Metatarsal | pex | 68 | 23 | 0.70 NS |
| | plip | | | 0.20 NS |
| | dex | | | 0.95 NS |
| | brd | | | 0.97 NS |
| | depr | | | 0.42 NS |
| Anterior first phalanx | pex | 52 | 21 | 0.78 NS |
| | plip | | | 0.06 NS |
| | dex | | | 0.65 NS |
| Posterior first phalanx | pex | 51 | 20 | 0.39 NS |
| | plip | | | 0.69 NS |
| | dex | | | 0.53 NS |
| Anterior second phalanx | pex | 54 | 21 | 0.89 NS |
| | plip | | | 0.66 NS |
| | dex | | | 0.24 NS |
| Posterior second phalanx | pex | 51 | 18 | 0.91 NS |
| | plip | | | 0.54 NS |
| | dex | | | 0.72 NS |

* = significant ($P \leq 0.05$), NS = non-significant ($P > 0.05$). See Table 5.4 for the trait abbreviations.

#### 5.5.2.3 Effect of body size on pathological traits

The effect of body size on pathological traits was analysed using size proxies, including the greatest length (GL) and breadth of the distal end (Bd) of the limb elements through a Spearman's rank correlation test (Tables 5.16-5.21). The distal broadening is the only trait recorded on metacarpals that shows a significant correlation with Bd, while it does not display a correlation with GL (Table 5.16). It is important to emphasise that this statistical significance arises primarily because the measurement of distal broadening is synonymous with Bd measurements. Distal exostoses on the anterior second phalanges correlate solely with Bd (Table 5.20). For the anterior first phalanges, proximal lipping positively

correlates with Bd and GL (Table 5.18). None of the anatomical elements from the hindlimbs is associated with either body size proxy (Tables 5.17, 5.19 and 5.21).

Table 5.16: Summary of Spearman's rank correlation analysis between body size proxies (metacarpal Bd and GL) and the score of each trait recorded on metacarpals.

| Element | Trait | n | Measurement | R | P |
|---|---|---|---|---|---|
| Metacarpal | pex | 100 | GL | 0.06 | 0.55 NS |
| | | 102 | Bd | 0.09 | 0.36 NS |
| | plip | 100 | GL | 0.07 | 0.48 NS |
| | | 102 | Bd | –0.04 | 0.65 NS |
| | dex | 100 | GL | –0.05 | 0.64 NS |
| | | 102 | Bd | –0.02 | 0.83 NS |
| | brd | 100 | GL | 0.18 | 0.08 NS |
| | | 102 | Bd | 0.39 | 0.00 *** |
| | depr | 100 | GL | –0.16 | 0.10 NS |
| | | 102 | Bd | –0.17 | 0.08 NS |
| | fus | 100 | GL | 0.62 | 0.06 NS |
| | | 102 | Bd | 0.12 | 0.22 NS |
| | facet | 100 | GL | –0.08 | 0.43 NS |
| | | 102 | Bd | –0.04 | 0.67 NS |

*** = very highly significant ($P \leq 0.001$ ), NS = non-significant ($P > 0.05$). See Table 5.4 for the trait abbreviations.

Table 5.17: Summary of Spearman's rank correlation analysis between body size proxies (metatarsal Bd and GL) and the score of each trait recorded on metatarsals.

| Element | Trait | n | Measurement | R | P |
|---|---|---|---|---|---|
| Metatarsal | pex | 90 | GL | –0.05 | 0.63 NS |
| | | 93 | Bd | –0.13 | 0.22 NS |
| | plip | 90 | GL | 0.16 | 0.14 NS |
| | | 93 | Bd | 0.03 | 0.81 NS |
| | dex | 90 | GL | –0.07 | 0.48 NS |
| | | 93 | Bd | –0.07 | 0.52 NS |
| | brd | 90 | GL | –0.10 | 0.32 NS |
| | | 93 | Bd | –0.01 | 0.92 NS |
| | depr | 90 | GL | 0.02 | 0.87 NS |
| | | 93 | Bd | –0.04 | 0.69 NS |

NS = non-significant ($P > 0.05$). See Table 5.4 for the trait abbreviations.

Table 5.18: Summary of Spearman's rank correlation analysis between body size proxies (anterior first phalanx Bd and GL) and the score of each trait recorded on anterior first phalanges.

| Element | Trait | n | Measurement | R | P |
|---|---|---|---|---|---|
| Anterior first phalanx | pex | 73 | GL | –0.11 | 0.31 NS |
| | | 75 | Bd | –0.04 | 0.67 NS |
| | plip | 73 | GL | –0.31 | 0.00 ** |
| | | 75 | Bd | –0.30 | 0.00 ** |
| | dex | 73 | GL | –0.11 | 0.31 NS |
| | | 75 | Bd | 0.01 | 0.92 NS |

** = highly significant ($P \leq 0.01$), NS = non-significant ($P > 0.05$). See Table 5.4 for the trait abbreviations.

Table 5.19: Summary of Spearman's rank correlation analysis between body size proxies (posterior first phalanx Bd and GL) and the score of each trait recorded on posterior first phalanges.

| Element | Trait | n | Measurement | R | P |
|---|---|---|---|---|---|
| Posterior first phalanx | pex | 72 | GL | –0.12 | 0.33 NS |
| | | 73 | Bd | 0.16 | 0.16 NS |
| | plip | 72 | GL | 0.01 | 0.89 NS |
| | | 73 | Bd | 0.14 | 0.23 NS |
| | dex | 72 | GL | –0.02 | 0.86 NS |
| | | 73 | Bd | 0.16 | 0.17 NS |

NS = non-significant ($P > 0.05$). See Table 5.4 for the trait abbreviations.

Table 5.20: Summary of Spearman's rank correlation analysis between body size proxies (anterior second phalanx Bd and GL) and the score of each trait recorded on anterior second phalanges.

| Element | Trait | n | Measurement | R | P |
|---|---|---|---|---|---|
| Anterior second phalanx | pex | 77 | GL | –0.08 | 0.46 NS |
| | | | Bd | 0.07 | 0.49 NS |
| | plip | 77 | GL | –0.15 | 0.18 NS |
| | | | Bd | 0.03 | 0.76 NS |
| | dex | 77 | GL | –0.04 | 0.67 NS |
| | | | Bd | 0.23 | 0.04 * |

* = significant ($P \leq 0.05$), NS = non-significant ($P > 0.05$). See Table 5.4 for the trait abbreviations.

Table 5.21: Summary of Spearman's rank correlation analysis between body size proxies (posterior second phalanx Bd and GL) and the score of each trait recorded on posterior second phalanges.

| Element | Trait | n | Measurement | R | P |
|---|---|---|---|---|---|
| Posterior second phalanx | pex | 69 | GL | 0.11 | 0.35 NS |
| | | 71 | Bd | 0.10 | 0.38 NS |
| | plip | 69 | GL | –0.04 | 0.68 NS |
| | | 71 | Bd | 0.01 | 0.90 NS |
| | dex | 69 | GL | 0.11 | 0.34 NS |
| | | 71 | Bd | 0.12 | 0.31 NS |

NS = non-significant ($P > 0.05$). See Table 5.4 for the trait abbreviations.

### 5.5.3 Variations between fore- and hindlimbs

As indicated in Section 5.5, bones from the forelimbs show a higher mean pathological value than the elements at the back (Figure 5.4). To further illustrate this variation, the Wilcoxon signed-rank test was performed to compare the pathological value of each trait between the forelimbs and hindlimbs (Table 5.22). Proximal lipping is the only trait on the metapodials that shows a significant difference between the front and back legs. None of the measured features on the first phalanges demonstrates significant variation. When all the traits on an independent element were calculated for a mean value, only the second phalanges varied significantly between the front and back legs (Table 5.23).

Table 5.22: Summary of the Wilcoxon signed-rank test on the Pathological Index value of each trait between the forelimb and hindlimb.

| Element | Trait | Number of pair | P |
|---|---|---|---|
| Metapodials | pex | 82 | 0.55 NS |
| | plip | 81 | 0.00 *** |
| | dex | 94 | 0.74 NS |
| | brd | 94 | 0.89 NS |
| | depr | 93 | 0.27 NS |
| First phalanges | pex | 73 | 0.24 NS |
| | plip | 73 | 0.62 NS |
| | dex | 73 | 0.34 NS |
| Second phalanges | pex | 66 | 0.17 NS |
| | plip | 66 | 0.14 NS |
| | dex | 66 | 0.03 * |

*** = very highly significant ($P \leq 0.001$ ), * = significant ($P \leq 0.05$), NS = non-significant ($P > 0.05$). See Table 5.4 for the trait abbreviations.

Table 5.23: Summary of Wilcoxon signed-rank test on the Pathological Index value on independent elements between the forelimb and hindlimb.

| Element | Number of pair | P |
|---|---|---|
| Metapodials | 93 | 0.47 NS |
| First phalanges | 73 | 0.18 NS |
| Second phalanges | 64 | 0.02 * |

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

### 5.5.4 Discussion: Pathological Index in modern cattle

This section analysed the Pathological Index in 124 modern non-draught cattle. The findings revealed consistently low average values within the studied sample, aligning with previous research on non-working Chillingham cattle (R. Thomas et al., 2021) and aurochs (Johannsen, 2005: 43). Nonetheless, a few individuals presented substantial exostoses on metacarpals and phalanges.

Several recorded traits demonstrated significant correlations with biological factors, particularly age. Similar trends have been identified in the analysis of semi-feral cattle; as such, it is suggested that these traits be excluded in future traction studies to prevent potential misinterpretation of the results (Johannsen, 2005: 44; R. Thomas et al., 2021). However, the features demonstrating correlations with age in this study differ from the findings reported in R. Thomas et al. (2021), with the exception of the distal exostoses in the first phalanges. A strong correlation between age and distal exostoses in the first phalanges has also been noticed in previous research by Johannsen (2005).

The inconsistent results of this study with previous works can be attributed to two main potential reasons. First, the scoring in the PI method is subjective. In the original study conducted on the modern Romanian draught cattle, inconsistencies in scoring among different observers were noticed. Notably, certain traits showed a high coefficient of variation above $10\%$ (Bartosiewicz et al., 1997b: 55–61). Second, sample differences between studies can lead to variations in the outcomes. For example, R. Thomas et al. (2021) primarily focused on the Chillingham herds containing 15 individuals. Despite the acknowledged small

sample size, it is important to note that Chillingham represents a specific population that has long been genetically isolated. Therefore, it may not accurately reflect the general situation, potentially overlooking the role that population differences could play in pathological changes. Consequently, the larger modern non-draught cattle samples from various breeds and species adopted in this study may produce results only partially comparable to previous studies.

Significant variations between sexes were explicitly found in the PI value of the distal broadening of metacarpals in this study. Bulls tended to have broader distal ends than cows. This trend can be attributed to the sexual dimorphism commonly seen in cattle. The breadth of the distal end of the metapodials is suggested to be the most useful measurement for distinguishing sexes, as bulls usually exhibit shorter and wider metapodials compared to cows (Albarella, 1997: 38; Telldahl et al., 2012; S. Davis et al., 2018). Similar results have been noted in the Chillingham herds, where the average PI value for bulls was higher, despite not reaching statistical significance (R. Thomas et al., 2021).

Conversely, no clear correlation between sex and PI value has been indicated in analysing phalanges from aurochs (Johannsen, 2005: 42). The author attributed the lack of significant results to the small sample size. However, the findings from this current study align with the prior observations. There were no significant sex variations identified in any of the traits examined on the metatarsals and phalanges, suggesting that sex has minimal impact on the recorded pathological conditions.

A previous study of modern draught cattle indicates a positive association between living weight and PI values (Bartosiewicz et al., 1997b: 67–8). The living weight data for the modern cattle used in this study are missing. As a result, this analysis utilised the greatest length (GL) and breadth of the distal end (Bd) of metacarpals as proxies for size. Positive correlations were identified in two traits solely with Bd, while proximal lipping of the anterior first phalanges showed correlations with both proxies. These results are consistent with previous analyses, indicating that larger and more robust animals tend to have higher PI

values (Telldahl et al., 2012; R. Thomas et al., 2021). Particularly pronounced proximal lipping occurs only in relatively larger individuals from a Neolithic site (Johannsen, 2005: 45). The positive correlation between PI values and body size creates difficulties in interpreting archaeological materials. It is challenging to determine whether the higher values of larger animals were due to their weight or if they were preferred for traction purposes, as larger animals were more powerful for draught work. Several previous studies have discussed this circular argument (R. Thomas, 2008; Telldahl et al., 2012; Holmes et al., 2021a). Nonetheless, as demonstrated by this study, only three traits were strongly associated with relative size, suggesting that body weight may have a minor effect on the PI value.

The non-draught samples in the present study generally showed higher mean PI values in the forelimb elements compared to the hindlimbs. Similar patterns have been observed in another modern non-draught cattle herd (R. Thomas et al., 2021) and in archaeological contexts (Telldahl, 2005; Johannsen, 2006). These trends likely result from the uneven weight distribution in quadrupeds, where the forelimbs support approximately two-thirds of the body weight (Bartosiewicz, 2008). It has been hypothesised that draught cattle experience heightened biomechanical stress in their hindlimbs, leading to higher PI values compared to the forelimbs. This idea has been suggested based on archaeological analyses (Johannsen, 2006; R. Thomas, 2008; Telldahl et al., 2012; Holmes et al., 2021a). However, empirical data supporting this hypothesis remain limited. Modern draught cattle studies have often shown overall trends of higher PI values in the forelimbs than the hindlimbs (Bartosiewicz et al., 1997b: 61).

A notable exception comes from Pigière and Smyth (2023: Fig. 6b), which suggested that the modified PI value of the posterior first phalanx (0.336) in Romanian draught oxen was higher than that of the anterior (0.292). This was considered consistent with patterns observed in their archaeological dataset, leading to the inference of draught use. However, this interpretation is based on misreading the original data from Kamjan et al. (2022: Tab.3). The 0.336 value

corresponds to the posterior second phalanx, not the first phalanx. The correct PI value for the posterior first phalanx is 0.240, which is lower than that of the anterior first phalanx, undermining their claim.

Nevertheless, modern draught cattle do occasionally show higher PI values in hindlimbs. For instance, individual cases have been observed where metatarsals exhibit greater PI values than metacarpals (Bartosiewicz et al., 1997b: 61). The posterior legs play a crucial role in generating the thrust required for pulling (Bartosiewicz, 2008; Johannsen, 2006). In such cases, the more severe lesions observed in hindlimbs can be attributed to the significant biomechanical stress they endure, leading to greater pathological or morphological changes. Repeated artificial loading from draught work may reduce or reverse the typical differences in PI values between the forelimbs and hindlimb (Holmes et al., 2021b). These results demonstrate that separate analyses of anterior and posterior phalanges—if at all possible —can be useful in studying draught exploitation in the past.

While there is no doubt that certain traits are more age-dependent than others, the overall trend in this study indicates a significantly lower PI value in non-draught cattle compared to Romanian draught cattle. Therefore, instead of concentrating on identifying individual draught cattle in archaeological contexts, the Pathological Index could be more beneficial in illustrating the overall changes or variations in trends among different sites and chronological phases, as demonstrated in previous research on historical periods (e.g. De Cupere et al., 2000; R. Thomas, 2008; Carlson Dietmeier, 2018; Holmes et al., 2021b; Lin, 2022).

It has been, however, argued that draught cattle likely constituted only a small part of the Neolithic herds; therefore, solely focusing on population trends may lead to a false assumption that draught cattle were absent (Johannsen, 2005: 42). While this is an important consideration, the PI approach might not be ideal for indicating portable draught individuals. It is evident from the findings here that non-draught individuals often display similar pathological grading as draught cattle, except for the absence of striation on metatarsals and eburnation in all elements. Eburnation on non-draught modern cattle phalanges has, however,

been noticed in herds of the Southern Uraks in Russia (Rassadnikov, 2021). It is not suggested that the pathologies recorded in the PI Index cannot be linked to traction; however, it is important to acknowledge that they are multifactorial. Relying solely on the presence of specific pathologies or high PI values in a single bone to identify draught individuals may, therefore, lead to misinterpretation.

Efforts have been made to indicate characters strongly related to biological factors, particularly age, thus advocating to exclude these traits in further studies (Johannsen, 2005; R. Thomas et al., 2021). Nonetheless, old age itself could indirectly indicate traction use, as draught animals are often kept for an extended period to maximise their value. Other factors, such as genetics, nutrition, or living environment, also play a part, which can be challenging to investigate. These additional factors could contribute to the observed high proximal exostosis prevalence on the metacarpal bones, even though this trait shows no significant association with any of the tested factors in this study. Therefore, it is difficult to rule out non-traction related traits entirely. The inconsistent results found in this study and previous research suggest that most, if not all, pathological conditions are influenced to some extent by biological factors. Whether these traits show statistical associations with these factors largely depends on the sample selection.

Furthermore, as R. Thomas et al. (2021: Fig. 5) demonstrated that the overall PI trends remain unchanged even after excluding the age-related traits. Based on this observation and the inconsistency between studies, it has been decided to retain all the traits in the original PI method for the later analyses of archaeological materials in this thesis. However, when applying this method to an archaeological context, it is essential to consider other factors rather than interpreting the results solely as a potential indication of draught exploitation.

Despite potential influences from non-traction factors, in archaeological contexts, the Pathological Index may capture overall trend shifts between chronological phases, aiding in inferring the changing use of draught cattle. Alternative approaches, such as biometry, can be a better method for classifying individuals used for draught. Consequently, it is recommended that the PI method be used

in conjunction with other methods when studying the exploitation of animal labour in the past.

## 5.6 Biometric analyses in modern cattle

### 5.6.1 Asymmetry and broadening in metapodial distal condyles

Although absolute size plays an irrelevant role in identifying draught animals, the asymmetry and broadening of the distal condyles in cattle have been proposed to be related to traction use. Nonetheless, current research lacks comprehensive analyses involving modern samples with documented life histories (see Bartosiewicz et al., 1993). This section investigates the effects of stress and biological factors on asymmetrical and splayed distal metapodials.

Figures 5.5 and 5.6 illustrate the ratios of the medio-lateral width of the medial condyle (a) and the medio-lateral width of the lateral condyle (b) for metacarpals and metatarsals. A ratio value of 1 indicates symmetry between the two condyles, while a value lower than 1 indicates that a is smaller than b. Conversely, when the ratio value is greater than 1, this means that a is larger than b.

#### 5.6.1.1 Metacarpal

As shown in Figure 5.5, irrespective of life histories, medial portions are generally larger than the lateral portions in metacarpals. In other words, most ratio values are greater than 1. Despite all non-draught individuals providing values lower than 1.15, there is an overlap with the results from draught cattle, as evidenced by the narrow $95\%$ confidence interval observed for both groups: draught cattle (1.04-1.12, mean = 1.08) and non-draught cattle (1.05-1.06, mean = 1.05) (Table 5.24). A Mann-Whitney test further indicates no significant differences between the types (Table 5.24). However, it is important to note that all three outliers with a significantly high a/b ratio are draught animals despite the relatively small size of the draught cattle sample (the likelihood of having outliers increases with sample size).

Table 5.24: Descriptive statistics and results of the Mann-Whitney test for comparison of metacarpal condyles ratios between draught and non-draught cattle.

| Type | n | Mean | 95%CI | Mann-Whitney test between type |
|---|---|---|---|---|
| Draught | 13 | 1.08 | 1.04-1.12 | P = 0.45 NS |
| Non-draught | 129 | 1.05 | 1.05-1.06 | |

NS = non-significant ($P > 0.05$).

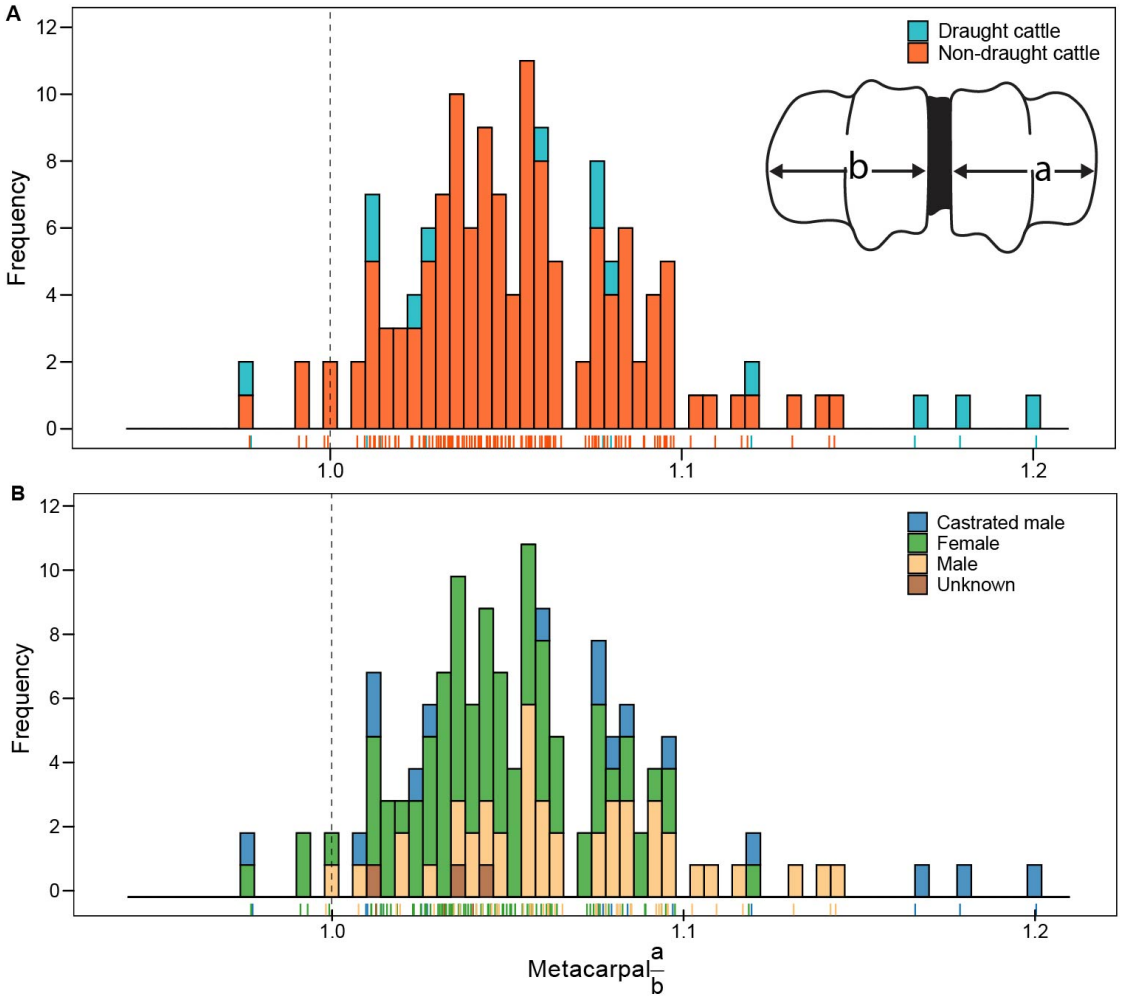



Figure 5.5: Frequency of asymmetry in the distal metacarpal condyles. [**A**] Grouped by type; [**B**] Grouped by sex. A ratio value of 1 indicates symmetry between the medio-lateral width of the medial condyle (*a*) and the medio-lateral width of the lateral condyle (*b*).

Bulls showed a higher tendency for broadening the medial portion in the distal metacarpal condyles than the other non-draught animals (Figure 5.5B). A Mann-Whitney test was performed to assess differences in the metacarpal a/b ratio between sexes of the non-draught group. Due to the insufficient number of

castrated males in the group, these were omitted from the analysis. The results show a significant difference between males and females, suggesting a distinct sexual dimorphism in the metacarpal a/b ratio (Table 5.25).

Table 5.25: Results of Mann-Whitney test between sex (female and male) and metapodials condyles ratios in non-draught cattle.

| Element | Female mean (n) | Male mean (n) | P |
|---|---|---|---|
| Metacarpal | 1.04 (63) | 1.07 (33) | 0.00 *** |
| Metatarsal | 1.04 (90) | 1.03 (37) | 0.07 NS |

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

#### 5.6.1.2 Metatarsal

Similarly, the medial condyles in the metatarsals are mostly broader than the lateral side (Figure 5.6). However, metatarsals exhibit a higher degree of symmetry compared to the metacarpals, with $92\%$ (n = 147) of the metatarsals displaying an a/b ratio between 1.0 and 1.1, whereas $88\%$ (n = 142) of the metacarpals fall within this range. It is worth mentioning that the highest observed a/b ratio of 1.16 was found in a non-draught crossbreed Kerry cattle (ID: 415, Bkry4). The a/b ratio of the metatarsals demonstrates much overlap between the draught and non-draught groups. For draught cattle, the $95\%$ CI for the ratio ranges from 1.01 to 1.07, while for non-draught cattle, it varies from 1.04 to 1.05 (Table 5.26. No statistically significant differences have been observed between the draught and non-draught cattle (Table 5.26).

In contrast with the metacarpals, there are no significant variations in the distal metatarsal condyles between female and male cattle (Figure 5.6B; Table 5.25). It is, nonetheless, noteworthy that there are more instances of reversed patterns, namely, the lateral portion is wider than the medial portion in the hindlimbs compared to the forelimbs.

Table 5.26: Descriptive statistics and results of the Mann-Whitney test for comparison of metatarsal condyles ratios between draught and non-draught cattle.

| Type | n | Mean | 95%CI | Mann-Whitney test between Type |
|---|---|---|---|---|
| Draught | 13 | 1.04 | 1.01-1.07 | P = 0.85 NS |
| Non-draught | 124 | 1.04 | 1.04-1.05 | |

NS = non-significant ($P > 0.05$).

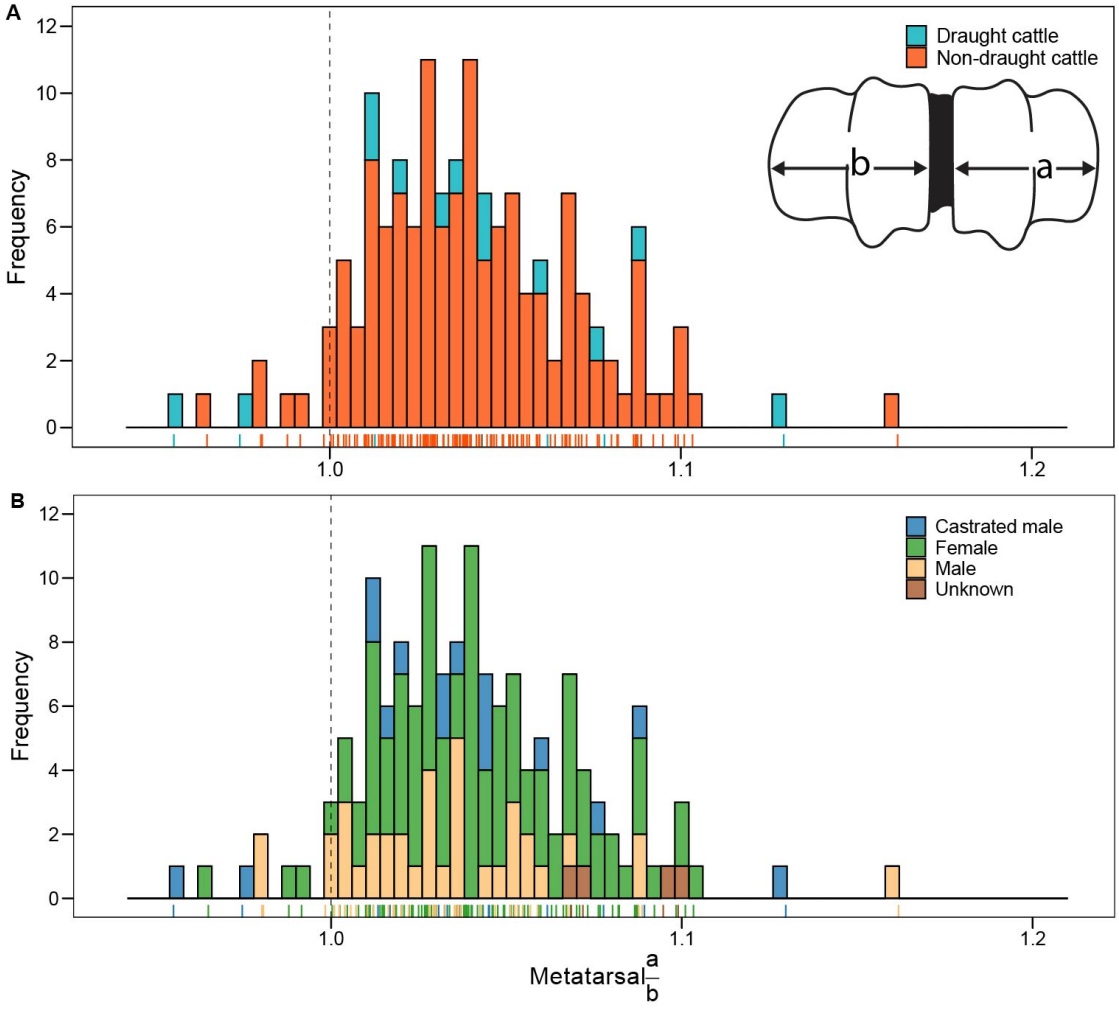



Figure 5.6: Frequency of asymmetry in the distal metatarsal condyles. [**A**] Grouped by type; [**B**] Grouped by sex. A ratio value of 1 indicates symmetry between the medio-lateral width of the medial condyle (*a*) and the medio-lateral width of the lateral condyle (*b*).

Table 5.27 reveals that there is no observed correlation between age and the asymmetry of the distal metapodials. Conversely, a correlation appears to exist between body size and the asymmetry of the distal metapodials. When the greatest breadth of the distal end (Bd) was used as a body size proxy, this

showed a significant correlation with the a/b ratio, but only within the non-draught cattle group (Table 5.28). These results, however, may be affected by the small sample size of the draught cattle. An alternative explanation for the non-significant result in the draught sample may be represented by the potential impact of long-term stress from traction. Therefore, the distal breadths in draught cattle do not entirely reflect their body size, as they may also be distorted by prolonged traction use. If weight is correlated with the asymmetry of the distal metapodials, pronounced asymmetrical condyles in draught cattle could be expected as external weight was added through traction work. However, this is not always true. The additional mechanical loading from draught use represents an unnatural weight surplus, which may not be comparable to natural weight bearing. Based on the ratios of a/b, it is evident that three draught cattle exhibited significantly larger medial condyles compared to their lateral condyles, particularly on the forelimb. The a/b ratio, however, does not account for the possibility that both condyles may have been equally affected by external stress. To further investigate this issue, scatter plots were used to plot the raw size measurements.

Table 5.27: Results of Spearman's rank correlation between age and metapodials condyles ratios in modern draught and non-draught cattle.

| Element | n | R | P |
|---|---|---|---|
| Metacarpal | 148 | –0.06 | 0.53 NS |
| Metatarsal | 147 | 0.04 | 0.67 NS |

NS = non-significant ($P > 0.05$).

Table 5.28: Results of Spearman's rank correlation between body size proxies (metapodials Bd) and metapodials condyles ratios in modern draught and non-draught cattle independently.

| Element | Type | n | R | P |
|---|---|---|---|---|
| Metacarpal | Draught | 13 | –0.29 | 0.33 NS |
| | Non-draught | 129 | 0.34 | 0.00 *** |
| Metatarsal | Draught | 13 | –0.14 | 0.64 NS |
| | Non-draught | 134 | –0.27 | 0.00 *** |

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

Figure 5.7A displays the relationship between the greatest length (GL) and the greatest breadth distal end (Bd) of the metacarpals. Overall, draught cattle display a broader distal end compared to non-draught cattle. However, the difference between the two groups is not merely due to size; the metacarpals of equal lengths have a wider distal end in draught animals. This observation is further supported by Figure 5.7B, where the smallest breadth of the diaphysis (SD) is plotted against the greatest length (GL), revealing complete size overlap between the two groups. Comparable trends were observed in the metatarsals, as shown in Figures 5.7C and 5.7D. The draught cattle exhibit a broader distal end than the non-draught cattle, despite having similar metapodial lengths. These results suggest that the widening of the distal end in the draught cattle is likely a result of abnormality due to traction.

After confirming the broadening of the distal end in the draught cattle, the next step is to investigate whether the external stress caused by traction had an equal impact on both condyles. Figure 5.7A illustrates the size of the metacarpals, where individuals 91.107.M2, 91.107.M12, and 91.107.M11 have the largest distal width. However, they do not necessarily exhibit higher asymmetry. For example, 91.107.M2 has the largest Bd measurement of 87.1 mm and an a/b value of 1.02, suggesting a relatively similar width between the two condyles. 91.107.M12 was the second largest individual, with a Bd measurement of 84.5 mm and the third highest a/b ratio of 1.17. Interestingly, the Bd measurement of 91.107.M11, the third largest at 83.6 mm, has an a/b ratio of 0.98, showing a slightly smaller medial portion than the lateral portion.

Comparable observations have been made on the metatarsals. Individual 91.107.M4 shows the highest a/b ratio of 1.13 within the draught group and the largest Bd measurement of 84.7mm. Nonetheless, 91.107.M5, with the second largest ratio of 1.09, does not display a notably wider distal end of the metatarsal compared to other cattle in the group. Although the degree of asymmetry presents a substantial overlap between draught and non-draught cattle in Figure 5.6A, Figure 5.7C indicates a distinct cluster of draught cattle with a broadened metatarsal

distal end. These results suggest that artificial loading, added through traction, comparably affected both condyles, which can only occasionally be inferred from the a/b ratio (see metacarpal outliers).

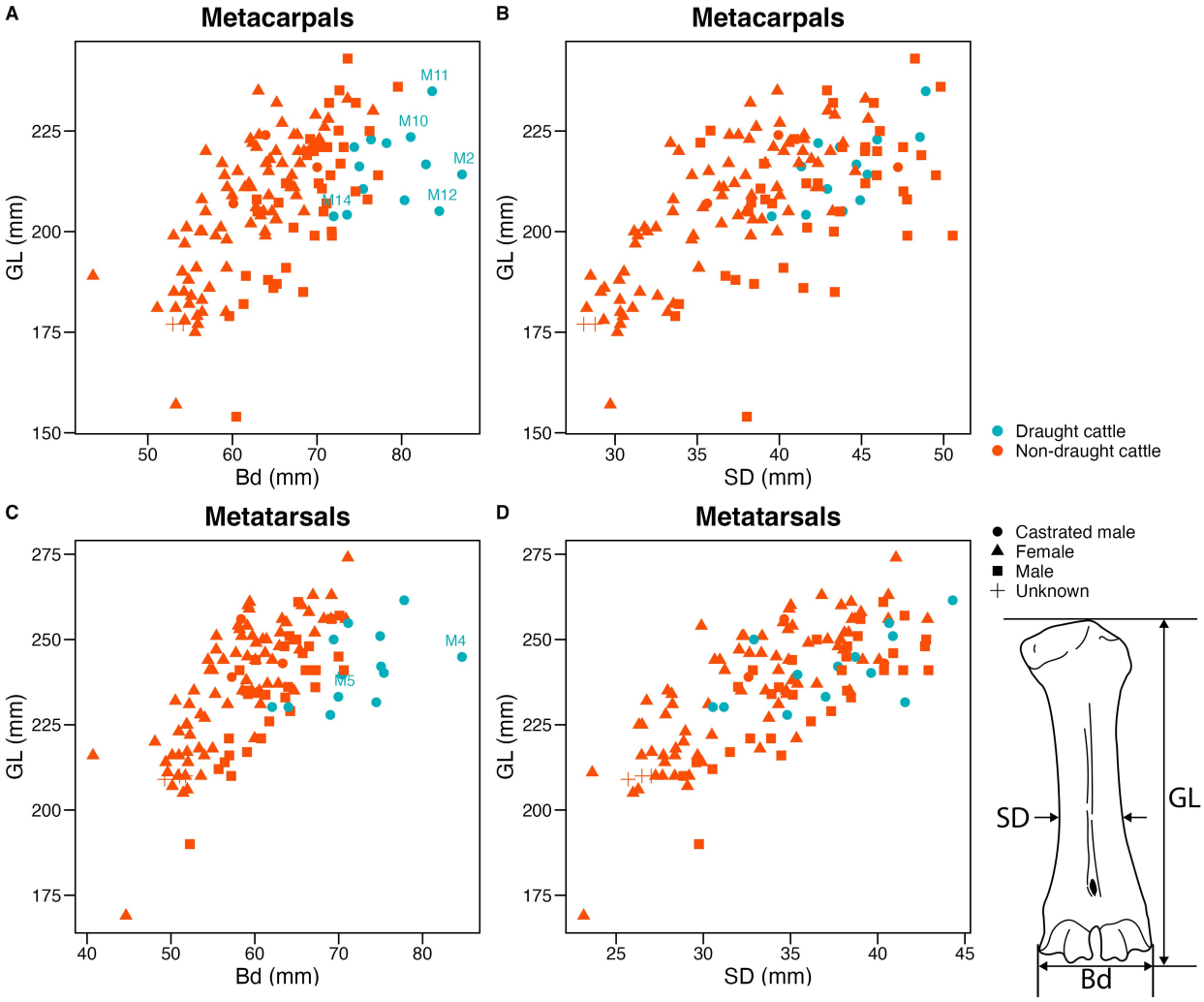



Figure 5.7: Size measurements of the draught and non-draught cattle metapodials. [**A**] The greatest length (GL) against the greatest breadth of the distal end (Bd) on metacarpals; [**B**] The greatest length (GL) against the smallest breadth of the diaphysis (SD) on metacarpals; [**C**] The greatest length (GL) against the greatest breadth of the distal end (Bd) on metatarsals; [**D**] The greatest length (GL) against the smallest breadth of the diaphysis (SD) on metatarsals.

Furthermore, it is worth noting that three oxen (IDs: 91.107.M1, 91.107.M5, and 91.107.M9) were documented in Bartosiewicz et al. (1997b: 18) as performers of exceptionally heavy logging work during their lifetimes. These oxen showed relatively symmetrical condyles on their metacarpals, with a/b ratios of 1.08,

1.01, and 1.08, respectively.

#### 5.6.1.3 Discussion: Asymmetry and broadening in the distal condyles of metapodials

The larger and more robust nature of the medial portion compared to the lateral portion of metapodials in ruminants has been suggested to result from unequal weight distribution across the body (Bartosiewicz et al., 1993; Páral et al., 2004). It has also been proposed that the asymmetry of the distal condyles could be exacerbated by the mechanical loading experienced during draught work, which imposes artificial weight on the animals (Bartosiewicz et al., 1993). The analyses of metapodials from both draught and non-draught cattle in this section are consistent with previous studies, indicating that the medial condyles are generally larger than the lateral condyles, especially in metacarpals. Conversely, the metatarsals exhibited a higher degree of symmetry, as indicated by the a/b ratio observed in both the draught and non-draught groups. Despite the lack of statistically significant differences in the a/b ratio between the draught and non-draught cattle, which might be attributed to the limited sample size of the draught group, the three most extreme cases of asymmetry (all metacarpals) are represented by draught animals.

Sexual dimorphism was observed in this study, with bulls displaying more pronounced asymmetry in the condyles. It has been previously suggested that the distal end of the metapodials, particularly the medial condyles of the metacarpals, are the most sexually dimorphic measurements in cattle (R. Thomas, 1988). The result of this study could be explained by the fact that bulls are generally heavier than cows, thus having a wider medial condyle because of the weight distribution. Based on this suggestion, it would be expected that the considerable loading during draught work would increase metapodial asymmetry in cattle. However, this is not always the case. Although three draught cattle presented a particularly high a/b ratio, most draught individuals had a similar a/b ratio to their non-draught counterparts. A plausible explanation for this outcome is that the artificial loading introduced by traction, representing an unnatural weight

surplus, might have prompted the animals to adapt their movement patterns to accommodate the additional load. The harnessing style may also affect how the draught cattle shift in their balance. This suggestion can be supported by the fact that the three oxen, which had performed weighty draught work, showed rather symmetrical distal condyles. Consequently, the impact from traction may not be directly comparable to the increase in natural body weight.

The results from this study have further revealed that the splaying of the distal end on metapodials does not necessarily indicate asymmetry of the two condyles. As illustrated by the size measurements on the greatest breadth of the distal end (Bd) and the greatest length (GL), several draught cattle show substantial splaying of the metapodial distal ends. Nonetheless, these cattle possessed two distal condyles that were symmetrical. The wider distal end observed in the draught cattle cannot be solely attributed to their larger body size because the analyses of measurements, such as the smallest breadth of the diaphysis (SD) and the greatest length (GL) of the metapodials in this study, indicate that the draught cattle were no larger than the non-draught cattle. Instead, it is more likely a result of the heavy use for traction work, leading to splaying in the distal end of the metapodials observed in the draught cattle. Therefore, although the metatarsal may exhibit more symmetrical distal condyles based on the a/b ratio, it should not be assumed that they are less susceptible to traction effects.

Overall, the results presented in this study align with previous research, suggesting that traction activities can have an impact on exacerbating the asymmetry in cattle metapodials. However, a significant overlap between draught and non-draught cattle of the a/b ratios has also been observed. Furthermore, it is evident that the splaying of the distal end, which is believed to be a result of draught work, does not consistently correspond to asymmetrical condyles. Thus, these results suggest that the asymmetry of metapodial condyles may not be an effective tool for classifying draught and non-draught cattle in archaeological materials.

### 5.6.2 Shape variations in modern cattle

The following section focuses on measurement ratios, aiming to reduce the impact of size variations that could interfere with the identification of draught and non-draught 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).

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.

Lastly, bivariate plots and logistic regression were employed to classify the draught and non-draught cattle based on different shape indices visually. The shape indices consist of two linear measurements (see Table 5.5).

#### 5.6.2.1 Statistical analyses on shape indices

Table 5.29 presents the results of the Mann-Whitney test comparing draught and non-draught cattle and shape indices on metacarpals. Apart from (b–f)/5, all of the tested shape indices show a significant variation among the two types of cattle. Similarly, shape indices from the metatarsals display statistical differences, with the exception of (b–f)/5 and SD/DD (Table 5.30). The non-significant results of (b–f)/5 on both metacarpals and metatarsals suggest that there is no evidence that external mechanical loading affected the medial part of the lateral condyle.

Table 5.29: Results of Mann-Whitney U test between type (draught and non-draught) and shape indices on metacarpals.

| Ratio | n. Draught Cattle | n. Non-draught | P |
|---|---|---|---|
| a/2 | 13 | 128 | 0.00 *** |
| b/5 | 13 | 128 | 0.00 *** |
| a/3 | 13 | 128 | 0.00 *** |
| b/6 | 13 | 128 | 0.00 *** |
| (a–e)/2 | 13 | 128 | 0.01 * |
| e/1 | 13 | 128 | 0.00 *** |
| (b–f)/5 | 13 | 128 | 0.21 NS |
| a/8 | 13 | 128 | 0.00 *** |
| b/10 | 13 | 128 | 0.00 *** |
| c/8 | 13 | 128 | 0.00 *** |
| d/10 | 13 | 128 | 0.00 *** |
| SD/DD | 13 | 128 | 0.00 *** |
| c/7 | 13 | 128 | 0.00 ** |
| d/9 | 13 | 128 | 0.00 *** |
| (a–e)/3 | 13 | 128 | 0.00 ** |
| (a–e)/7 | 13 | 128 | 0.00 *** |
| c/2 | 13 | 128 | 0.00 *** |
| d/5 | 13 | 128 | 0.00 *** |
| f/4 | 13 | 128 | 0.00 *** |
| Bd/GL | 13 | 124 | 0.00 *** |
| a/1 | 13 | 128 | 0.00 *** |
| b/4 | 13 | 128 | 0.00 *** |
| a/7 | 13 | 128 | 0.00 *** |
| b/9 | 13 | 128 | 0.00 *** |
| Bp/GL | 13 | 128 | 0.00 *** |
| BatF/GL | 13 | 123 | 0.00 *** |

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

All six shape indices tested on the first phalanges demonstrate highly significant variation (Table 5.31), while only Bp/Dp on the second phalanges shows no significant shape differences between the types (Table 5.32).

Table 5.30: Results of Mann-Whitney U test between type (draught and non-draught) and shape indices on metatarsals.

| Ratio | n. Draught Cattle | n. Non-draught | P |
|---|---|---|---|
| a/2 | 13 | 132 | 0.00 *** |
| b/5 | 12 | 133 | 0.00 *** |
| a/3 | 13 | 132 | 0.00 ** |
| b/6 | 13 | 132 | 0.00 *** |
| (a–e)/2 | 13 | 132 | 0.04 * |
| e/1 | 13 | 133 | 0.00 *** |
| (b–f)/5 | 12 | 133 | 0.71 NS |
| a/8 | 13 | 132 | 0.00 ** |
| b/10 | 13 | 132 | 0.00 ** |
| c/8 | 13 | 132 | 0.00 ** |
| d/10 | 13 | 132 | 0.00 ** |
| SD/DD | 13 | 133 | 0.76 NS |
| c/7 | 13 | 132 | 0.00 ** |
| d/9 | 13 | 132 | 0.00 *** |
| (a–e)/3 | 13 | 132 | 0.00 ** |
| (a–e)/7 | 13 | 133 | 0.00 *** |
| c/2 | 13 | 132 | 0.00 *** |
| d/5 | 12 | 132 | 0.00 *** |
| f/4 | 13 | 132 | 0.00 *** |
| Bd/GL | 13 | 114 | 0.00 *** |
| a/1 | 13 | 133 | 0.00 *** |
| b/4 | 13 | 132 | 0.00 *** |
| a/7 | 13 | 133 | 0.00 ** |
| b/9 | 13 | 133 | 0.00 *** |
| Bp/GL | 13 | 114 | 0.00 *** |
| BatF/GL | 13 | 113 | 0.00 *** |

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

Table 5.31: Results of Mann-Whitney U test between type (draught and non-draught) and shape indices on first phalanges.

| Anatomical element | Ratio | n. Draught | n. Non-draught | P |
|---|---|---|---|---|
| Anterior first phalanx | Bp/Dp | 17 | 100 | 0.00 *** |
| | Bd/GL | 17 | 100 | 0.00 *** |
| | Bd/GLpe | 17 | 100 | 0.00 *** |
| | Bp/GLpe | 17 | 100 | 0.00 *** |
| | Bp/Bd | 17 | 100 | 0.00 ** |
| | Dp/GLpe | 17 | 100 | 0.00 *** |
| Posterior first phalanx | Bp/Dp | 13 | 97 | 0.00 ** |
| | Bd/GL | 13 | 97 | 0.00 *** |
| | Bd/GLpe | 13 | 97 | 0.00 *** |
| | Bp/GLpe | 13 | 97 | 0.00 *** |
| | Bp/Bd | 13 | 97 | 0.00 *** |
| | Dp/GLpe | 13 | 97 | 0.00 *** |

*** = very highly significant ($P \leq 0.001$ ), ** = highly significant ($P \leq 0.01$).

Table 5.32: Results of Mann-Whitney U test between type (draught and non-draught) and shape indices on second phalanges.

| Anatomical element | Ratio | n. Draught | n. Non-draught | P |
|---|---|---|---|---|
| Anterior second phalanx | Bp/Dp | 15 | 104 | 0.24 NS |
| | Bd/GL | 15 | 104 | 0.00 *** |
| | Bd/GLpe | 15 | 104 | 0.00 *** |
| | Bp/GLpe | 15 | 104 | 0.00 *** |
| | Bp/Bd | 15 | 104 | 0.00 *** |
| | Dp/GLpe | 15 | 104 | 0.00 *** |
| Posterior second phalanx | Bp/Dp | 16 | 95 | 0.87 NS |
| | Bd/GL | 16 | 95 | 0.00 *** |
| | Bd/GLpe | 16 | 95 | 0.00 *** |
| | Bp/GLpe | 16 | 95 | 0.00 *** |
| | Bp/Bd | 16 | 95 | 0.00 *** |
| | Dp/GLpe | 16 | 95 | 0.00 *** |

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

#### 5.6.2.2 Effect of age on shape variations

The prior section has revealed significant variations in most shape indices on the metapodials and phalanges between draught and non-draught cattle. Nevertheless, given that the mean age of the draught cattle group (10.2 years) is higher than that of the non-draught group (7.4 years), caution should be taken to ascertain whether ageing is a confounding factor that might contribute to these findings. Thus, this section adopted Spearman's rank correlation and multiple linear regression to test the correlation between age and morphological changes in cattle limb elements.

**Metacarpals**

Spearman's rank correlation tests between metacarpal shape indices and age show that six indices, including b/6, a/8, b/10, c/8, b/4, and b/9, demonstrated a weak positive correlation with age (Table 5.33). The fact that modern traction cattle were generally kept alive for longer may lead to the wrong assumption that the morphological changes could be attributed to ageing. Bivariate analysis, examining one dependent variable against one independent variable, may oversimplify the complex interplay of factors. This method isolates the relationship

Table 5.33: Summary of Spearman's rank correlation analysis between age and shape indices on metacarpals in modern draught and non-draught cattle.

| Ratio | n | R | P |
|---|---|---|---|
| a/2 | 111 | 0.14 | 0.13 NS |
| b/5 | 111 | 0.16 | 0.09 NS |
| a/3 | 111 | 0.17 | 0.08 NS |
| b/6 | 111 | 0.23 | 0.01 * |
| (a–e)/2 | 111 | –0.03 | 0.78 NS |
| e/1 | 111 | 0.13 | 0.16 NS |
| (b–f)/5 | 111 | 0.03 | 0.73 NS |
| a/8 | 111 | 0.21 | 0.03 * |
| b/10 | 111 | 0.22 | 0.02 * |
| c/8 | 111 | 0.20 | 0.04 * |
| d/10 | 111 | 0.17 | 0.08 NS |
| SD/DD | 111 | 0.11 | 0.26 NS |
| c/7 | 111 | 0.14 | 0.17 NS |
| d/9 | 111 | 0.17 | 0.07 * |
| (a–e)/3 | 111 | –0.02 | 0.86 NS |
| (a–e)/7 | 111 | –0.03 | 0.75 NS |
| c/2 | 111 | 0.12 | 0.19 NS |
| d/5 | 111 | 0.10 | 0.31 NS |
| f/4 | 111 | 0.16 | 0.08 NS |
| Bd/GL | 110 | 0.08 | 0.37 NS |
| a/1 | 111 | 0.19 | 0.06 NS |
| b/4 | 111 | 0.20 | 0.04 * |
| a/7 | 111 | 0.16 | 0.10 NS |
| b/9 | 111 | 0.22 | 0.02 * |
| Bp/GL | 110 | 0.06 | 0.50 NS |
| BatF/GL | 110 | 0.00 | 0.93 NS |

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

between variables, potentially leading to the misleading suggestion that these ratios are solely related to old age. To address this issue and consider potential confounding factors, a multivariable linear regression analysis was applied to the six indices that exhibited correlations with age.

The multivariable analysis illustrates that age did not maintain a significant association with the shape indices (Table 5.34). However, significant variations between the draught and non-draught animals were observed. These findings suggest that the working history of the cattle, rather than age itself, probably had a more substantial impact on the morphological changes in draught cattle.

Table 5.34: Results of multivariable linear regression on two variables (age and type) and shape indices on metacarpals in modern draught and non-draught cattle.

| Ratio | Variable | T | P |
|---|---|---|---|
| b/6 | Age | 0.24 | 0.81 NS |
| | Type | –6.37 | 0.00 *** |
| a/8 | Age | 0.38 | 0.70 NS |
| | Type | –7.12 | 0.00 *** |
| b/10 | Age | 0.61 | 0.54 NS |
| | Type | –5.69 | 0.00 *** |
| c/8 | Age | 0.36 | 0.73 NS |
| | Type | –4.98 | 0.00 *** |
| d/9 | Age | 0.10 | 0.92 NS |
| | Type | –3.06 | 0.00 ** |
| b/4 | Age | 0.01 | 0.99 NS |
| | Type | –7.99 | 0.00 *** |
| b/9 | Age | 0.57 | 0.57 NS |
| | Type | –6.06 | 0.00 *** |

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

### Metatarsals

Likewise, five shape indices from the metatarsals show correlations with age (Table 5.35). When considering the multivariable linear regression model in Table 5.36, indices including e/1, f/4, a/1, and a/7 ratios show no significant association with age. Conversely, SD/DD is correlated with age, with no variation between draught and non-draught cattle. It should be noted that the lack of variation in this index was previously identified in Table 5.30.

Table 5.35: Summary of Spearman's rank correlation analysis between age and shape indices on metatarsals in modern draught and non-draught cattle.

| Ratio | n | R | P |
|---|---|---|---|
| a/2 | 116 | 0.16 | 0.07 NS |
| b/5 | 115 | 0.10 | 0.25 NS |
| a/3 | 116 | 0.15 | 0.09 NS |
| b/6 | 116 | 0.13 | 0.17 NS |
| (a–e)/2 | 116 | –0.07 | 0.43 NS |
| e/1 | 116 | 0.28 | 0.00 * |
| (b–f)/5 | 115 | –0.06 | 0.53 NS |
| a/8 | 116 | 0.15 | 0.10 NS |
| b/10 | 116 | 0.11 | 0.21 NS |
| c/8 | 116 | 0.08 | 0.35 NS |
| d/10 | 116 | 0.04 | 0.67 NS |
| SD/DD | 116 | –0.20 | 0.03 * |
| c/7 | 116 | 0.11 | 0.21 NS |
| d/9 | 116 | 0.15 | 0.11 NS |
| (a–e)/3 | 116 | –0.07 | 0.44 NS |
| (a–e)/7 | 116 | –0.06 | 0.54 NS |
| c/2 | 116 | 0.12 | 0.20 NS |
| d/5 | 115 | 0.04 | 0.67 NS |
| f/4 | 116 | 0.33 | 0.00 ** |
| Bd/GL | 101 | 0.11 | 0.27 NS |
| a/1 | 116 | 0.21 | 0.02 * |
| b/4 | 116 | 0.13 | 0.14 NS |
| a/7 | 116 | 0.19 | 0.04 * |
| b/9 | 116 | 0.18 | 0.06 NS |
| Bp/GL | 101 | 0.16 | 0.12 NS |
| BatF/GL | 101 | 0.03 | 0.77 NS |

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

Table 5.36: Results of multivariable linear regression on two variables (age and type) and shape indices on metatarsals in modern draught and non-draught cattle.

| Ratio | Variable | T | P |
|---|---|---|---|
| e/1 | Age | 1.37 | 0.17 NS |
| | Type | –7.97 | 0.00 *** |
| SD/DD | Age | –2.65 | 0.00 ** |
| | Type | –0.74 | 0.46 NS |
| f/4 | Age | 2.11 | 0.14 NS |
| | Type | –6.86 | 0.00 *** |
| a/1 | Age | 0.82 | 0.41 NS |
| | Type | –5.66 | 0.00 *** |
| a/7 | Age | 0.96 | 0.34 NS |
| | Type | –3.73 | 0.00 *** |

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

### First phalanges

The shape indices Bd/GL and Bd/GLpe on the anterior first phalanges exhibit significant associations with ageing (Table 5.37), whilst none of the tested indices on the posterior first phalanges is associated with age (Table 5.38). Nonetheless, both the shape indices on the anterior first phalanges show no significant variation with age in the multivariable analysis (Table 5.39).

Table 5.37: Summary of Spearman's rank correlation analysis between age and shape indices on anterior first phalanges in modern draught and non-draught cattle.

| Ratio | n | R | P |
|---|---|---|---|
| Bp/Dp | 87 | 0.08 | 0.46 NS |
| Bd/GL | 87 | 0.24 | 0.02 * |
| Bd/GLpe | 87 | 0.22 | 0.04 * |
| Bp/GLpe | 87 | 0.20 | 0.06 NS |
| Bp/Bd | 87 | –0.10 | 0.34 NS |
| Dp/GLpe | 87 | 0.12 | 0.25 NS |

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

Table 5.38: Summary of Spearman's rank correlation analysis between age and shape indices on posterior first phalanges in modern draught and non-draught cattle.

| Ratio | n | R | P |
|---|---|---|---|
| Bp/Dp | 86 | –0.07 | 0.53 NS |
| Bd/GL | 86 | 0.16 | 0.15 NS |
| Bd/GLpe | 86 | 0.23 | 0.34 NS |
| Bp/GLpe | 86 | 0.13 | 0.21 NS |
| Bp/Bd | 86 | –0.09 | 0.37 NS |
| Dp/GLpe | 86 | 0.27 | 0.12 NS |

NS = non-significant ($P > 0.05$).

Table 5.39: Results of multivariable linear regression on two variables (age and type) and shape indices on anterior first phalanges in modern draught and non-draught cattle.

| Ratio | Variable | T | P |
|---|---|---|---|
| Bd/GL | Age | 0.02 | 0.99 NS |
| | Type | –12.26 | 0.00 *** |
| Bd/GLpe | Age | –0.21 | 0.83 NS |
| | Type | 10.48 | 0.00 *** |

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

### Second phalanges

Table 5.40 presents Spearman's rank correlation results for the anterior second phalanges, indicating no significant association between the shape indices in the forelimbs and age. Significant results are noticed in Bp/GLpe and Dp/GLpe of the posterior second phalanges (Table 5.41). Nonetheless, it is further confirmed by the multivariable linear regression that age was not a critical factor contributing to the shape variations between draught and non-draught cattle (Table 5.42).

Table 5.40: Summary of Spearman's rank correlation analysis between age and shape indices on anterior second phalanges in modern draught and non-draught cattle.

| Ratio | n | R | P |
|---|---|---|---|
| Bp/Dp | 86 | –0.01 | 0.91 NS |
| Bd/GL | 86 | 0.04 | 0.67 NS |
| Bd/GLpe | 86 | 0.02 | 0.84 NS |
| Bp/GLpe | 86 | 0.12 | 0.27 NS |
| Bp/Bd | 86 | 0.00 | 0.93 NS |
| Dp/GLpe | 86 | 0.11 | 0.30 NS |

NS = non-significant ($P > 0.05$).

Table 5.41: Summary of Spearman's rank correlation analysis between age and shape indices on posterior second phalanges in modern draught and non-draught cattle.

| Ratio | n | R | P |
|---|---|---|---|
| Bp/Dp | 85 | 0.01 | 0.91 NS |
| Bd/GL | 85 | 0.14 | 0.20 NS |
| Bd/GLpe | 85 | 0.16 | 0.14 NS |
| Bp/GLpe | 85 | 0.26 | 0.02 * |
| Bp/Bd | 85 | 0.00 | 0.96 NS |
| Dp/GLpe | 85 | 0.24 | 0.02 * |

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

Table 5.42: Results of multivariable linear regression on two variables (age and type) and shape indices on posterior second phalanges in modern draught and non-draught cattle.

| **Ratio** | **Variable** | **T** | **P** |
|---|---|---|---|
| Bp/GLpe | Age | 0.67 | 0.50 NS |
| | Type | –8.98 | 0.00 *** |
| Dp/GLpe | Age | 0.31 | 0.76 NS |
| | Type | –8.26 | 0.00 *** |

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

#### 5.6.2.3 Principal component analysis on shape ratio and breed

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 to two dimensions for recognising breed/type clusters with similar morphological characteristics.

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

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. These two White Park ancient cattle herds are local to England. 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). It has been observed in the previous bivariate plots that there may be a similarity in morphology between the Chartley cattle and the draught cattle, suggesting that they are both large and robust.

**Metapodials**

Figure 5.8A illustrates the PCA result for the metacarpals categorised by breeds. There is a clear distinction between the non-draught cattle and the draught oxen, although two non-draught cattle plot closely with the draught cattle. In particular, the Romanian non-draught bulls form a distinct cluster with the non-draught group, aligning well with this subgroup and distinctly differing from the

draught cattle within the same crossbreed. This finding further supports the idea that traction activities have contributed to the observed skeletal morphology variations, as evidenced by the discernible morphological differences within the same crossbreed.

The Chartley cattle are plot towards the draught oxen. Although the sample size for the Chartley is small, this result aligns with analyses discussed later in this chapter, suggesting that Chartley bulls may have similar morphological characteristics to draught oxen. The potential overlap between non-draught and working cattle further highlights that the greater robustness of skeletal morphology may be an intrinsic characteristic of certain cattle breeds. Thus, caution is needed when interpreting biometric results from archaeological materials to identify traction animals, as stocky morphological features may be inherent to particular breeds and unrelated to their use in traction.

In the metatarsals, a comparable pattern is observed as with the metacarpals. The non-draught cattle group shows distinct clustering from the draught cattle group, with minimal overlap (Figure 5.8B). The Romanian non-draught bulls display a greater similarity to the non-draught group rather than the draught group. This finding suggests that traction has a significant impact on the morphological characteristics of metatarsals.

**First phalanges**

The draught oxen show significantly distinct anterior first phalanges compared to the non-draught group, as represented by the purple group (Figure5.8C). The Romanian non-draught bulls, however, tend to cluster closely with their draught counterparts rather than the non-draught group.

Figure 5.8D illustrates the PCA results obtained from the posterior first phalanges. A clear separation between the draught and non-draught groups can be observed. Interestingly, the Romanian non-draught bulls form a distinct cluster that sits between the draught and non-draught groups, suggesting that the Romanian non-draught cattle may have some morphological features that are intermediate between the two groups.

### Second phalanges

The analysis of the shape variation of the anterior second phalanges (Figure 5.8E) demonstrates a similar pattern to the anterior first phalanges, in which the Romanian bulls are positioned closer to the draught cattle group. Figure 5.8F shows an equally clear separation between the non-draught and draught cattle in the posterior second phalanges. The Romanian bulls are also positioned closer to the draught cattle, indicating morphological similarities.

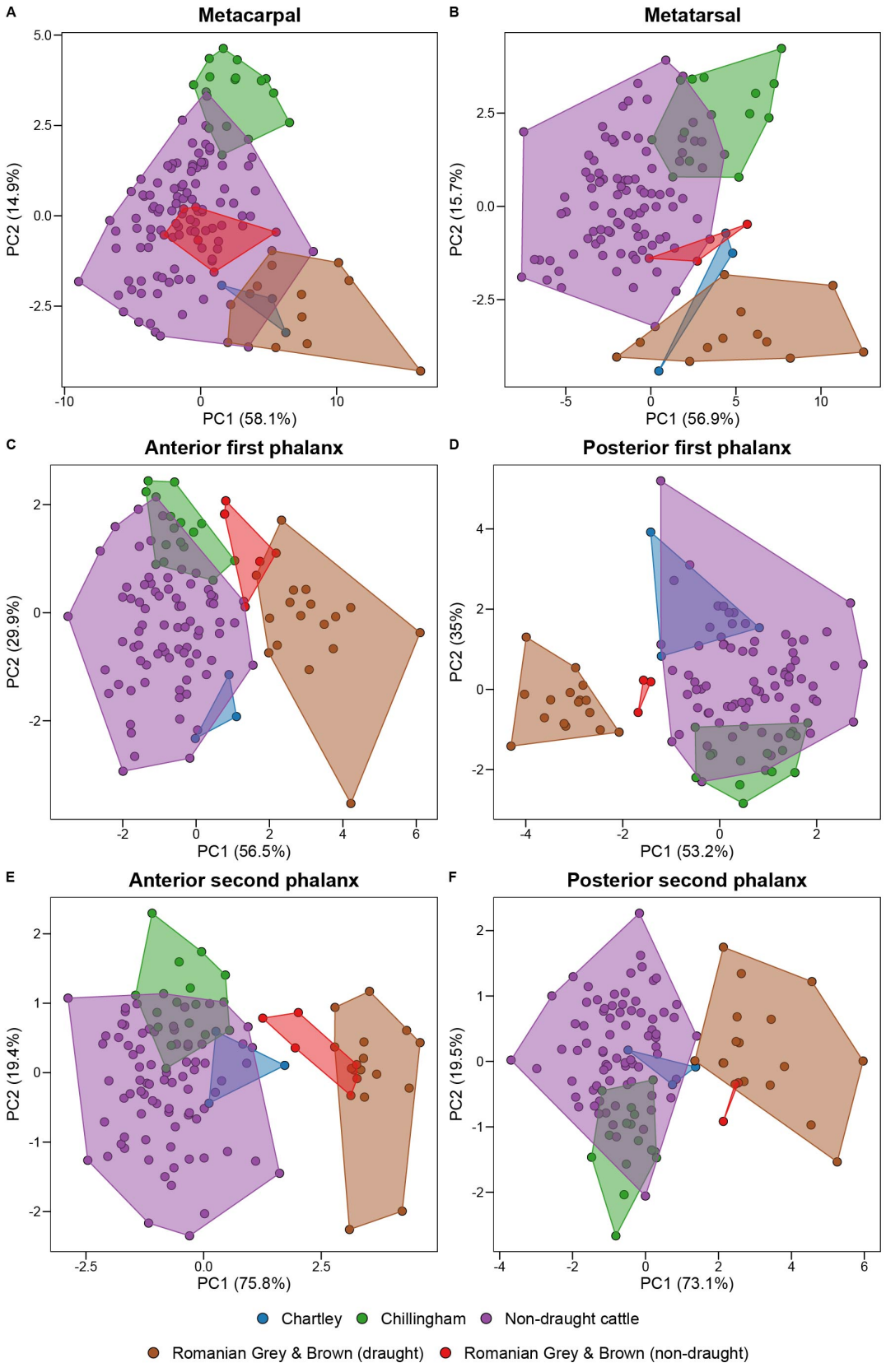



Figure 5.8: Principal component analysis results on shape ratios show that the first component (PC1) captures the direction of maximum variance in the data, while the second component (PC2) captures additional variability, which is orthogonal to PC1. See Figure 5.9 for the contributions of variables to PC1 and PC2.

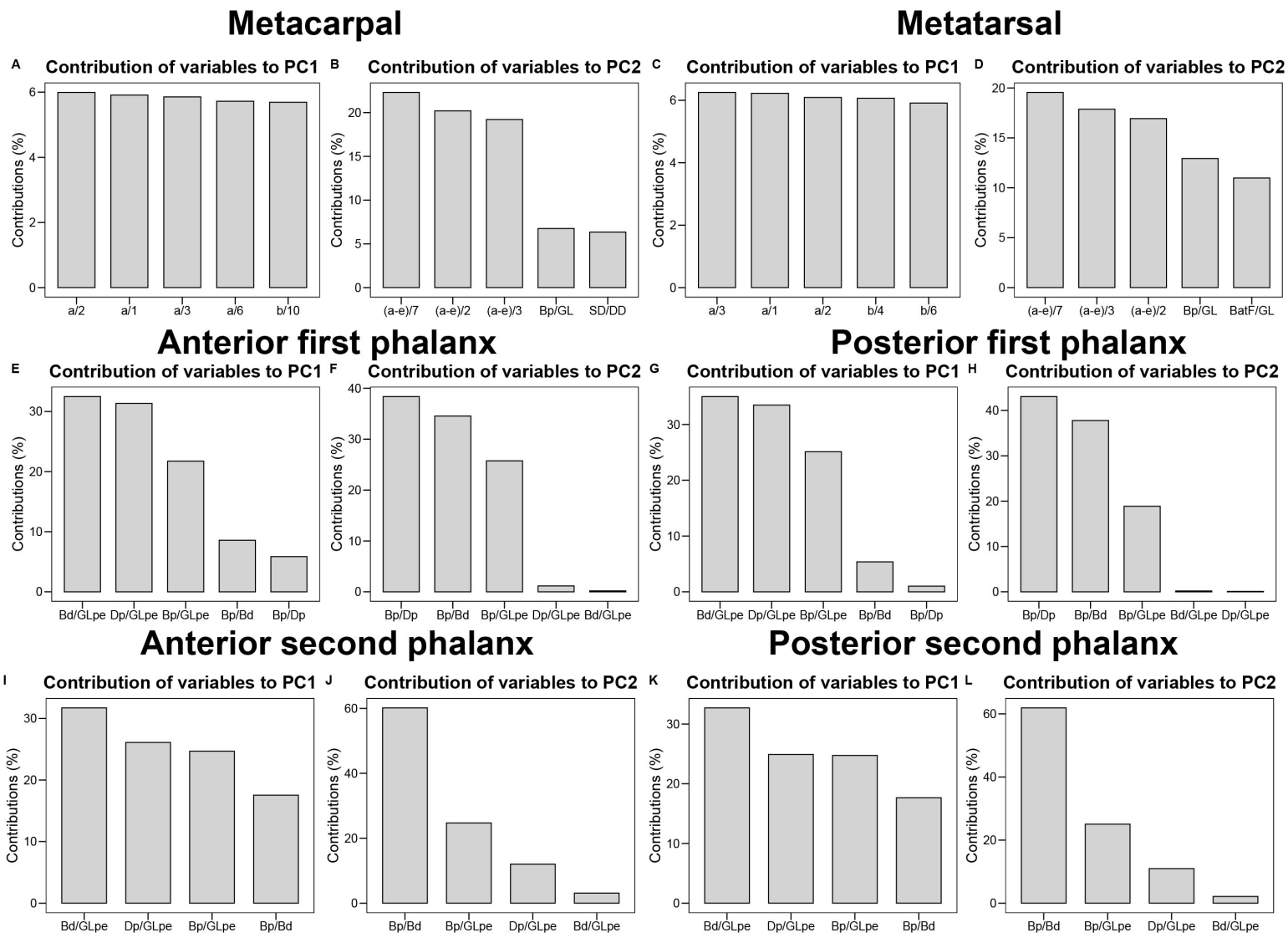



Figure 5.9: The top five contributing variables to the first component (PC1) and second component (PC2) for [**A-B**] metacarpal, [**C-D**] metatarsal, [**E-F**] anterior first phalanx, [**G-H**] posterior first phalanx, [**I-J**] anterior second phalanx, and [**K-L**] posterior second phalanx. See Table 5.5 for the abbreviations of the measurements.

The proximity of the Romanian bulls to the draught group in the PCA results suggests that this particular crossbreed possibly has a distinct morphology in the phalanges compared to other cattle. Nonetheless, it is important to mention that the non-draught group was represented by numerous breeds and species of cattle. The significant clustering observed between the non-draught and draught cattle implies that breeds may have a minor effect on the classification. Interestingly, the Chartley cattle display a similar morphology to the draught cattle primarily in the metapodials, while the Chillingham herd consistently shows variations compared to the non-draught group across all anatomical elements tested. Overall, breeds appear to have a moderate influence on the morphology of limb bones, particularly the anterior phalanges. However, the Romanian non-draught bulls exhibit distinct characteristics compared to the Romanian draught oxen in most scenarios, supporting the argument that traction contributes significantly to morphological differences observed among the two groups.

#### 5.6.2.4 Bivariate plots and logistic regression

The previous sections have confirmed that most shape indices exhibit significant variations between draught and non-working cattle. To further analyse the data, bivariate plots were employed for visual classification. Logistic regression was applied to create decision boundaries between two shape indices used in the scatter plot. 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 5.3 (Train, 2009: 39).

$$P(Y=1) = \frac{1}{1+e^{-(\beta^0+\beta^1 X^1+\beta^2 X^2+\cdots+\beta^p X^p)}} \tag{5.3}$$

In Equation 5.3, $P(Y=1)$ is the probability of a specimen being classified as Class 1 (i.e. draught cattle). $\beta^0$ represents the constant term in the equation, 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. 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).

The constants and coefficients related to the predictor ratios in the subsequent plots are provided in a later section. By substituting the measurements from archaeological specimens into the provided equations, it is possible to classify unknown specimens and estimate the probability of class membership without the need for the dataset used here.

The actual size of the animals has limited utility in classifying draught cattle due to potential confounding factors such as sex and breed; shape indices were adopted to mitigate the effect of size. Nonetheless, size measurements were incorporated as one axis in several bivariate plots of metapodials, a methodology previously advocated by Lin et al. (2016) as the most effective combination for distinguishing draught individuals. As discussed in Section 5.6.1, it should be noted that the broadened distal end of metapodials in draught cattle does not indicate that they were larger than non-draught cattle.

Various attempts have been made to find the optimal combination for classifying draught and non-draught cattle. In the following section, only those metric pairs that provided the greatest level of separation are presented. For results of the less effective combinations, see Appendix B.

**Metacarpals**

Figure 5.10A provides a reasonably good result, with only seven individuals plotting in the 'wrong' area when using the f/4 against the e/1 ratio. Both ratios have higher values in draught cattle, indicating a wider width relative to the diameter of the trochlea.

Even though fewer non-draught cattle are incorrectly classified in Figure 5.10B when comparing the a/1 and f/4 ratio, more draught cattle are plotted into the non-draught area. The less effective classification of using the a/1 ratio compared

to the e/1, as presented in Figure 5.10A, may suggest that traction has less impact on the medial part of the medial condyle, as 'a' represents the entire width of the condyle while 'e' only represents the most medial part.

Another notable trend observed in Figure 5.10C is the high degree of correlation between the b/4 and a/1 ratios in non-draught cattle, indicating a similarity in condyle width relative to the diameter on both sides of the condyles. Conversely, draught cattle display scattered distributions, with several animals showing a larger a/1 ratio.

In Figure 5.10, all non-draught cattle that plot in the draught cattle area are bulls, including a yak. Given the distinct morphological differences in the metacarpals, particularly the wider lateral portion in proportion to the diameter of the trochlea on the medial condyles of the yak compared to domestic cattle (Plate 5.13), it is unsurprising that the yak is consistent with the draught cattle, given the distinct shape of its distal metacarpal. Plate 5.13 indicates that this yak specimen could have pathologies, which may further influence the biometric pattern. These results also highlight the presence of sexual dimorphism in the shape of the metacarpal condyles, suggesting that bulls may develop robust distal condyles similar to draught cattle that were affected by external loadings.

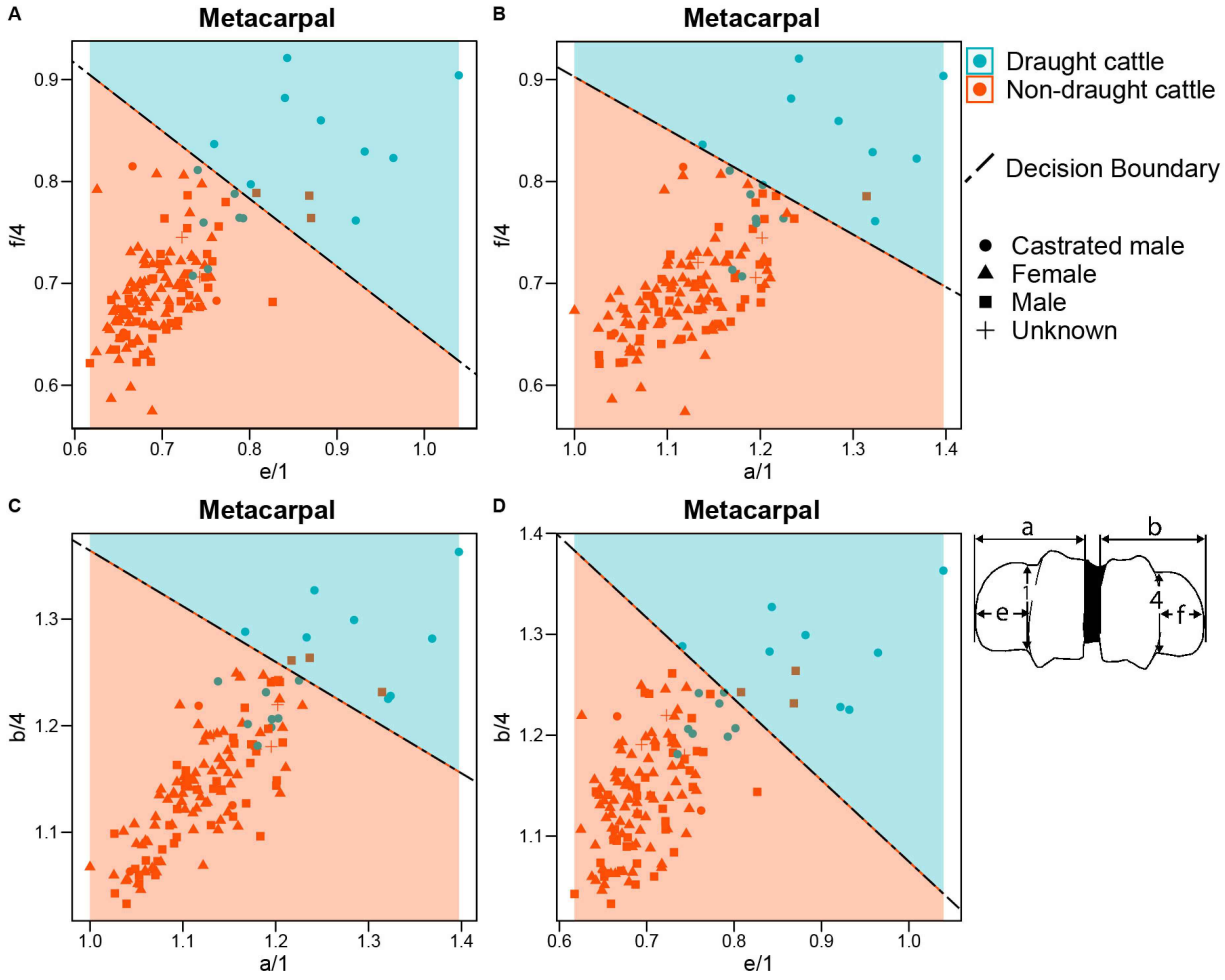



Figure 5.10: Shape ratios on metacarpal condyles of draught and non-draught cattle. [**A**] The greatest breadth from medial condyle ridge to medial articulation edge (e) to the antero-posterior diameter of the external trochlea of the medial condyle (1) against the greatest breadth from lateral condyle ridge to lateral articulation edge (f) to the antero-posterior diameter of the external trochlea of the lateral condyle (4) ; [**B**] The medio-lateral width of the medial condyle (a) to the antero-posterior diameter of the external trochlea of the medial condyle (1) against the greatest breadth from lateral condyle ridge to lateral articulation edge (f) to the antero-posterior diameter of the external trochlea of the lateral condyle (4); [**C**] The medio-lateral width of the medial condyle (a) to the antero-posterior diameter of the external trochlea of the medial condyle (1) against the medio-lateral width of the lateral condyle (b) to the antero-posterior diameter of the external trochlea of the lateral condyle (4); [**D**] The greatest breadth from medial condyle ridge to medial articulation edge (e) to the antero-posterior diameter of the external trochlea of the medial condyle (1) against the medio-lateral width of the lateral condyle (b) to the antero-posterior diameter of the external trochlea of the lateral condyle (4).

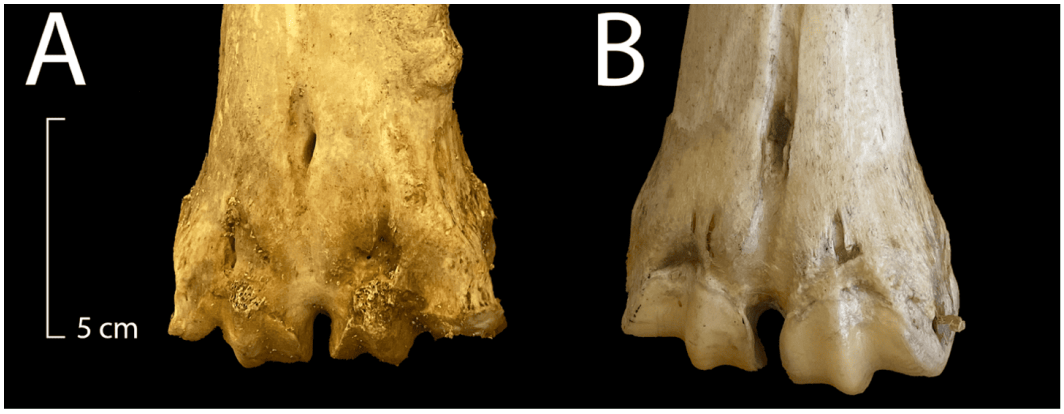



Plate 5.13: Comparison of the right distal metacarpal between [**A**] a yak (*Bos grunniens*) and [**B**] non-draught domestic cattle (Holländer cow). The yak metacarpal could be deformed due to pathology.

Figure 5.11 illustrates the Bd/GL ratio against the shape ratios of medial and lateral condyles separately. The draught group not only shows a high Bd/GL ratio but also demonstrates higher ratios in f/4, e/1, b/4, and a/1 than the non-draught counterparts. Specifically, the f/4 ratio with Bd/GL in Figure 5.11A shows a relatively distinct pattern.

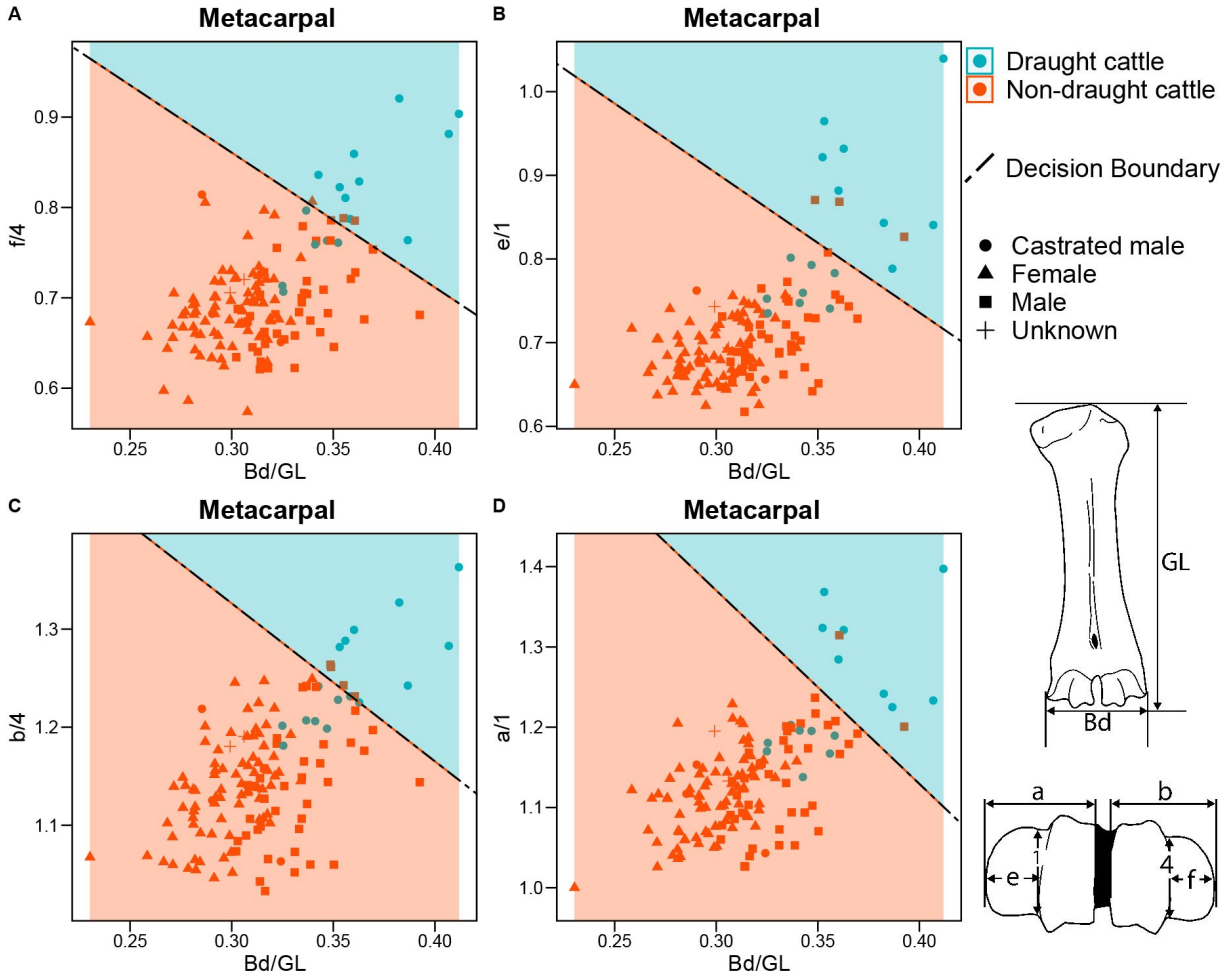



Figure 5.11: Shape ratios of metacarpal condyles against the greatest breadth of the distal end (Bd) to the greatest length (GL) of draught and non-draught cattle. [**A**] The greatest breadth of the distal end (Bd) to the greatest length (GL) against the greatest breadth from lateral condyle ridge to lateral articulation edge (f) to the antero-posterior diameter of the external trochlea of the lateral condyle (4); [**B**] The greatest breadth of the distal end (Bd) to the greatest length (GL) against the greatest breadth from medial condyle ridge to medial articulation edge (e) to the antero-posterior diameter of the external trochlea of the medial condyle (1); [**C**] The greatest breadth of the distal end (Bd) to the greatest length (GL) against the medio-lateral width of the lateral condyle (b) to the antero-posterior diameter of the external trochlea of the lateral condyle (4); [**D**] The greatest breadth of the distal end (Bd) to the greatest length (GL) against the medio-lateral width of the medial condyle (a) to the antero-posterior diameter of the external trochlea of the medial condyle (1).

The above analyses primarily focused on the morphological changes observed in the distal end of the metapodials, as prior studies have suggested that these areas are more likely to be affected by traction. When considering the greatest

breadth of the proximal end on the y-axis, it is evident that there is no distinction based on the Bp/GL ratio (Figure 5.12A). The classification of draught and non-draught types primarily relies on the x-axis, representing the distal width (Bd/GL). A similar pattern is illustrated by the SD/GL and Bd/GL ratios in Figure 5.12B, where the variation between the two groups is only visible on the x-axis. These observed patterns support the idea that traction has a limited impact on the proximal and diaphyseal regions of the metacarpals, whereas the distal end appears to be more susceptible to modifications associated with traction.

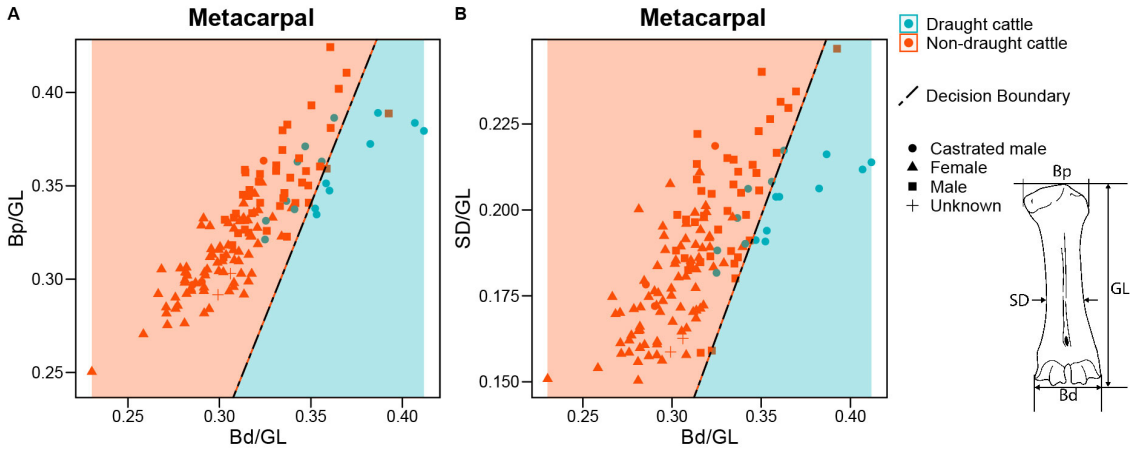



Figure 5.12: Shape ratios of proximal and diaphyseal regions against the greatest breadth of the distal end (Bd) to the greatest length (GL) on metacarpals of draught and non-draught cattle. [**A**] The greatest breadth of the distal end (Bd) to the greatest length (GL) against the greatest breadth of the proximal end (Bp) to the greatest length (GL); [**B**] The greatest breadth of the distal end (Bd) to the greatest length (GL) against the smallest breadth of the diaphysis (SD) to the greatest length (GL).

### Metatarsals

When shape ratios of the metatarsals are applied to both axes in Figure 5.13, the distinctions between groups are less evident. Figure 5.13A provides better separation than Figure 5.13B when applying the e/1 and f/4 ratios. A substantial overlap in both axes is indicated in 5.13B, suggesting that the shape ratios of the lateral portions of each condyle (e/1 and f/4) are more effective for classification.

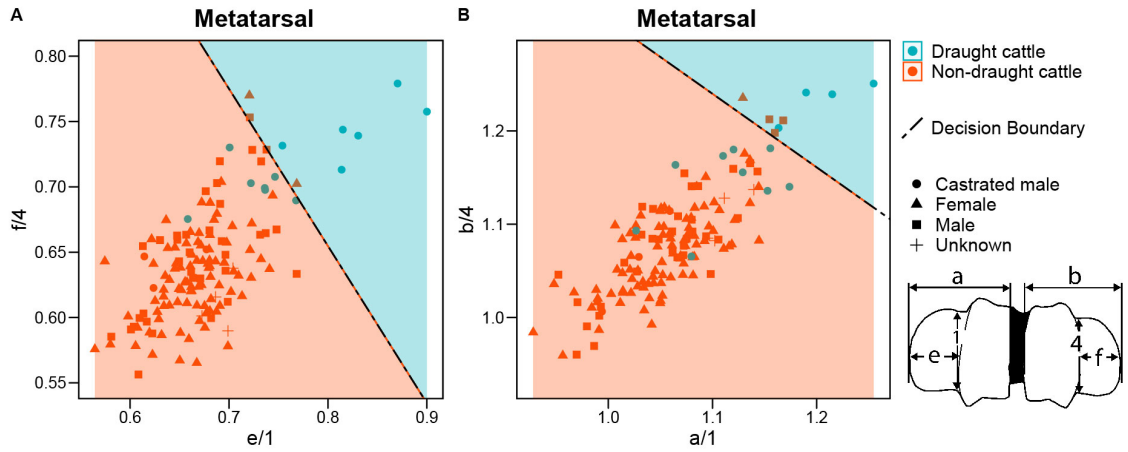



Figure 5.13: Shape ratios on metatarsal condyles of draught and non-draught cattle. [**A**] The greatest breadth from medial condyle ridge to medial articulation edge (e) to the antero-posterior diameter of the external trochlea of the medial condyle (1) against the greatest breadth from lateral condyle ridge to lateral articulation edge (f) to the antero-posterior diameter of the external trochlea of the lateral condyle (4); [**B**] The medio-lateral width of the medial condyle (a) to the antero-posterior diameter of the external trochlea of the medial condyle (1) against the medio-lateral width of the lateral condyle (b) to the antero-posterior diameter of the external trochlea of the lateral condyle (4).

Effective classifications are demonstrated by plotting condyle shape ratios with Bd/GL on metatarsals (Figure 5.14). Nonetheless, the differentiation between draught and non-draught animals is primarily determined by the x-axis, indicating that draught cattle tend to have an overall larger Bd/GL ratio than their non-draught counterparts.

There are no clear distinctions between draught and non-draught cattle based on the condyle ratios of the metatarsals. The Bd/GL ratio is, however, significantly higher in the draught group (Figure 5.14). These patterns may indicate that the impact of draught work contributes to the deformation of the distal end of the metatarsals, resulting in high Bd/GL values. Meanwhile, the condyles show alterations in their overall dimensions; thus, the ratios of independent condyles remain relatively constant, similar to the non-draught cattle.

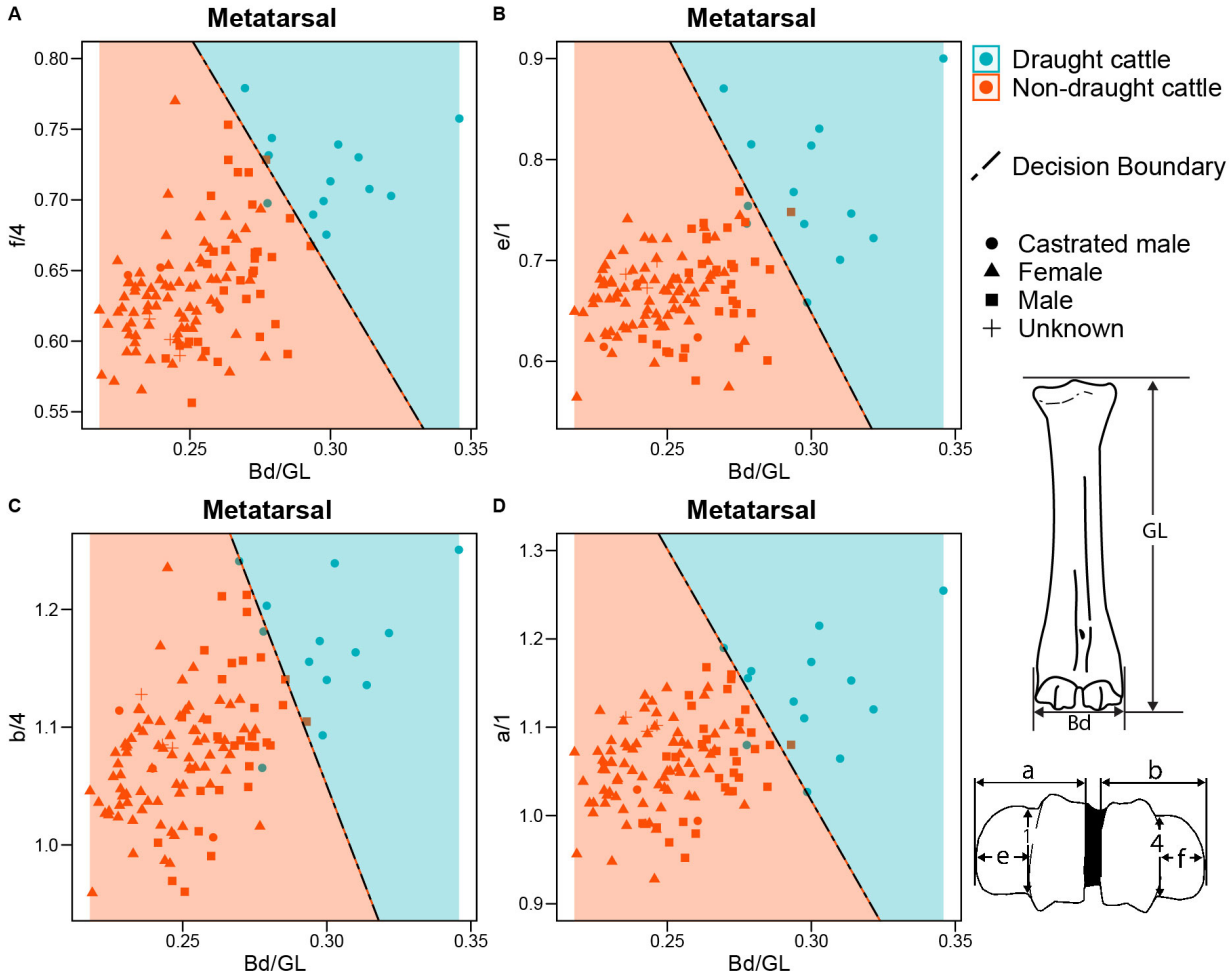



Figure 5.14: Shape ratios of metatarsal condyles against the greatest breadth of the distal end (Bd) to the greatest length (GL) of draught and non-draught cattle. [**A**] The greatest breadth of the distal end (Bd) to the greatest length (GL) against the greatest breadth from lateral condyle ridge to lateral articulation edge (f) to the antero-posterior diameter of the external trochlea of the lateral condyle (4); [**B**] The greatest breadth of the distal end (Bd) to the greatest length (GL) against the greatest breadth from medial condyle ridge to medial articulation edge (e) to the antero-posterior diameter of the external trochlea of the medial condyle (1); [**C**] The greatest breadth of the distal end (Bd) to the greatest length (GL) against the medio-lateral width of the lateral condyle (b) to the antero-posterior diameter of the external trochlea of the lateral condyle (4); [**D**] The greatest breadth of the distal end (Bd) to the greatest length (GL) against the medio-lateral width of the medial condyle (a) to the antero-posterior diameter of the external trochlea of the medial condyle (1).

Figure 5.15 shows the relationship between the ratios of Bp/GL and SD/GL with respect to Bd/GL. Fairly promising results were observed in Figure 5.15, with most of the draught cattle clustered in the right region. These results are

consistent with the previous patterns observed in the metacarpals, where the x-axis largely determines the classifications, suggesting that traction primarily affects the distal end of the metatarsals.

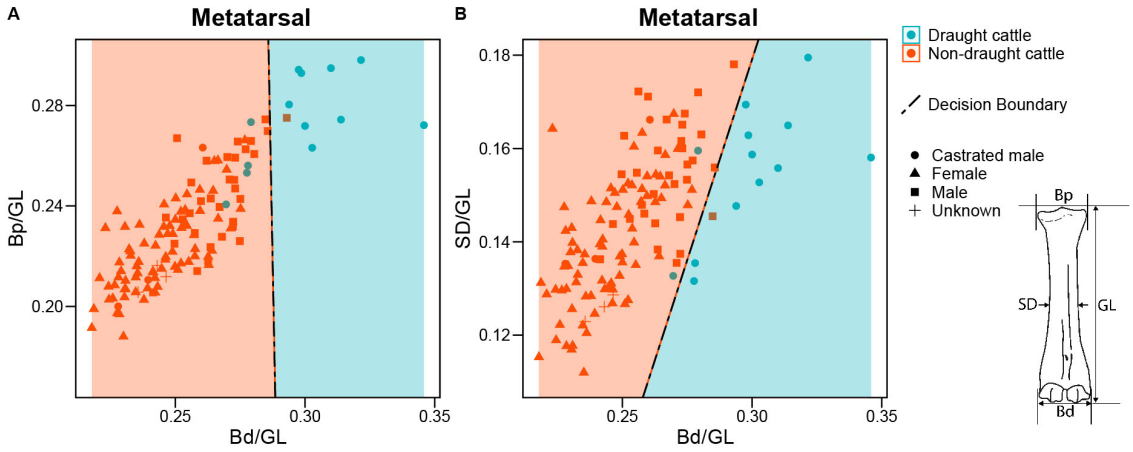



Figure 5.15: Shape ratios of proximal and diaphyseal regions against the greatest breadth of the distal end (Bd) to the greatest length (GL) on metatarsals of draught and non-draught cattle. [**A**] The greatest breadth of the distal end (Bd) to the greatest length (GL) against the greatest breadth of the proximal end (Bp) to the greatest length (GL); [**B**] The greatest breadth of the distal end (Bd) to the greatest length (GL) against the smallest breadth of the diaphysis (SD) to the greatest length (GL).

### Anterior first phalanges

The shape ratios of the anterior first phalanges provided good separation between draught and non-draught animals. The Bd/GLpe ratios are clearly higher in the draught group, indicating an enlarged distal end on their phalanges, while no obvious differences occur for the Bp/Dp ratio (Figure 5.16A).

When the greatest breadth of the proximal end (Bp) and the depth of the proximal end (Dp) are considered separately in relation to the greatest length of the peripheral (abaxial) half (GLpe), distinct patterns are observed. Figure 5.16B shows the scatter plot of Bp/GLpe against Bd/GLpe, revealing that the draught group tends to plot in the top right area. Figure 5.16D plots Dp/GLpe versus Bd/GLpe and shows a similar pattern in which the draught cattle exhibit high values in both ratios.

The Bp/Dp ratio of the draught cattle shows no obvious differences from the non-draught cattle. However, Bp/GLpe and Dp/GLpe ratios are noticeably higher in the draught group. These findings possibly indicate that the external loading experienced by the draught cattle affects both the breadth (Bd) and depth (Dp) dimensions of the proximal end of the anterior first phalanges.

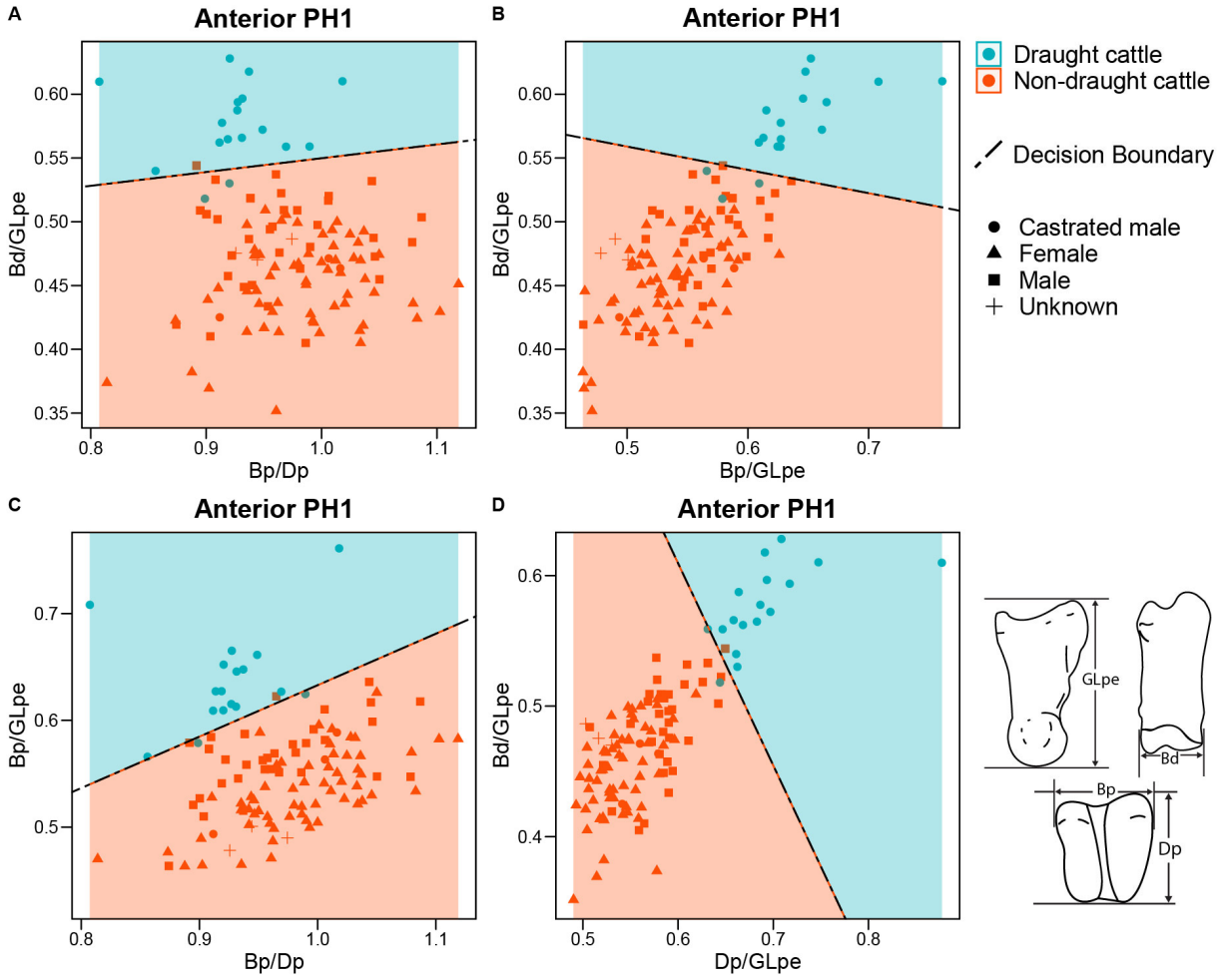



Figure 5.16: Shape ratios on anterior first phalanges of draught and non-draught cattle. [**A**] The greatest breadth of the proximal end (Bp) to the depth of the proximal end (Dp) against the greatest breadth of the distal end (Bd) to the greatest length of the peripheral (abaxial) half (GLpe); [**B**] The greatest breadth of the proximal end (Bp) to the greatest length of the peripheral (abaxial) half (GLpe) against the greatest breadth of the distal end (Bd) to the greatest length of the peripheral (abaxial) half (GLpe); [**C**] The greatest breadth of the proximal end (Bp) to the depth of the proximal end (Dp) against the greatest breadth of the proximal end (Bp) to the greatest length of the peripheral (abaxial) half (GLpe); [**D**] The depth of the proximal end (Dp) to the greatest length of the peripheral (abaxial) half (GLpe) against the greatest breadth of the distal end (Bd) to the greatest length of the peripheral (abaxial) half (GLpe).

### Posterior first phalanges

A clear separation between draught and non-draught cattle is observed in the shape ratio combinations of the posterior first phalanges (Figure 5.17). Like for the anterior phalanges, the distinction between draught and non-draught cattle

in the posterior first phalanges is predominantly determined by the Bd/GLpe ratio on the y-axis, whilst no significant variation is observed in the Bp/Dp ratio (Figure 5.17A). This trend suggests that the distal ends of the posterior first phalanges were splayed in draught cattle.

The Bp/GLpe ratio on the posterior first phalanges displays less pronounced variations between the two types of cattle compared to the forelimb results. The main separation between the two types of cattle is observed along the y-axis (Bd/GLpe) in Figure 5.17B, indicating that the breadth of the proximal end was not significantly affected by draught work. Conversely, the Dp/GLpe ratio is notably higher in the draught group, as evidenced by a clear cluster at the top right when plotting it against the Bd/GLpe ratio (Figure 5.17D).

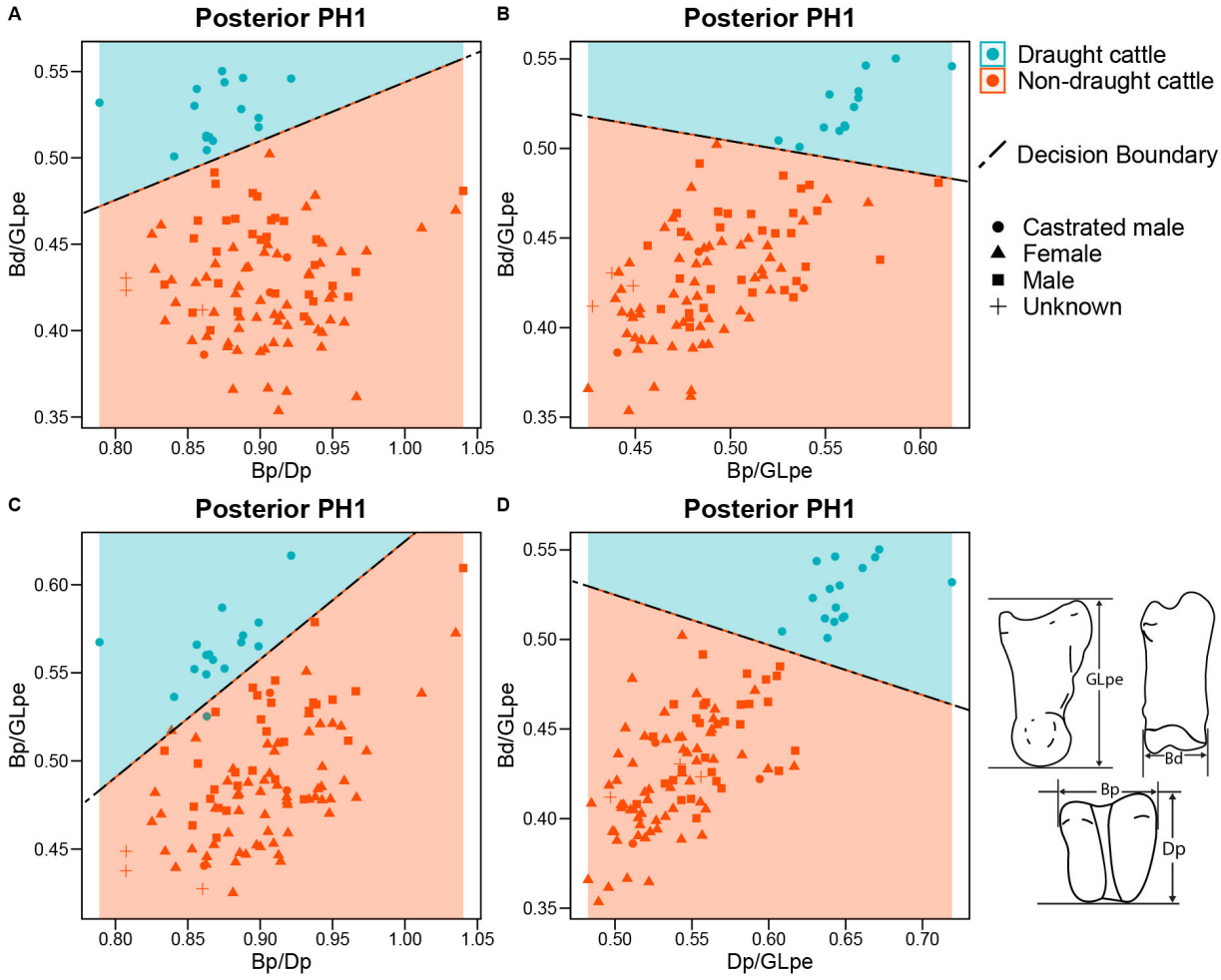



Figure 5.17: Shape ratios on posterior first phalanges of draught and non-draught cattle. [**A**] The greatest breadth of the proximal end (Bp) to the depth of the proximal end (Dp) against the greatest breadth of the distal end (Bd) to the greatest length of the peripheral (abaxial) half (GLpe); [**B**] The greatest breadth of the proximal end (Bp) to the greatest length of the peripheral (abaxial) half (GLpe) against the greatest breadth of the distal end (Bd) to the greatest length of the peripheral (abaxial) half (GLpe); [**C**] The greatest breadth of the proximal end (Bp) to the depth of the proximal end (Dp) against the greatest breadth of the proximal end (Bp) to the greatest length of the peripheral (abaxial) half (GLpe); [**D**] The depth of the proximal end (Dp) to the greatest length of the peripheral (abaxial) half (GLpe) against the greatest breadth of the distal end (Bd) to the greatest length of the peripheral (abaxial) half (GLpe).

To further illustrate the diverse impact of traction on the anterior and posterior phalanges, scatter plots of Dp/GLpe and Bp/GLpe are presented in Figure 5.18. Compared to the hindlimbs, the Dp/GLpe and Bp/GLpe ratios on the first phalanges from the forelimbs exhibit a stronger positive correlation, suggesting

that traction had an impact on both the depth and breadth dimensions of the proximal end (Figure 5.18A). In the posterior first phalanges, the main distinction between the two types of cattle is primarily driven by the high values of the Dp/GLpe ratio in the draught cattle (Figure 5.18B). The higher Dp/GLpe and Bp/GLpe ratios in the forelimbs compared to the hindlimbs in both draught and non-draught cattle suggest fundamental anatomical differences arising from an unequal weight distribution between the two limbs.

The morphological variations between the posterior first phalanges of non-draught cattle and the anterior first phalanges from draught cattle become apparent in Figure 5.19, which combines Figures 5.18A and5.18B. A significant overlap is presented between the posterior first phalanges of non-draught cattle and the anterior first phalanges of draught cattle.

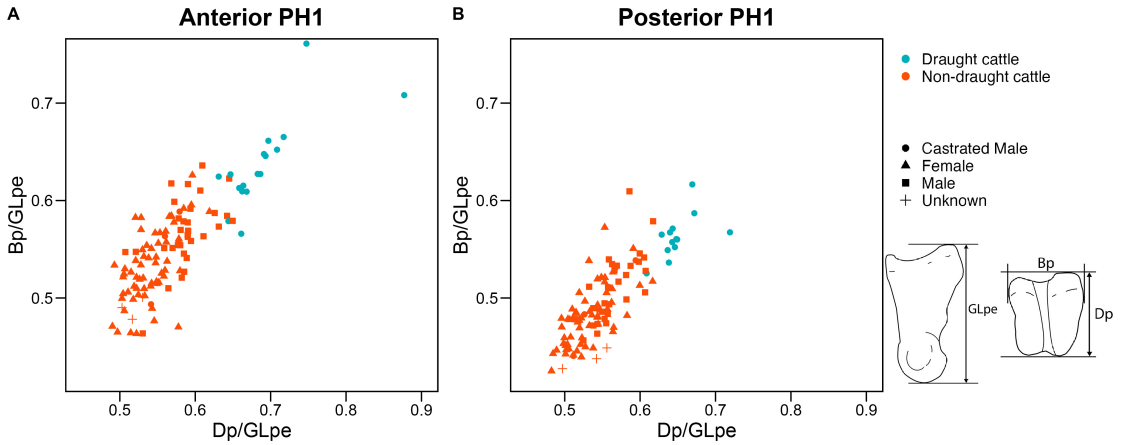



Figure 5.18: The depth of the proximal end (Dp) to the greatest length of the peripheral (abaxial) half (GLpe) against the greatest breadth of the proximal end (Bp) to the greatest length of the peripheral (abaxial) half (GLpe) on [**A**] anterior first phalanges and [**B**] posterior first phalanges.

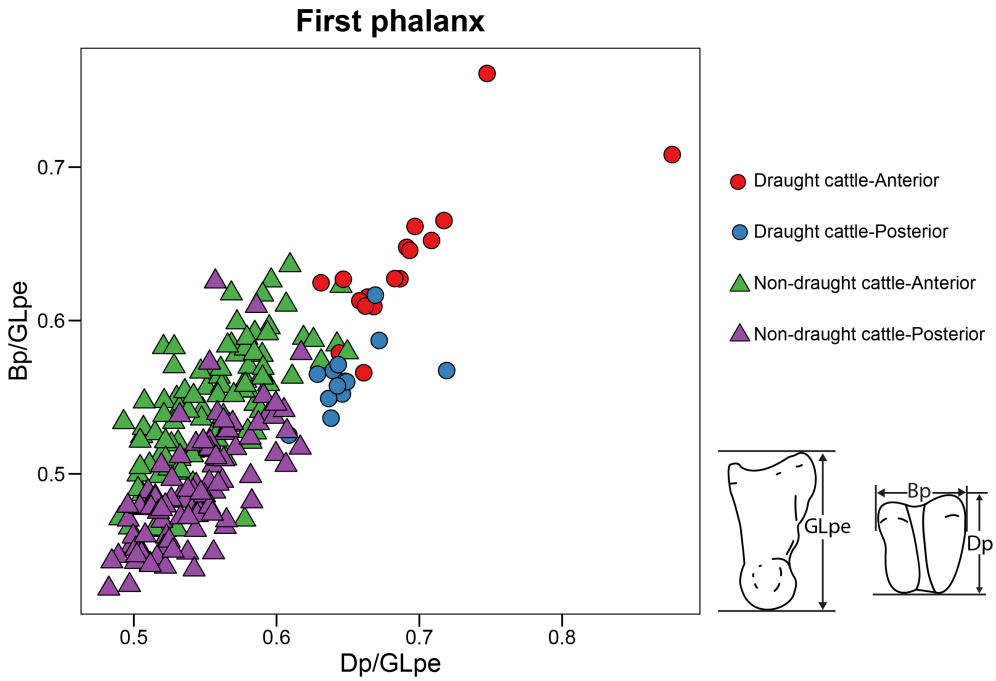



Figure 5.19: The depth of the proximal end (Dp) to the greatest length of the peripheral (abaxial) half (GLpe) against the greatest breadth of the proximal end (Bp) to the greatest length of the peripheral (abaxial) half (GLpe) on first phalanges.

Various shape ratios from the anterior and posterior first phalanges have shown promising results in independently distinguishing draught cattle. The morphological separation of anterior and posterior phalanges based on Dottrens' method (1946), however, may not always be accurate, especially when dealing with incomplete sets and mixed individuals in archaeological contexts. Thus, additional analyses were performed on the combined dataset of anterior and posterior phalanges from the first phalanges.

Overall, satisfactory results are observed in Figure 5.20, although there is, unsurprisingly, more overlap than in the previously analysed separate phalanges. As anticipated by the comparison in Figures 5.18 and 5.19, the increased overlap is a consequence of the inherent morphological differences between the forelimbs and hindlimbs. Furthermore, it is noteworthy that the majority of non-draught cattle misclassified as draught are exclusively bulls, with the exception of a single cow located within the draught area in Figure 5.20B.

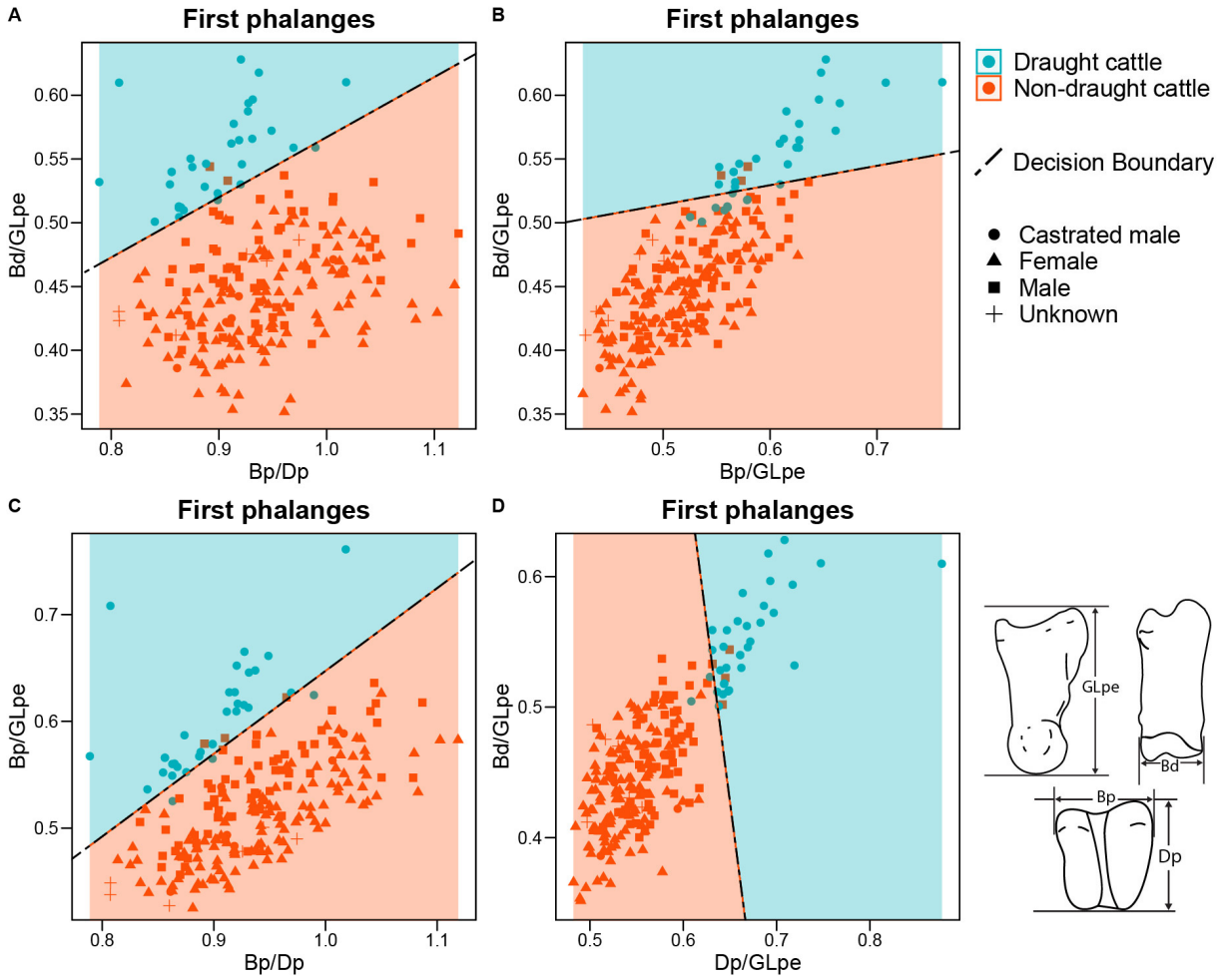



Figure 5.20: Shape ratios on first phalanges of draught and non-draught cattle. [**A**] The greatest breadth of the proximal end (Bp) to the depth of the proximal end (Dp) against the greatest breadth of the distal end (Bd) to the greatest length of the peripheral (abaxial) half (GLpe); [**B**] The greatest breadth of the proximal end (Bp) to the greatest length of the peripheral (abaxial) half (GLpe) against the greatest breadth of the distal end (Bd) to the greatest length of the peripheral (abaxial) half (GLpe); [**C**] The greatest breadth of the proximal end (Bp) to the depth of the proximal end (Dp) against the greatest breadth of the proximal end (Bp) to the greatest length of the peripheral (abaxial) half (GLpe); [**D**] The depth of the proximal end (Dp) to the greatest length of the peripheral (abaxial) half (GLpe) against the greatest breadth of the distal end (Bd) to the greatest length of the peripheral (abaxial) half (GLpe).

**Anterior second phalanges**

Figure 5.21A shows the Bp/Dp in relation to Bd/GLpe of the anterior second phalanges. The separation is predominantly along the y-axis, suggesting that deformations occurred primarily at the distal end in draught cattle.

Figure 5.21B, however, indicates that the draught group generally exhibits higher values in both the Bp/GLpe and Bd/GLpe ratios compared to the non-working cattle. Further, the Dp/GLpe ratio is significantly higher in the draught group, although three bulls also display a similarly high ratio, which plots into the opposite area. These findings suggest that both the breadth (Bd) and depth (Dp) of the proximal end of the anterior second phalanges were similarly affected by overloading due to traction work, concurring with the patterns observed previously on the anterior first phalanges.

Notably, four non-draught bulls and one castrated animal plot within the draught area when various shape combinations are applied in all plots in Figure 5.21. These non-draught young bulls belong to the same crossbreeds as the Romanian draught oxen, while the castrated animal is a Hungarian Grey. It was highlighted in Bartosiewicz et al. (1997b: 15) that the young bulls and the draught oxen in the study were a crossbreed between Hungarian Grey and brown dairy cattle. Therefore, the similarity in shape ratios between these non-draught cattle and the draught oxen could be attributed to the influence of breed on skeletal morphology. However, distinct differences are evident in the overall patterns between the two groups, especially considering that the non-draught collection comprises various breeds and species. These findings imply that breed alone cannot solely account for the differences between the two groups (see Section 5.6.2.3 on PCA for further discussion of breed and morphological variations).

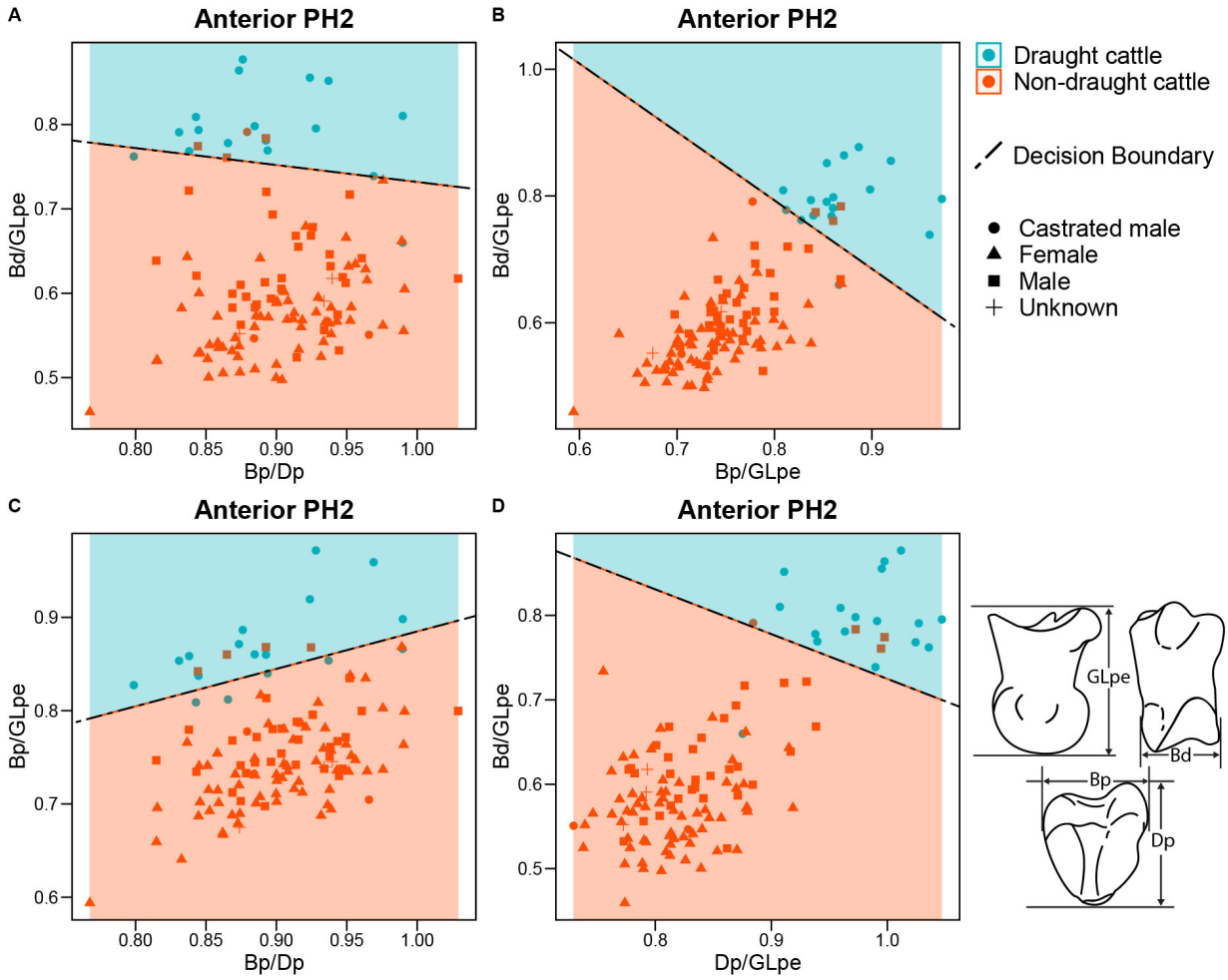



Figure 5.21: Shape ratios on anterior second phalanges of draught and non-draught cattle. [**A**] The greatest breadth of the proximal end (Bp) to the depth of the proximal end (Dp) against the greatest breadth of the distal end (Bd) to the greatest length of the peripheral (abaxial) half (GLpe); [**B**] The greatest breadth of the proximal end (Bp) to the greatest length of the peripheral (abaxial) half (GLpe) against the greatest breadth of the distal end (Bd) to the greatest length of the peripheral (abaxial) half (GLpe); [**C**] The greatest breadth of the proximal end (Bp) to the depth of the proximal end (Dp) against the greatest breadth of the proximal end (Bp) to the greatest length of the peripheral (abaxial) half (GLpe); [**D**] The depth of the proximal end (Dp) to the greatest length of the peripheral (abaxial) half (GLpe) against the greatest breadth of the distal end (Bd) to the greatest length of the peripheral (abaxial) half (GLpe).

### Posterior second phalanges

The posterior second phalanges display considerable morphological variation between draught and non-draught cattle (Figure 5.22). Most traction cattle exhibit a higher Bd/GLpe ratio, indicating a wider distal end than non-draught cattle (Figure 5.22A).

The Bp/Dp ratio displays no difference between the two groups. However, an effective classification becomes apparent when plotted alongside the Bp/GLpe ratio, presenting minimal overlap between the draught and non-draught cattle (Figure 5.22). Similarly, the draught cattle exhibit a noticeably high Dp/GLpe ratio (Figure 5.22D). Combined with the findings from Figure 5.22B, it suggests that draught activity influenced both the width and depth of the posterior second phalanges.

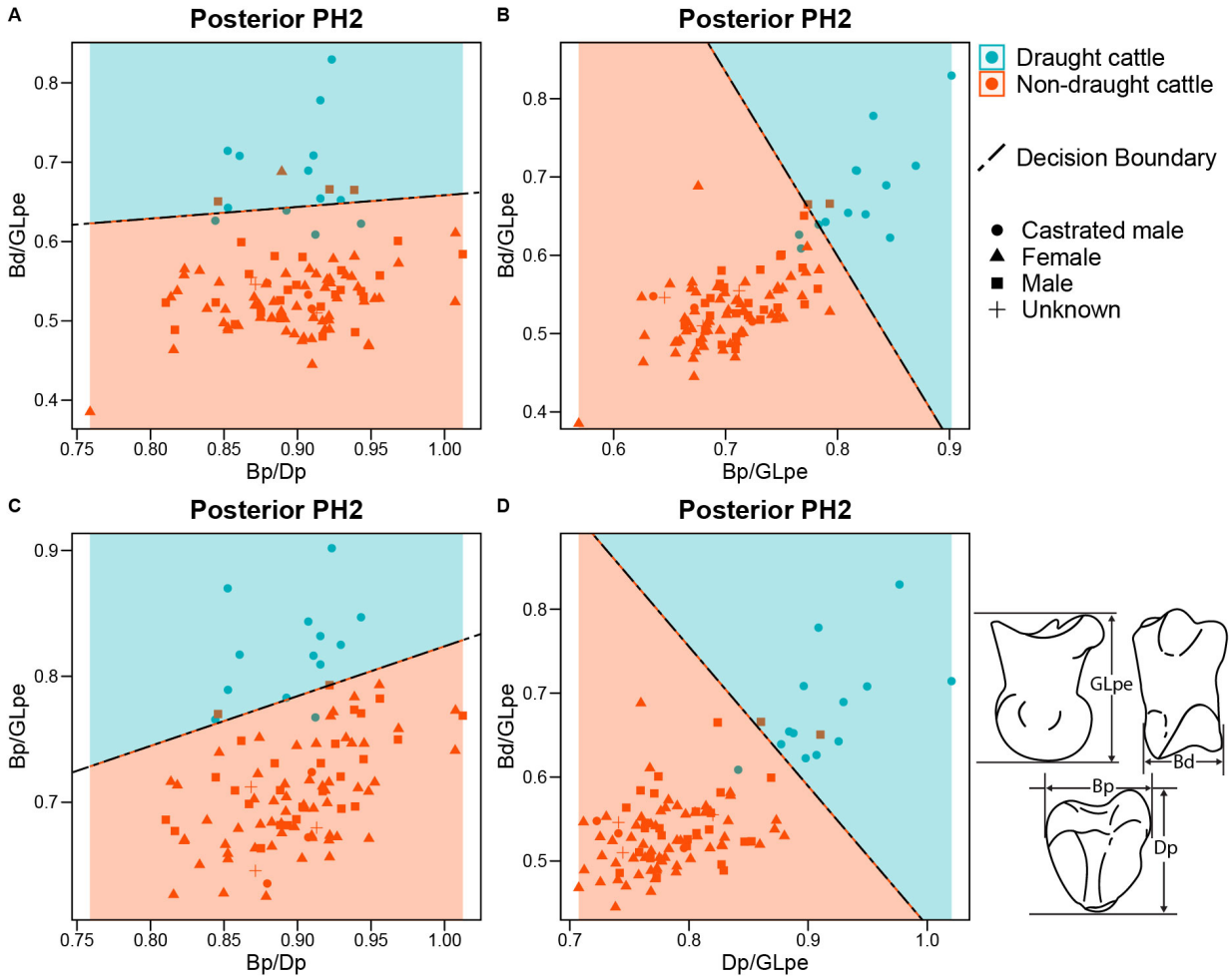



Figure 5.22: Shape ratios on posterior second phalanges of draught and non-draught cattle. [**A**] The greatest breadth of the proximal end (Bp) to the depth of the proximal end (Dp) against the greatest breadth of the distal end (Bd) to the greatest length of the peripheral (abaxial) half (GLpe); [**B**] The greatest breadth of the proximal end (Bp) to the greatest length of the peripheral (abaxial) half (GLpe) against the greatest breadth of the distal end (Bd) to the greatest length of the peripheral (abaxial) half (GLpe); [**C**] The greatest breadth of the proximal end (Bp) to the depth of the proximal end (Dp) against the greatest breadth of the proximal end (Bp) to the greatest length of the peripheral (abaxial) half (GLpe); [**D**] The depth of the proximal end (Dp) to the greatest length of the peripheral (abaxial) half (GLpe) against the greatest breadth of the distal end (Bd) to the greatest length of the peripheral (abaxial) half (GLpe).

Comparisons between anterior and posterior second phalanges based on Dp/GLpe and Bp/GLpe are presented in Figure 5.23. The non-draught cattle tend to cluster in a similar area in both plots, indicating that they share comparable ratios on both limbs. Nonetheless, it is noticed that a greater number of non-draught cattle, especially among the bulls, show similar ratios to draught cattle in the anterior phalanges compared to the posterior ones.

Additionally, the draught cattle exhibit a more pronounced positive correlation between the Dp/GLpe and Bp/GLpe ratios in the hindlimb (Figure 5.23B) compared to the front (Figure 5.23A). This suggests that as Dp/GLpe ratio increases, the Bp/GLpe ratio also tends to increase in the hindlimb of the draught cattle. In contrast, the forelimbs demonstrated slightly greater deformation in the breadth of the proximal end compared to the depth.

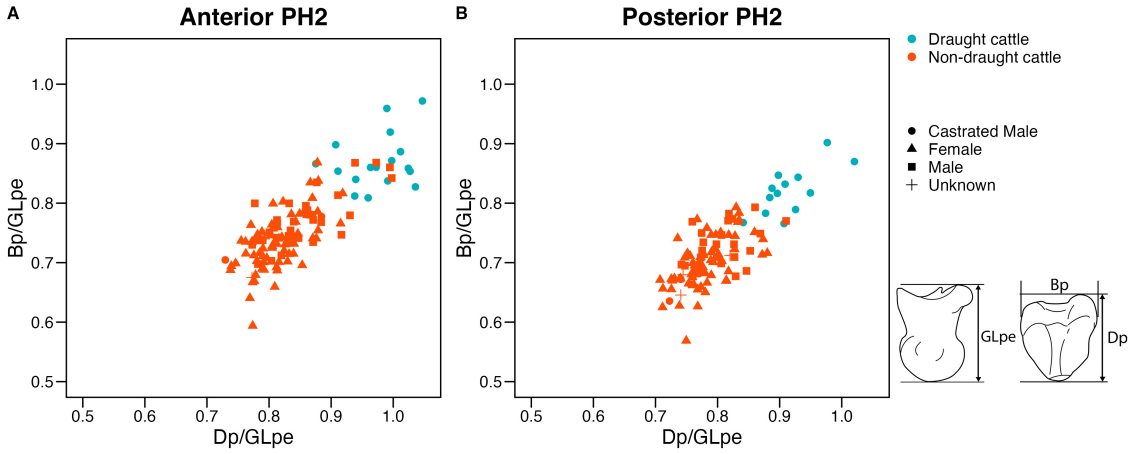



Figure 5.23: The depth of the proximal end (Dp) to the greatest length of the peripheral (abaxial) half (GLpe) against the greatest breadth of the proximal end (Bp) to the greatest length of the peripheral (abaxial) half (GLpe) on [**A**] anterior second phalanges and [**B**] posterior second phalanges.

As evident in Figure 5.24, the shape ratios in the anterior phalanges are generally higher than those in the posterior phalanges, even in the non-draught group. Consequently, when the datasets of anterior and posterior phalanges are combined, there is a higher likelihood of data points from the posterior phalanges of the draught cattle overlapping with the anterior phalanges of the non-draught cattle. Nonetheless, acceptable classification results were obtained

when combining the anterior and posterior second phalanges in Figure 5.25, despite the increased overlap of data points in relation to the previous independent results. The blurred classification after combining the anterior and posterior phalanges is, however, inevitable.

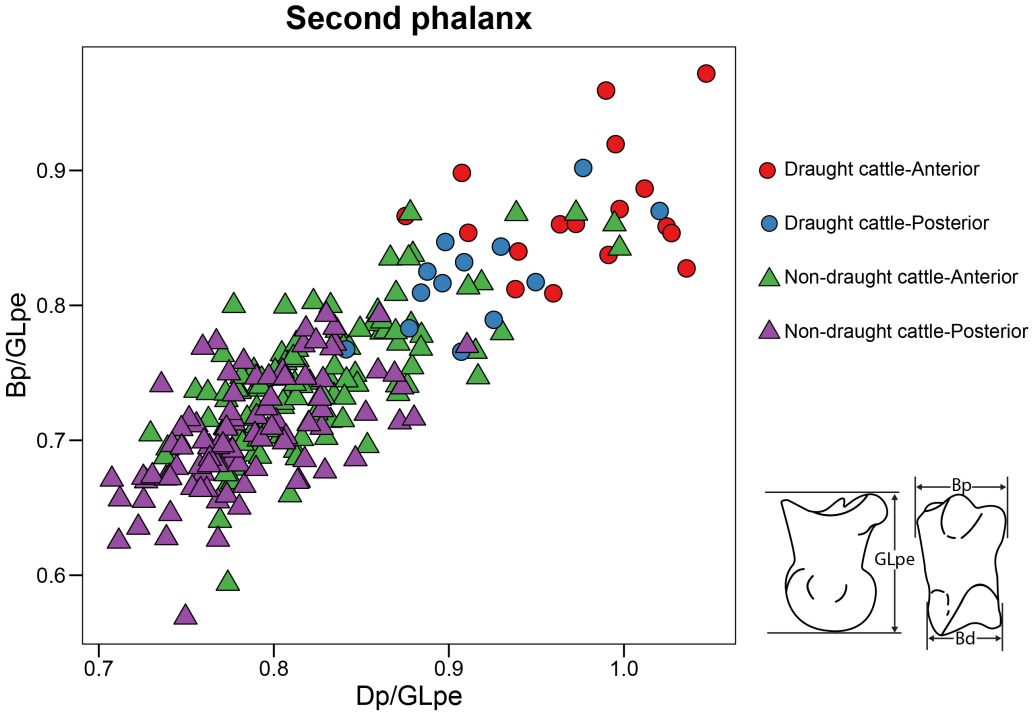



Figure 5.24: The depth of the proximal end (Dp) to the greatest length of the peripheral (abaxial) half (GLpe) against the greatest breadth of the proximal end (Bp) to the greatest length of the peripheral (abaxial) half (GLpe) on second phalanges.

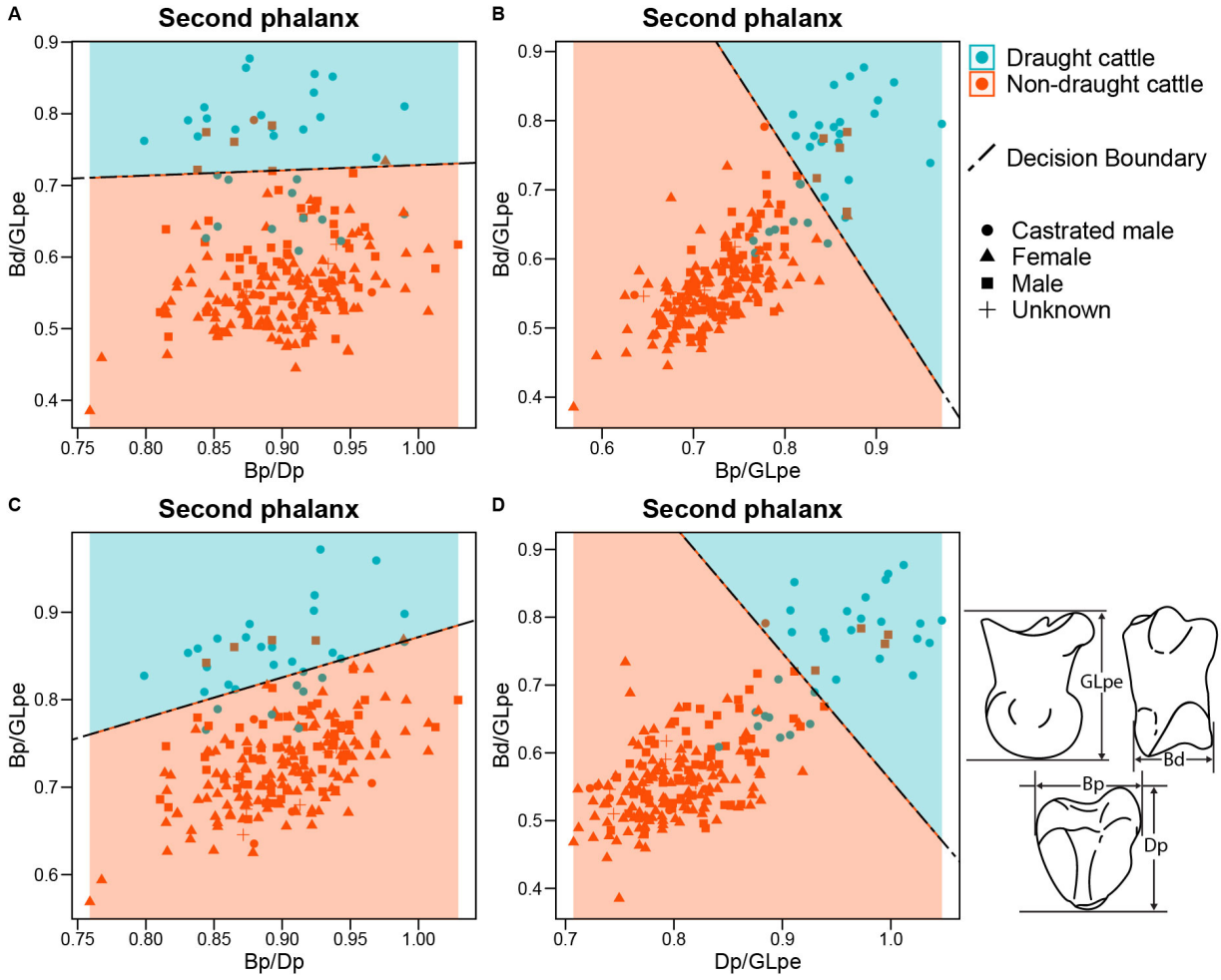



Figure 5.25: Shape ratios on second phalanges of draught and non-draught cattle. [**A**] The greatest breadth of the proximal end (Bp) to the depth of the proximal end (Dp) against the greatest breadth of the distal end (Bd) to the greatest length of the peripheral (abaxial) half (GLpe); [**B**] The greatest breadth of the proximal end (Bp) to the greatest length of the peripheral (abaxial) half (GLpe) against the greatest breadth of the distal end (Bd) to the greatest length of the peripheral (abaxial) half (GLpe); [**C**] The greatest breadth of the proximal end (Bp) to the depth of the proximal end (Dp) against the greatest breadth of the proximal end (Bp) to the greatest length of the peripheral (abaxial) half (GLpe); [**D**] The depth of the proximal end (Dp) to the greatest length of the peripheral (abaxial) half (GLpe) against the greatest breadth of the distal end (Bd) to the greatest length of the peripheral (abaxial) half (GLpe).

### Decision Boundary

As mentioned at the beginning of this section, the decision boundaries shown in the scatter plots were determined using logistic regression to classify draught and non-draught cattle. Logistic regression is represented by Equation 5.3, which

consists of three components: the constant term ($\beta^0$), the coefficients ($\beta^1$ and $\beta^2$), and the predictor variables ($X^1$ and $X^2$). $P(Y = 1)$ represents the probability of belonging to class 1 (draught cattle). Using the equations derived from the logistic regression model, predictions can be made for unknown specimens based on their predictor values, without requiring the complete dataset used in this study.

The constant terms and coefficients of each decision boundary in the aforementioned plots are presented in Table 5.43. For example, in Figure 5.20A, the scatter plot shows a clear separation based on the variables Bp/Dp and Bd/GLpe in the first phalanges. By adopting the values provided (Table 5.43), the decision boundary equation for this plot can be expressed by Equation 5.4.

$$P(Y = 1) = \frac{1}{1 + e^{-(-10.09+(-49.73)(Bp/Dp)+105.48(Bd/GLpe))}} \tag{5.4}$$

For instance, if an archaeological specimen has a $Bp/Dp = 0.95$ and $Bd/GLpe = 0.52$ the calculation proceeds as Equation 5.5:

$$P(\text{Draught cattle}) = \frac{1}{1 + e^{-(-10.09+(-49.73)(0.95)+105.48(0.52))}} = 0.08 \tag{5.5}$$

Given that $P = 0.08$, the probability of this specimen belonging to the draught cattle is smaller than the threshold probability of 0.5. Thus, this specimen is classified as non-draught cattle.

Table 5.43: Decision boundary of the logistic regression model for classification based on shape ratios of metapodials and phalanges.

| **Figure** | $\beta^0$ | $\beta^1$ | $X^1$ | $\beta^2$ | $X^2$ |
|---|---|---|---|---|---|
| 5.10A | –58.33 | 21.79 | e/1 | 51.8 | f/4 |
| 5.10B | –65.4 | 19.09 | a/1 | 53.13 | f/4 |
| 5.10C | –66.09 | 15.62 | a/1 | 37.48 | b/4 |
| 5.10D | –58.9 | 21.75 | e/1 | 33.29 | b/4 |
| 5.11A | –74.28 | 81.25 | Bd/GL | 58 | f/4 |
| 5.11B | –33.55 | 45.25 | Bd/GL | 21.13 | e/1 |
| 5.11C | –66.62 | 63.63 | Bd/GL | 35.39 | b/4 |
| 5.11D | –41.94 | 55.64 | Bd/GL | 17.66 | a/1 |
| 5.12A | –30.22 | 126.99 | Bd/GL | –42.96 | Bp/GL |
| 5.12B | –44.2 | 203.1 | Bd/GL | –136.8 | SD/GL |
| 5.13A | –45.02 | 33.49 | e/1 | 27.84 | f/4 |
| 5.13B | –40.17 | 15.03 | a/1 | 19.07 | b/4 |
| 5.14A | –157.77 | 319.15 | Bd/GL | 95.64 | f/4 |
| 5.14B | –84.45 | 201.85 | Bd/GL | 36.87 | e/1 |
| 5.14C | –89.98 | 193.47 | Bd/GL | 30.4 | b/4 |
| 5.14D | –126.5 | 264.4 | Bd/GL | 46.4 | a/1 |
| 5.15A | –48.97 | 167.93 | Bd/GL | 3.141 | Bp/GL |
| 5.15B | –56.86 | 290.31 | Bd/GL | –168.81 | SD/GL |
| 5.16A | –50.7 | –12.41 | Bp/Dp | 114.78 | Bd/GLpe |
| 5.16B | –69.88 | 19.63 | Bp/GLpe | 107.46 | Bd/GLpe |
| 5.16C | –30.2 | –96.3 | Bp/Dp | 199.8 | Bp/GLpe |
| 5.16D | –102.96 | 103.63 | Dp/GLpe | 66.92 | Bd/GLpe |
| 5.17A | –631.8 | –1062 | Bp/Dp | 3114.8 | Bd/GLpe |
| 5.17B | –4146 | 1261 | Bp/GLpe | 6973 | Bd/GLpe |
| 5.17C | 11.26 | –167.08 | Bp/Dp | 249.43 | Bp/GLpe |
| 5.17D | –1557.5 | 654.4 | Dp/GLpe | 2344.2 | Bd/GLpe |
| 5.20A | –10.09 | –49.73 | Bp/Dp | 105.48 | Bd/GLpe |
| 5.20B | –42.62 | –14.81 | Bp/GLpe | 97.27 | Bd/GLpe |
| 5.20C | 15.18 | –92.01 | Bp/Dp | 118.7 | Bp/GLpe |
| 5.20D | –67.34 | 92.51 | Dp/GLpe | 16.84 | Bd/GLpe |
| 5.21A | –37.856 | 8.154 | Bp/Dp | 40.585 | Bd/GLpe |
| 5.21B | –60.41 | 17.66 | Bp/GLpe | 59.97 | Bd/GLpe |
| 5.21C | –28.29 | –23.48 | Bp/Dp | 58.49 | Bp/GLpe |
| 5.21D | –34.1 | 14.41 | Dp/GLpe | 27.17 | Bd/GLpe |
| 5.22A | –22.045 | –6.348 | Bp/Dp | 43.128 | Bd/GLpe |
| 5.22B | –65.81 | 60.53 | Bp/GLpe | 28.79 | Bd/GLpe |
| 5.22C | –51.33 | –47.47 | Bp/Dp | 119.93 | Bp/GLpe |
| 5.22D | –58.38 | 46.53 | Dp/GLpe | 28 | Bd/GLpe |
| 5.25A | –16.143 | –1.817 | Bp/Dp | 24.658 | Bd/GLpe |
| 5.25B | –30.67 | 23.34 | Bp/GLpe | 16.31 | Bd/GLpe |
| 5.25C | 19.82 | 22.32 | Bp/Dp | –48.35 | Bp/GLpe |
| 5.25D | –29.1 | 22.44 | Dp/GLpe | 11.92 | Bd/GLpe |

#### 5.6.2.5 Model performance metrics

The previous section presented various shape ratio combinations in separating draught and non-draught cattle. Table 5.44 shows the five performance metrics of each model, including:

1. **Accuracy**: It measures the proportion of correct predictions from the total number of predictions.

2. **Sensitivity** (True positive rate): It evaluates the model's ability to correctly predict the actual positive cases as positive.

3. **Specificity** (True negative rate): It assesses the model's ability to correctly predict the actual negative cases as negative.

4. **Balanced Accuracy**: It is calculated as the average of sensitivity (True positive rate) and specificity (True negative rate). Balanced Accuracy is a more effective metric than Accuracy, especially when the dataset is imbalanced.

5. **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.

The combinations that show the highest Balanced Accuracy for each anatomical element will be adapted to archaeological specimens (Section 6.4.4). However, although the combinations of Bd/GL and f/4 yielded the best results in metatarsal, archaeological specimens are often incomplete. Therefore, ratios e/1 and f/4 will be applied. Table 5.44 also indicates that the first phalanx, particularly when analysed anterior and posterior separately, shows the best results among all elements.

Table 5.44: Model performance metrics.

| Elements | Model | Sensitivity | Specificity | Balanced Accuracy | F-score |
|---|---|---|---|---|---|
| Metacarpal | 5.10A (e/1 and f/4) | 0.69 | 0.97 | 0.83 | 0.72 |
| | 5.10B (a/1 and f/4) | 0.62 | 0.99 | 0.8 | 0.73 |
| | 5.10C (a/1 and b/4) | 0.61 | 0.97 | 0.78 | 0.66 |
| | 5.10D (e/1 and b/4) | 0.61 | 0.97 | 0.79 | 0.66 |
| | 5.11A (Bd/GL and f/4) | 0.62 | 0.97 | 0.8 | 0.68 |
| | 5.11B (Bd/GL and e/1) | 0.5 | 0.97 | 0.73 | 0.59 |
| | 5.11C (Bd/GL and b/4) | 0.5 | 0.96 | 0.73 | 0.57 |
| | 5.11D (Bd/GL and a/1) | 0.5 | 0.98 | 0.74 | 0.61 |
| | 5.12A (Bd/GL and Bp/GL) | 0.50 | 0.98 | 0.74 | 0.61 |
| | 5.12B (Bd/GL and SD/GL) | 0.56 | 0.98 | 0.77 | 0.66 |
| Metatarsal | 5.13A (e/1 and f/4) | 0.46 | 0.97 | 0.71 | 0.54 |
| | 5.13B (a/1 and b/4) | 0.31 | 0.96 | 0.63 | 0.38 |
| | 5.14A (Bd/GL and f/4) | 0.92 | 0.99 | 0.95 | 0.92 |
| | 5.14B (Bd/GL and e/1) | 0.84 | 0.99 | 0.91 | 0.88 |
| | 5.14C (Bd/GL and b/4) | 0.76 | 0.99 | 0.88 | 0.83 |
| | 5.14D (Bd/GL and a/1) | 0.84 | 0.99 | 0.91 | 0.88 |
| | 5.15A (Bd/GL and Bp/GL) | 0.69 | 0.99 | 0.84 | 0.78 |
| | 5.15B (Bd/GL and SD/GL) | 0.84 | 0.99 | 0.91 | 0.88 |
| First phalanx (Anterior) | 5.16A (Bp/Dp and Bd/GLpe) | 0.88 | 0.97 | 0.93 | 0.88 |
| | 5.16B (Bp/GLpe and Bd/GLpe) | 0.82 | 0.97 | 0.9 | 0.84 |
| | 5.16C (Bp/Dp and Bp/GLpe) | 0.88 | 0.97 | 0.93 | 0.88 |
| | 5.16D (Dp/GLpe and Bd/GLpe) | 0.94 | 0.98 | 0.96 | 0.94 |
| First phalanx (Posterior) | 5.17A (Bp/Dp and Bd/GLpe) | 1 | 1 | 1 | 1 |
| | 5.17B (Bp/GLpe and Bd/GLpe) | 1 | 1 | 1 | 1 |
| | 5.17C (Bp/Dp and Bp/GLpe) | 0.92 | 0.98 | 0.95 | 0.92 |
| | 5.17D (Dp/GLpe and Bd/GLpe) | 1 | 1 | 1 | 1 |
| First phalanx (Combined) | 5.20A (Bp/Dp and Bd/GLpe) | 1 | 0.98 | 0.99 | 0.96 |
| | 5.20B (Bp/GLpe and Bd/GLpe) | 0.7 | 0.97 | 0.83 | 0.76 |
| | 5.20C (Bp/Dp and Bp/GLpe) | 0.9 | 0.98 | 0.94 | 0.9 |
| | 5.20D (Dp/GLpe and Bd/GLpe) | 0.93 | 0.97 | 0.95 | 0.9 |
| Second phalanx (Anterior) | 5.21A (Bp/Dp and Bd/GLpe) | 0.88 | 0.96 | 0.92 | 0.83 |
| | 5.21B (Bp/GLpe and Bd/GLpe) | 0.82 | 0.97 | 0.89 | 0.82 |
| | 5.21C (Bp/Dp and Bp/GLpe) | 0.7 | 0.96 | 0.83 | 0.72 |
| | 5.21D (Dp/GLpe and Bd/GLpe) | 0.94 | 0.96 | 0.95 | 0.86 |
| Second phalanx (Posterior) | 5.22A (Bp/Dp and Bd/GLpe) | 0.69 | 0.95 | 0.82 | 0.69 |
| | 5.22B (Bp/GLpe and Bd/GLpe) | 0.84 | 0.97 | 0.91 | 0.84 |
| | 5.22C (Bp/Dp and Bp/GLpe) | 0.92 | 0.97 | 0.95 | 0.88 |
| | 5.22D (Dp/GLpe and Bd/GLpe) | 0.92 | 0.97 | 0.95 | 0.88 |
| Second phalanx (Combined) | 5.25A (Bp/Dp and Bd/GLpe) | 0.6 | 0.96 | 0.78 | 0.66 |
| | 5.25B (Bp/GLpe and Bd/GLpe) | 0.7 | 0.96 | 0.83 | 0.73 |
| | 5.25C (Bp/Dp and Bp/GLpe) | 0.7 | 0.95 | 0.82 | 0.75 |
| | 5.25D (Dp/GLpe and Bd/GLpe) | 0.66 | 0.97 | 0.82 | 0.72 |

Shaded cells represent the highest Balanced Accuracy for each anatomical element.

#### 5.6.2.6 Discussion: shape variations between modern draught and non-draught cattle

The biometric approaches employed for identifying draught cattle have produced promising results. This section compared limb bone shape ratios from a group of non-draught cattle representing diverse breeds and species to the modern Romanian draught oxen data obtained from Bartosiewicz et al. (1997b) and Lin et al. (2016). Significant variations were observed in most shape ratios of the metapodials and phalanges between draught and non-draught cattle. Nonetheless, the correlation between age and tested shape ratios was not supported by the results of this study.

Cattle breed is also a factor that affects skeletal morphology (Albarella, 1997; Berteaux and Guintard, 1995). 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. It is important to note that the non-draught group in this study encompassed various species, breeds, and landraces of modern cattle, capturing a wide range of morphological

differences. Despite the potential influence of breed, the clear differentiation between draught and non-draught cattle highlights the significant impact of traction on bone morphology.

Shape ratios from the distal ends provided the most effective results in classifying draught cattle in metapodials. Prior studies highlight that the deformations of the cattle distal metapodials, such as asymmetry and splaying, could potentially be linked to traction use (Jewell, 1963: 89; Bartosiewicz et al., 1997b; Johnstone and Albarella, 2015: 20). In the original study of the Romanian draught cattle by Bartosiewicz et al. (1997b), it is noticed that the working herds exhibited a significant broadening in the distal ends, particularly on the metacarpals. The results of this study align with the previous observations and support that the proximal end and diaphysis of the metapodials in draught cattle were unaffected.

A subsequent analysis revealed that the combination of the greatest breadth of the distal end (Bd) and greatest breadth from the medial condyle ridge to medial articulation edge (e) to the antero-posterior diameter of the external trochlea of the medial condyle (1) is the most effective metapodials measurement in distinguishing between draught and non-draught cattle (Lin et al., 2016). This study focuses on the metapodial biometrical analysis of Romanian draught cattle, modern non-draught cattle, and aurochs. The results of the present study align with this prior finding, as the combination of Bd and e/1 in the metapodials yielded a clear separation between the two groups.

More recent studies have suggested that the e/1 shape ratio can serve as a 'diagnostic/pathological index' for identifying draught individuals when it equals or exceeds 0.75 for archaeological specimens (Gaastra et al., 2018; Pigière and Smyth, 2023). However, 0.75 is the median e/1 value of the modern traction cattle in the metatarsal (Lin et al., 2016: Tab. 7). It is unclear why the value has been used as a threshold. The maximum value e/1 in the metacarpals of modern non-draught cattle is indicated as 0.81 by Lin et al. (2016). The results from this present study have shown that an e/1 ratio of 0.75 is commonly observed in non-draught cattle, particularly in bulls. Notably, two domestic bulls and a yak exhibited an

e/1 ratio exceeding 0.82. These results suggest that certain breeds of bulls may possess a robust bone structure similar to that of draught cattle.

Furthermore, the findings here reveal that there may be a diverse loading impact among the metapodials. High e/1 ratios are more prevalent in the metacarpals than in the metatarsals, even in non-draught cattle. Thus, these new results indicate that relying on a single value as a threshold indication of draught animals could lead to spurious conclusions. Considering the results presented in this section, logistic regression or equivalent predictive modelling could be a more effective approach rather than depending on a single ratio.

The linear measurements have limited use in archaeological contexts for identifying working animals because they depend on the absolute size. However, the application of the breadth of the distal end (Bd) as one of the axes has been suggested for identifying sex preferences in choosing draught animals (Lin et al., 2016), given the sexual dimorphism marked in the distal end of metapodials. Using bulls for traction is uncommon (see Section 2.7.2 for discussion); identifying oxen based on bone morphology is not straightforward, as the castration time could influence bone morphology. Attributing the sex and working status of an unknown specimen based on the breadth of the distal end could, therefore, be problematic.

Bulls and cows show sexual dimorphism in the distal end of metapodials, with bulls generally displaying a wider width (Higham, 1969; R. Thomas, 1988; Albarella, 1997: 38; S. Davis et al., 2018). This trend is indicated in the studied non-draught cattle sample, where bulls tend to have a broader distal end and more robust structures than cows. However, at the same time, the metapodials' distal end of the draught oxen were broadened because of traction. Consequently, an archaeological specimen showing a wide distal end and a high shape ratio could indicate a non-draught bull due to its inherent robustness. It is also possible that it is from a cow or ox used for traction, which could have caused the deformation. Traction as a possible confusing factor in sexing cattle metacarpals has been highlighted in previous studies (S. Davis et al., 2018; R. Thomas, 1988). The analyses

in this chapter support the prior arguments and raise doubts about the validity of determining the sex of portable draught cattle based on metapodial distal width.

Even though the broadened distal end cannot be merely attributed to the larger size of draught cattle, bivariate plots of the smallest breadth of the diaphysis (SD) against the greatest length (GL) of this study demonstrate that draught cattle and non-draught cattle were of similar size. Therefore, the deformations of the distal end were likely affected by long-term excessive loading from draught work. This pattern, however, may not necessarily reflect the situation in the past, as there is a possibility that cattle during that time were smaller in size compared to modern draught cattle. Consequently, even if the splaying of their distal end occurred due to traction, relying solely on absolute size for classification purposes would not be effective for archaeological materials. As such, shape ratios of individual distal condyles, including e/1, a/1, b/4, and f/4, were employed to mitigate the potential impact of size variations, these combinations also demonstrating good discrimination in the metacarpals. A promising separation can be observed while comparing the Bd/GL ratio with the shape ratios of distal condyles in metatarsals.

Thus far, phalanges have been less used than metapodials for identifying draught cattle. In a previous study comparing phalanges from Romanian herds with domestic cattle and aurochs from archaeological sites, it has been suggested that the differences between traction animals and their counterparts are characterised by a decrease in the greatest length of the peripheral (abaxial) half (GLpe) and widening at both ends (Bd and Bp) (Helmer et al., 2018). As demonstrated here, compared to various breeds and species of modern cattle, the Romanian draught cattle were not larger. This finding suggests that relying solely on absolute size measurements is not useful in identifying possible working animals.

Shape ratios, on the other hand, yielded compelling results in separating draught and non-draught cattle. Notably, the ratios of Bp/Dp against Bd/GLpe in the first phalanges provided a very good distinction of draught and non-draught cattle groups. The separation of anterior and posterior phalanges, based on

morphology posited by Dottrens (1946), may not always guarantee clear differentiation in archaeological contexts where it is likely to involve mixed individuals. Nonetheless, even when the front and back elements were mixed, reasonably good distinctions can still be carried out, especially on the first phalanges.

Although distinguishing between anterior and posterior phalanges can be challenging, the classifications of draught and non-draught cattle tended to produce better results when they were separated. This tendency is due to the intrinsic morphological variations of phalanges between the forelimbs and hindlimbs. Therefore, combining anterior and posterior elements may result in ambiguous outcomes. The importance of analysing anterior and posterior phalanges separately has been advocated by Holmes et al. (2021b) in their study on the Pathological Index in working cattle, taking into account the varying effects of traction on different body parts.

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 purposes prior to their slaughter. They may, therefore, not entirely mirror the conditions in the prehistorical context. The intensity of draught work, determined by the number of years the cattle have been utilised and the duration of work per year, could contribute to varying degrees of morphological changes in the cattle. Nevertheless, the non-draught cattle dataset generated in this study serves as a helpful baseline for future comparisons with archaeological materials, as well as for understanding the impact of draught activities on skeletal morphology.

## 5.7 Entheseal changes in modern cattle

Entheseal changes were recorded for the 105 modern non-draught cattle from the Julius Kühn collection and three individuals from the Zooarchaeology Laboratory of the University of Sheffield. Comparative data from the draught group are

unavailable as only the metapodials and phalanges were collected. The recording of each enthesis was based on a three-point scale, where Grade 1 referred to minimal modification, and Grade 3 indicated prominent changes. Illustrations of the grading system on each enthesis can be found in Appendix C

Potential confounding factors, including age, sex, and body weight, were analysed in this section, considering their influence on the research findings. These factors have been highlighted in prior studies as important variables that may impact entheses modification other than physical activities.

### 5.7.1 Effect of age on entheseal changes

In general, Figures 5.26-5.31 demonstrate that individuals who exhibited prominent entheseal changes indicated as Grade 3 tended to be older. The positive correlations observed between age and severity of entheseal changes in modern non-draught cattle are further supported by Spearman's rank correlation analysis (Table 5.45). The analysis revealed that twelve entheses positively correlate with ageing, including two fibrous entheses.

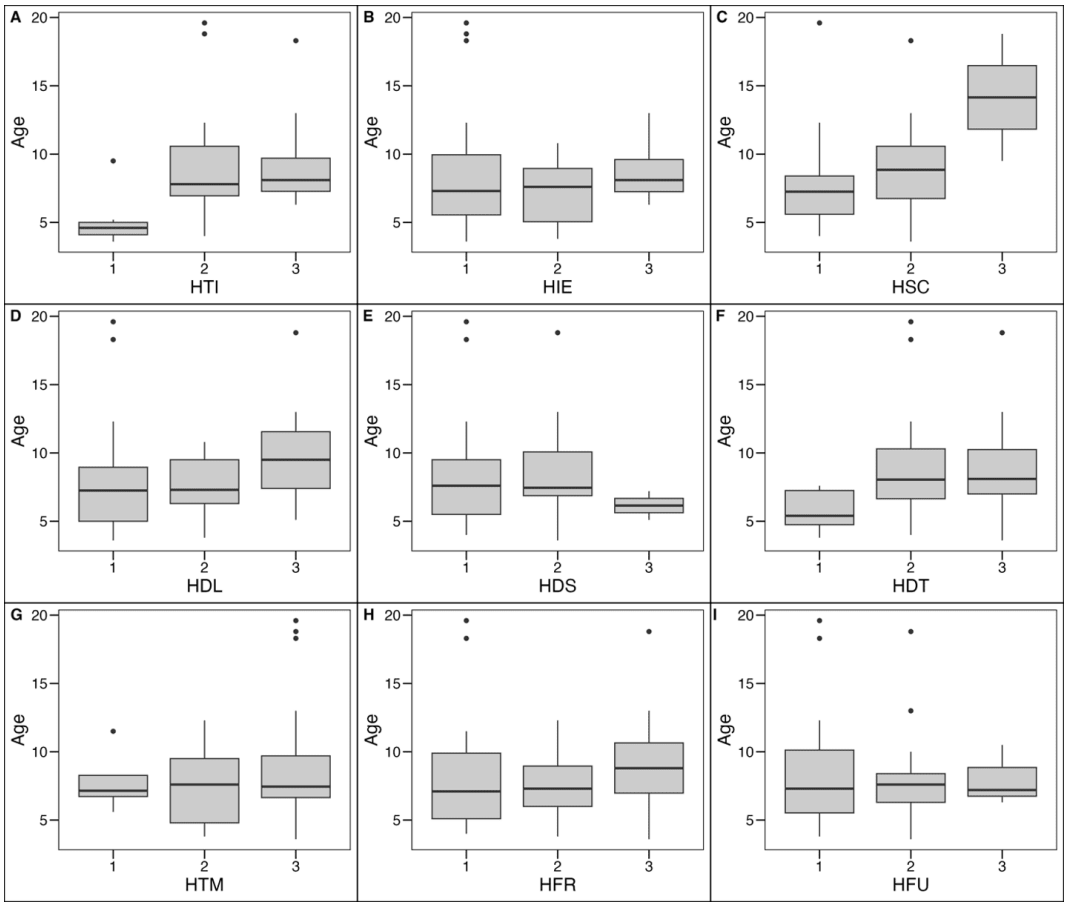



Figure 5.26: Distribution of enthesis grading on humerus in relation to age. [**A**] Teres minor; [**B**] Infraspinatus; [**C**] Subscapulari; [**D**] Extensor digitorum communi; [**E**] Flexor digitorum profundus; [**F**] Deltoideus; [**G**] Teres major; [**H**] Flexor carpi radialis; [**I**] Flexor carpi unlari.

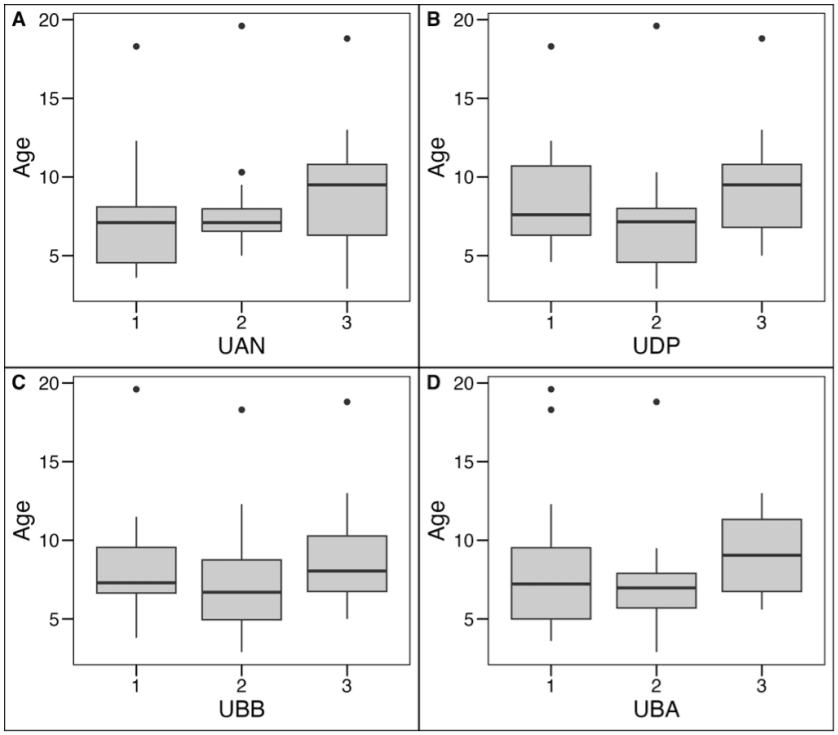



Figure 5.27: Distribution of enthesis grading on radius-ulnar in relation to age. [**A**] Anconeus; [**B**] Flexor digitorum profundus; [**C**] Biceps brachii; [**D**] Brachialis anticus.

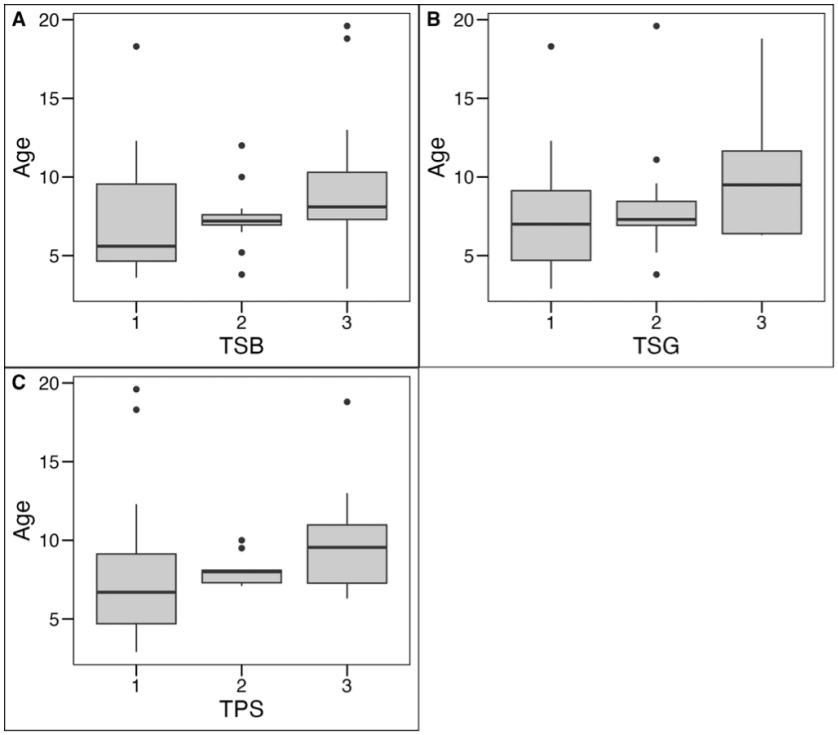



Figure 5.28: Distribution of enthesis grading on tibia in relation to age. [**A**] Semimembranosus; [**B**] Gracilis; [**C**] Popliteus.

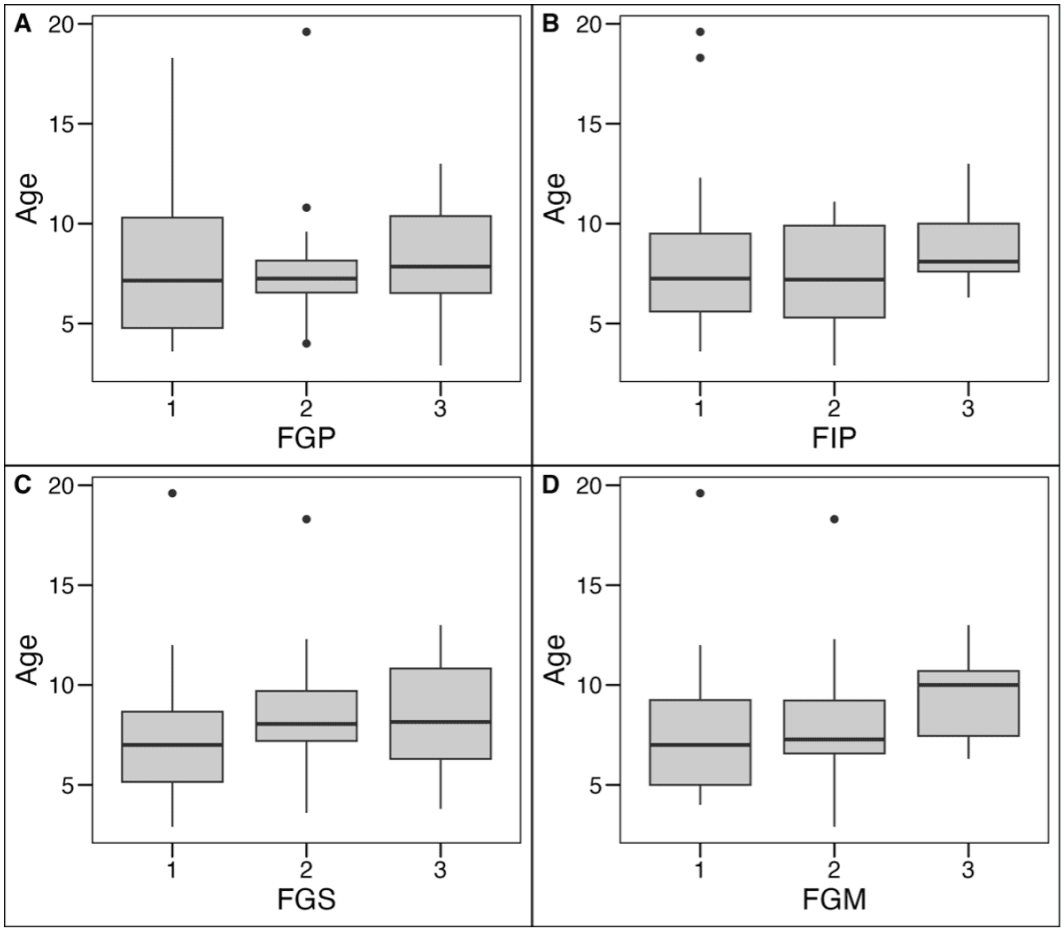



Figure 5.29: Distribution of enthesis grading on femur in relation to age. [**A**] Gluteus profundus; [**B**] Iliopsoas; [**C**] Gastrocnemius caput laterale; [**D**] Gastrocnemius caput mediale.

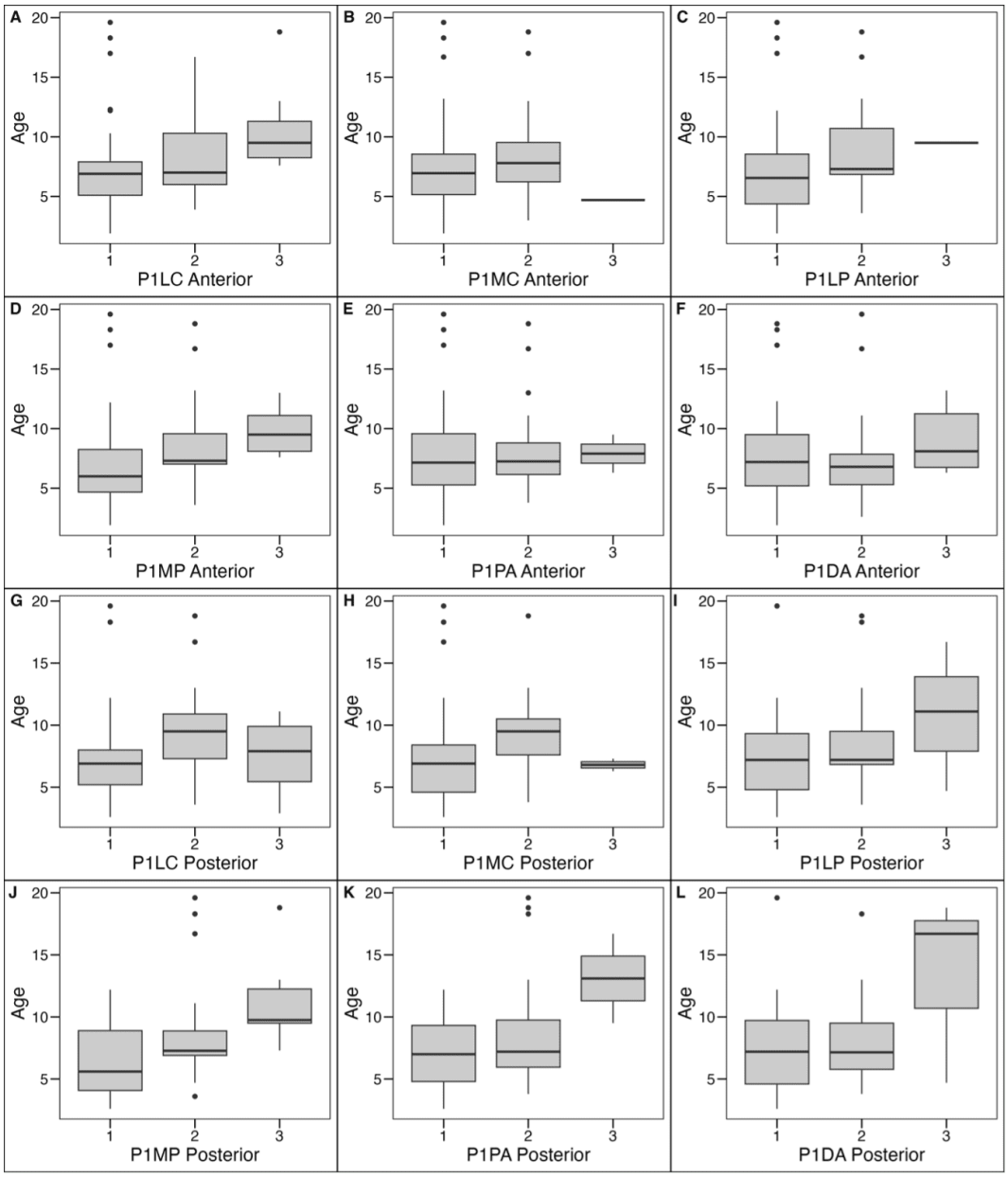



Figure 5.30: Distribution of enthesis grading on first phalanx in relation to age. [**A**] Lateral collateral metacarpophalangeal ligament; [**B**] Medial collateral metacarpophalangeal; [**C**] Lateral collateral proximal interphalangeal ligament (anterior phalanx); [**D**] Medial collateral proximal interphalangeal ligament (anterior phalanx); [**E**] Proximal digital annular ligament (anterior phalanx); [**F**] Distal digital annular ligament (anterior phalanx); [**G**] Lateral collateral metatarsophalangeal ligament; [**H**] Medial collateral metatarsophalangeal ligament; [**I**] Lateral collateral proximal interphalangeal ligament (posterior phalanx); [**J**] Medial collateral proximal interphalangeal ligament (posterior phalanx); [**K**] Proximal digital annular ligament (posterior phalanx); [**L**] Distal digital annular ligament (posterior phalanx).

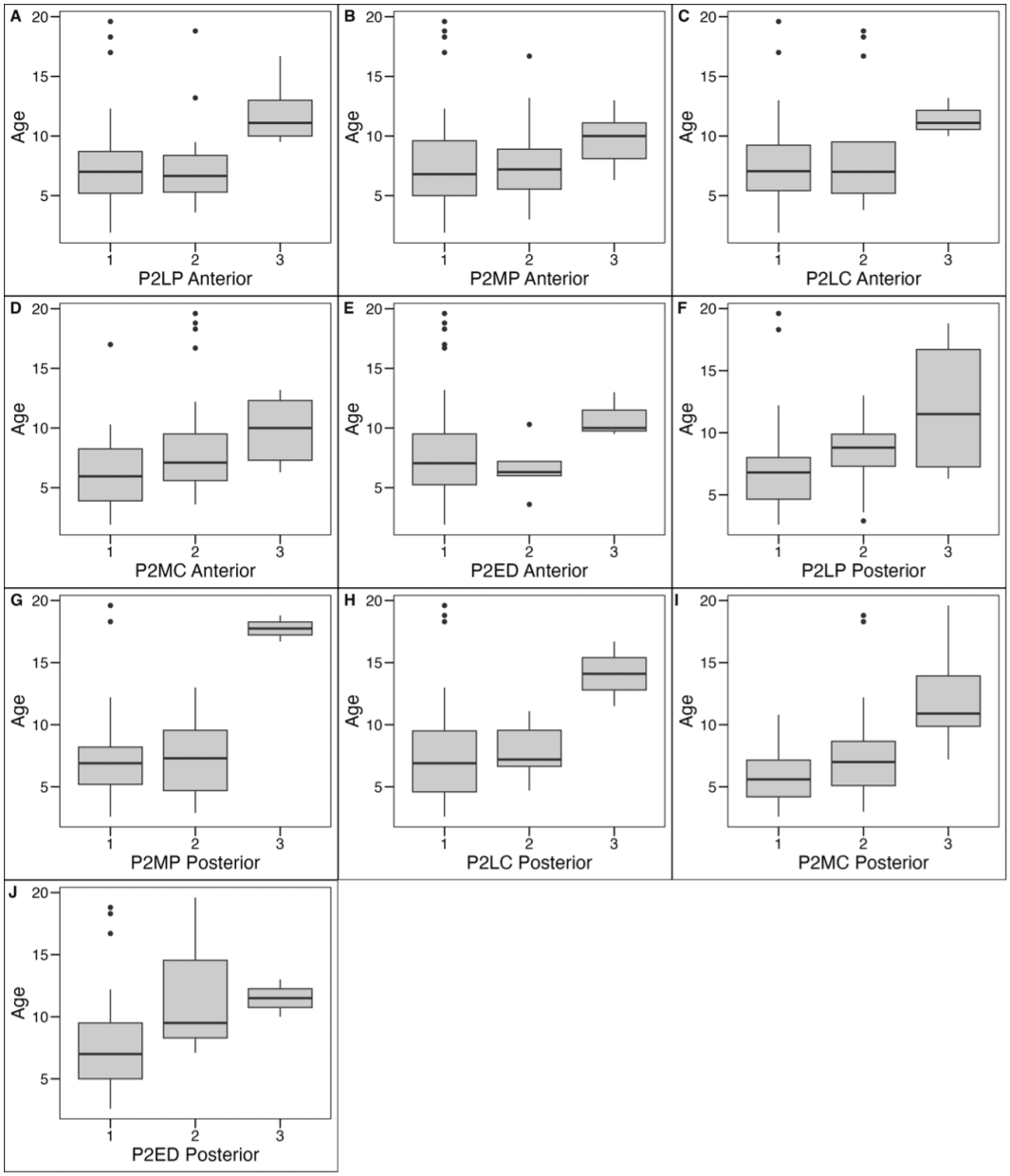



Figure 5.31: Distribution of enthesis grading on second phalanx in relation to age. [**A**] Lateral interphalangeal proximal collateral ligament (anterior phalanx); [**B**] Medial interphalangeal proximal collateral ligament (anterior phalanx); [**C**] Lateral interphalangeal distal collateral ligament (anterior phalanx); [**D**] Medial interphalangeal distal collateral ligament (anterior phalanx); [**E**] Extensor digitorum communis (anterior phalanx); [**F**] Lateral interphalangeal proximal collateral ligament (posterior phalanx); [**G**] Medial interphalangeal proximal collateral ligament (posterior phalanx); [**H**] Lateral interphalangeal distal collateral ligament (posterior phalanx); [**I**] Medial interphalangeal distal collateral ligament (posterior phalanx); [**J**] Extensor digitorum communis (posterior phalanx).

Table 5.45: Summary of Spearman's rank correlation analysis between age and the score of each enthesis.

| Enthesis | Type | n | mean | R | P |
|---|---|---|---|---|---|
| HTI | FCE | 55 | 2.12 | 0.47 | 0.00 *** |
| HIE | FCE | 55 | 1.67 | 0.05 | 0.68 NA |
| HSC | FCE | 55 | 1.29 | 0.25 | 0.06 NA |
| HDL | FCE | 55 | 1.67 | 0.22 | 0.09 NA |
| HDS | FCE | 55 | 1.54 | 0.00 | 0.95 NA |
| HDT | FE | 55 | 2.15 | 0.36 | 0.00 ** |
| HTM | FE | 55 | 2.58 | 0.13 | 0.32 NA |
| HFR | FCE | 55 | 1.95 | 0.15 | 0.27 NA |
| HFU | FCE | 55 | 1.51 | -0.04 | 0.77 NA |
| UAN | FCE | 58 | 1.99 | 0.25 | 0.05 NA |
| UDP | FCE | 58 | 2.14 | 0.10 | 0.44 NA |
| UBB | FCE | 58 | 1.77 | 0.04 | 0.74 NA |
| UBA | FCE | 58 | 1.42 | 0.11 | 0.37 NA |
| TSB | FE | 60 | 1.69 | 0.27 | 0.03 * |
| TSG | FE | 60 | 1.48 | 0.24 | 0.06 NA |
| TPS | FCE | 60 | 1.47 | 0.35 | 0.00 ** |
| FGP | FCE | 57 | 1.91 | 0.07 | 0.60 NA |
| FIP | FCE | 57 | 1.36 | 0.08 | 0.53 NA |
| FGS | FCE | 57 | 1.56 | 0.18 | 0.16 NA |
| FGM | FCE | 57 | 1.67 | 0.20 | 0.12 NA |
| P1LC (Anterior) | FCE | 55 | 1.56 | 0.32 | 0.02 * |
| P1MC (Anterior) | FCE | 55 | 1.47 | 0.09 | 0.47 NA |
| P1LP (Anterior) | FCE | 55 | 1.44 | 0.28 | 0.04 * |
| P1MP (Anterior) | FCE | 55 | 1.53 | 0.38 | 0.00 ** |
| P1PA (Anterior) | FCE | 55 | 1.40 | 0.05 | 0.72 NA |
| P1DA (Anterior) | FCE | 55 | 1.55 | 0.06 | 0.65 NA |
| P1LC (Posterior) | FCE | 56 | 1.43 | 0.25 | 0.06 NA |
| P1MC (Posterior) | FCE | 56 | 1.52 | 0.25 | 0.05 NA |
| P1LP (Posterior) | FCE | 56 | 1.45 | 0.18 | 0.17 NA |
| P1MP (Posterior) | FCE | 56 | 1.56 | 0.41 | 0.00 ** |
| P1PA (Posterior) | FCE | 56 | 1.46 | 0.21 | 0.11 NA |
| P1DA (Posterior) | FCE | 56 | 1.56 | 0.13 | 0.31 NA |
| P2LP (Posterior) | FCE | 58 | 1.36 | 0.20 | 0.13 NA |
| P2MP (Posterior) | FCE | 58 | 1.60 | 0.14 | 0.28 NA |
| P2LC (Anterior) | FCE | 58 | 1.35 | 0.20 | 0.12 NA |
| P2MC (Anterior) | FCE | 58 | 1.81 | 0.35 | 0.00 ** |
| P2ED (Anterior) | FCE | 58 | 1.18 | 0.09 | 0.47 NA |
| P2LP (Posterior) | FCE | 54 | 1.50 | 0.37 | 0.00 ** |
| P2MP (Posterior) | FCE | 54 | 1.47 | 0.15 | 0.24 NA |
| P2LC (Posterior) | FCE | 54 | 1.29 | 0.21 | 0.11 NA |
| P2MC (Posterior) | FCE | 54 | 1.85 | 0.44 | 0.00 *** |
| P2ED (Posterior) | FCE | 54 | 1.19 | 0.31 | 0.02 * |

Codes for the enthesis refer to Table 5.6. FCE = fibrocartilaginous enthesis; FE = fibrous enthesis. *** = very highly significant ($P \leq 0.001$), ** = highly significant ($P \leq 0.01$), * = significant ($P \leq 0.05$), NS = non-significant ($P > 0.05$).

### 5.7.2 Effect of sex on entheseal changes

Castrated males were omitted in this analysis as only three non-draught oxen are in the dataset. Figures 5.32-5.37 show that bulls generally demonstrated more substantial changes on the attachment sites than cows, evidenced by the higher ratio of bulls reaching Grade 3. Six entheses differ significantly between females and males, although it should be noted that the male sample size is smaller than the female (Table 5.46). An alternative explanation for these discrepancies could be the uneven age distribution between the two groups. However, the average age was 6.35 years for bulls and 8.14 years for cows, indicating that the observed differences could not be solely attributed to age.

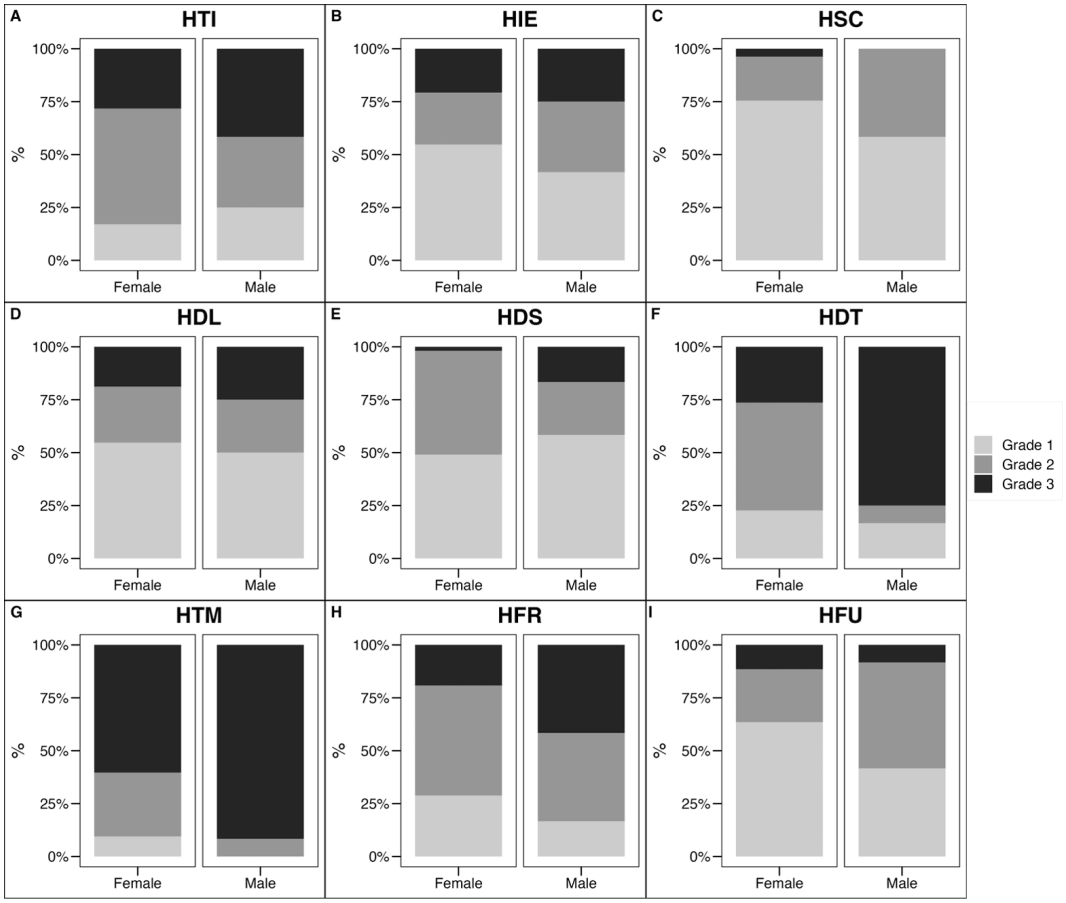



Figure 5.32: Distribution of enthesis grading on humerus in relation to sex. [**A**] Teres minor; [**B**] Infraspinatus; [**C**] Subscapulari; [**D**] Extensor digitorum communi; [**E**] Flexor digitorum profundus; [**F**] Deltoideus; [**G**] Teres major; [**H**] Flexor carpi radialis; [**I**] Flexor carpi unlari.

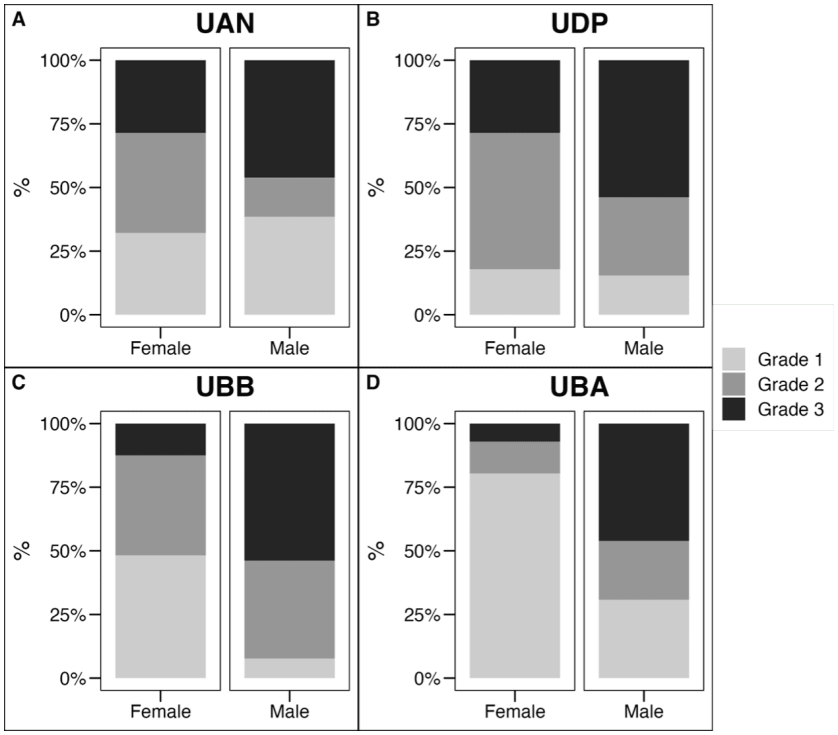



Figure 5.33: Distribution of enthesis grading on radius-ulnar in relation to sex. [**A**] Anconeus; [**B**] Flexor digitorum profundus; [**C**] Biceps brachii; [**D**] Brachialis anticus.

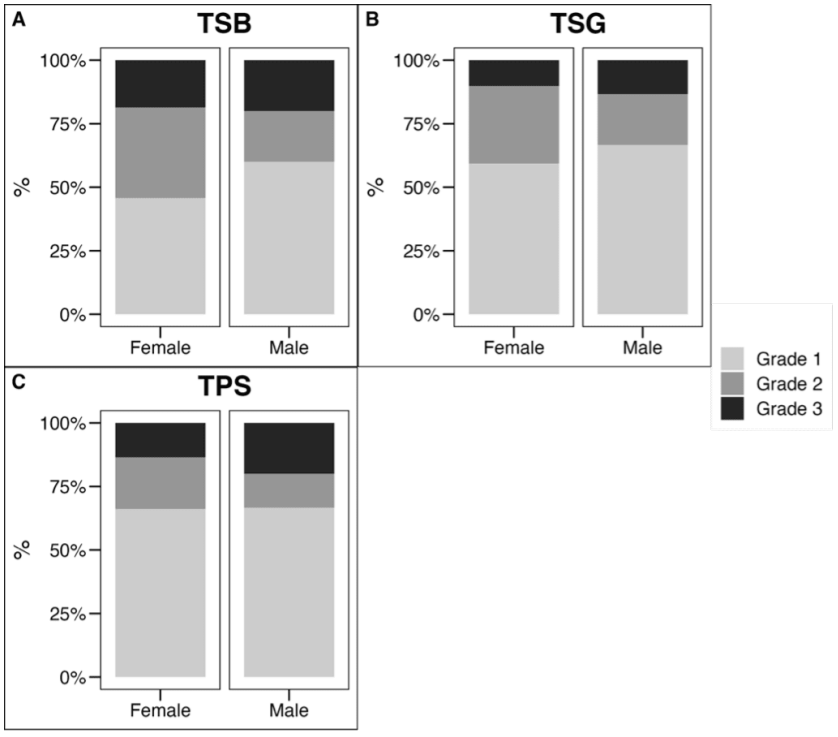



Figure 5.34: Distribution of enthesis grading on tibia in relation to sex. [**A**] Semimembranosus; [**B**] Gracilis; [**C**] Popliteus.

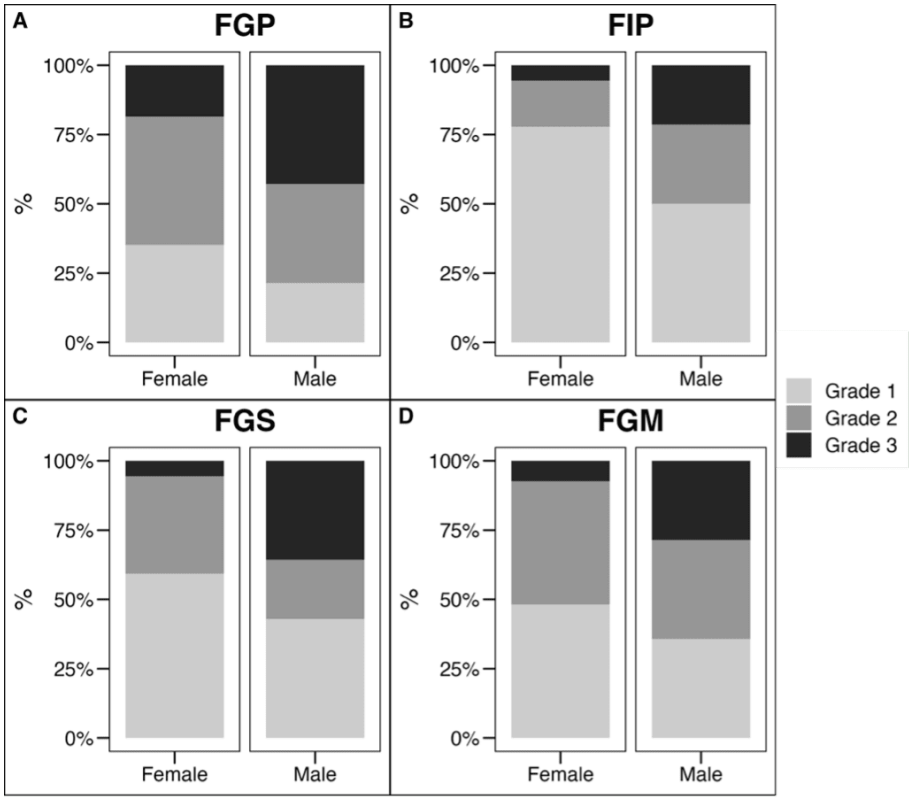



Figure 5.35: Distribution of enthesis grading on femur in relation to sex. [**A**] Gluteus profundus; [**B**] Iliopsoas; [**C**] Gastrocnemius caput laterale; [**D**] Gastrocnemius caput mediale.

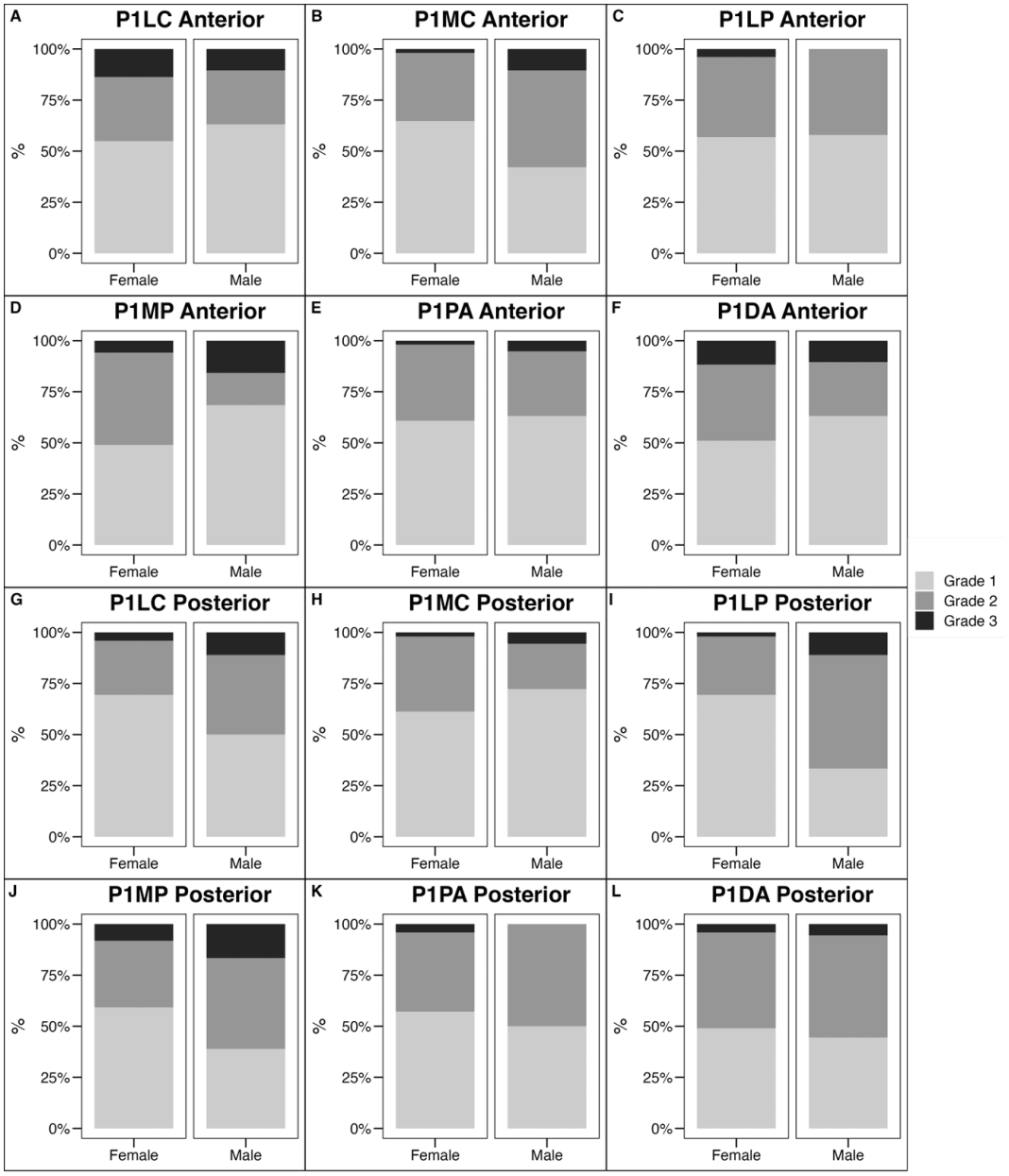



Figure 5.36: Distribution of enthesis grading on first phalanx in relation to sex. [**A**] Lateral collateral metacarpophalangeal ligament; [**B**] Medial collateral metacarpophalangeal; [**C**] Lateral collateral proximal interphalangeal ligament (anterior phalanx); [**D**] Medial collateral proximal interphalangeal ligament (anterior phalanx); [**E**] Proximal digital annular ligament (anterior phalanx); [**F**] Distal digital annular ligament (anterior phalanx); [**G**] Lateral collateral metatarsophalangeal ligament; [**H**] Medial collateral metatarsophalangeal ligament; [**I**] Lateral collateral proximal interphalangeal ligament (posterior phalanx); [**J**] Medial collateral proximal interphalangeal ligament (posterior phalanx); [**K**]Proximal digital annular ligament (posterior phalanx); [**L**] Distal digital annular ligament (posterior phalanx).

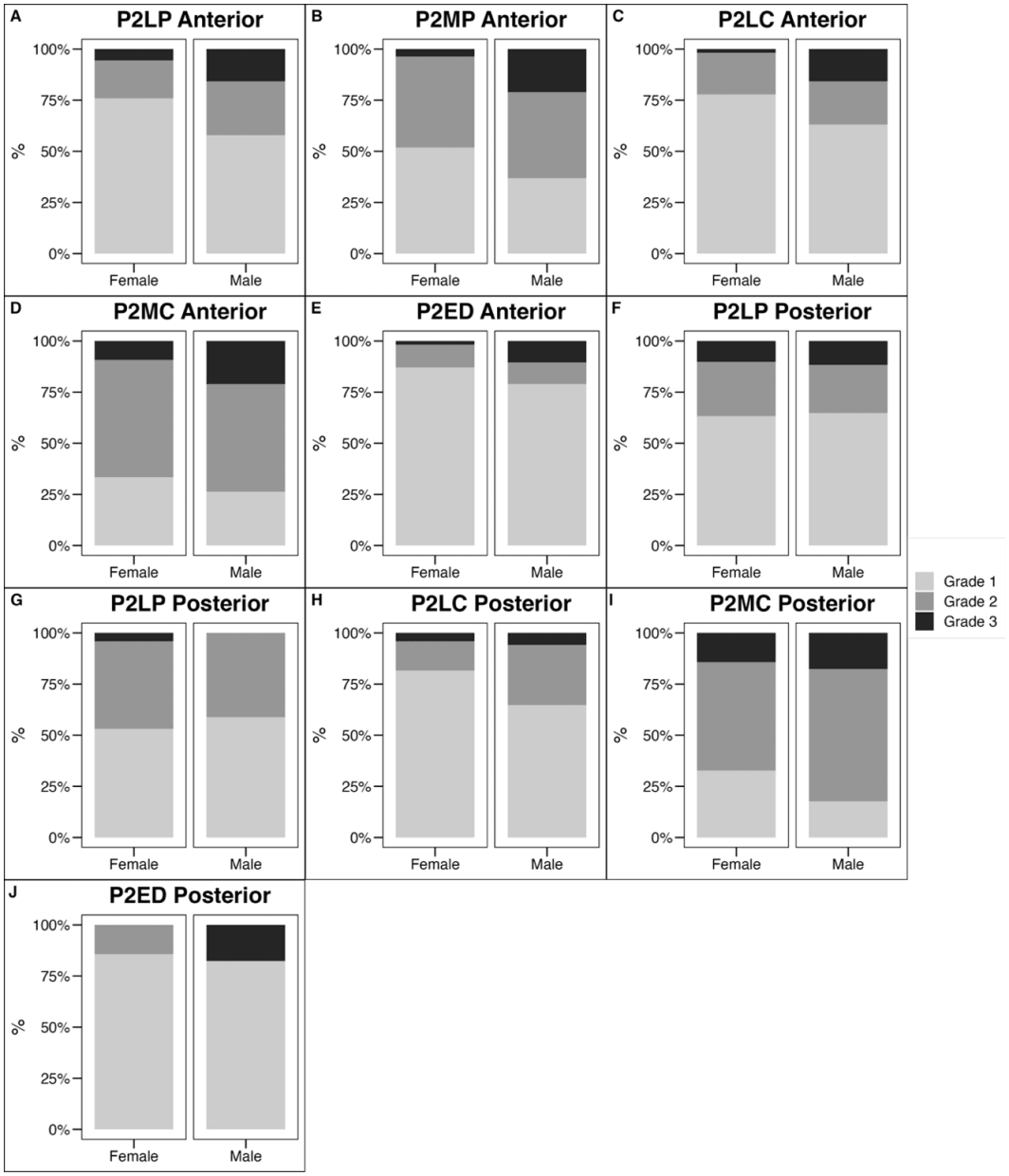



Figure 5.37: Distribution of enthesis grading on second phalanx in relation to age. [**A**] Lateral interphalangeal proximal collateral ligament (anterior phalanx); [**B**] Medial interphalangeal proximal collateral ligament (anterior phalanx); [**C**] Lateral interphalangeal distal collateral ligament (anterior phalanx); [**D**] Medial interphalangeal distal collateral ligament (anterior phalanx); [**E**] Extensor digitorum communis (anterior phalanx); [**F**] Lateral interphalangeal proximal collateral ligament (posterior phalanx); [**G**] Medial interphalangeal proximal collateral ligament (posterior phalanx); [**H**] Lateral interphalangeal distal collateral ligament (posterior phalanx); [**I**] Medial interphalangeal distal collateral ligament (posterior phalanx); [**J**] Extensor digitorum communis (posterior phalanx).

Table 5.46: Summary of Mann-Whitney test on the score of each enthesis between sexes.

| Enthesis | Type | n Female | n Male | P |
|---|---|---|---|---|
| HTI | FCE | 53 | 12 | 0.75 NA |
| HIE | FCE | 53 | 12 | 0.47 NA |
| HSC | FCE | 53 | 12 | 0.28 NA |
| HDL | FCE | 53 | 12 | 0.70 NA |
| HDS | FCE | 53 | 12 | 0.93 NA |
| HDT | FE | 53 | 12 | 0.01 * |
| HTM | FE | 53 | 12 | 0.03 * |
| HFR | FCE | 53 | 12 | 0.13 NA |
| HFU | FCE | 53 | 12 | 0.27 NA |
| UAN | FCE | 56 | 13 | 0.66 NA |
| UDP | FCE | 56 | 13 | 0.17 NA |
| UBB | FCE | 56 | 13 | 0.00 *** |
| UBA | FCE | 56 | 13 | 0.00 *** |
| TSB | FE | 59 | 15 | 0.48 NA |
| TSG | FE | 59 | 15 | 0.72 NA |
| TPS | FCE | 59 | 15 | 0.91 NA |
| FGP | FCE | 54 | 14 | 0.09 NA |
| FIP | FCE | 54 | 14 | 0.03 * |
| FGS | FCE | 54 | 14 | 0.07 NA |
| FGM | FCE | 54 | 14 | 0.15 NA |
| P1LC (Anterior) | FCE | 51 | 19 | 0.54 NA |
| P1MC (Anterior) | FCE | 51 | 19 | 0.06 NA |
| P1LP (Anterior) | FCE | 51 | 19 | 0.84 NA |
| P1MP (Anterior) | FCE | 51 | 19 | 0.34 NA |
| P1PA (Anterior) | FCE | 51 | 19 | 0.94 NA |
| P1DA (Anterior) | FCE | 51 | 19 | 0.42 NA |
| P1LC (Posterior) | FCE | 49 | 18 | 0.12 NA |
| P1MC (Posterior) | FCE | 49 | 18 | 0.38 NA |
| P1LP (Posterior) | FCE | 49 | 18 | 0.00 ** |
| P1MP (Posterior) | FCE | 49 | 18 | 0.12 NA |
| P1PA (Posterior) | FCE | 49 | 18 | 0.72 NA |
| P1DA (Posterior) | FCE | 49 | 18 | 0.72 NA |
| P2LP (Posterior) | FCE | 54 | 19 | 0.11 NA |
| P2MP (Posterior) | FCE | 54 | 19 | 0.10 NA |
| P2LC (Anterior) | FCE | 54 | 19 | 0.14 NA |
| P2MC (Anterior) | FCE | 54 | 19 | 0.30 NA |
| P2ED (Anterior) | FCE | 54 | 19 | 0.35 NA |
| P2LP (Posterior) | FCE | 49 | 17 | 0.96 NA |
| P2MP (Posterior) | FCE | 49 | 17 | 0.60 NA |
| P2LC (Posterior) | FCE | 49 | 17 | 0.16 NA |
| P2MC (Posterior) | FCE | 49 | 17 | 0.30 NA |
| P2ED (Posterior) | FCE | 49 | 17 | 0.57 NA |

Codes for the enthesis refer to Table 5.6. FCE = fibrocartilaginous enthesis; FE = fibrous enthesis. *** = very highly significant ($P \leq 0.001$), ** = highly significant ($P \leq 0.01$), * = significant ($P \leq 0.05$), NS = non-significant ($P > 0.05$).

### 5.7.3 Effect of body weight on entheseal changes

The greatest breadth of the distal end (Bd) of metacarpals was adopted as a body size proxy to analyse the correlation between entheseal modification and weight (Table 5.47). There are significant positive correlations between five attachment sites and Bd, indicating that cattle with wider metacarpals were likely to show more pronounced changes at these entheses.

Body size and sex could be interrelated, as sexual size dimorphism in mammals often results in larger males compared to females. However, it can be noticed that deltoideus (HDT), brachialis anticus (UBA), andthe lateral collateral proximal interphalangeal ligament on the posterior first phalanx (P1LP) show significant results on both size and sex factors. In contrast, the lateral collateral metatarsophalangeal ligament (P1LC) and lateral interphalangeal distal collateral ligament on the posterior phalanx (P2LC) show correlations solely with the body size proxy. These findings may demonstrate that although sex is correlated with body size, the effects of these two factors varied between the entheses.

Table 5.47: Summary of Spearman's rank correlation analysis between body size proxy (metacarpal Bd) and the score of each enthesis.

| Enthesis | Type | n | R | P |
|---|---|---|---|---|
| HTI | FCE | 65 | –0.04 | 0.69 NA |
| HIE | FCE | 65 | 0.22 | 0.06 NA |
| HSC | FCE | 65 | 0.08 | 0.51 NA |
| HDL | FCE | 65 | 0.03 | 0.76 NA |
| HDS | FCE | 65 | –0.02 | 0.86 NA |
| HDT | FE | 65 | 0.25 | 0.04 * |
| HTM | FE | 65 | 0.23 | 0.06 NA |
| HFR | FCE | 63 | 0.09 | 0.45 NA |
| HFU | FCE | 63 | 0.07 | 0.55 NA |
| UAN | FCE | 66 | 0.14 | 0.23 NA |
| UDP | FCE | 66 | 0.10 | 0.41 NA |
| UBB | FCE | 66 | 0.17 | 0.15 NA |
| UBA | FCE | 66 | 0.38 | 0.00 *** |
| TSB | FE | 69 | 0.02 | 0.86 NA |
| TSG | FE | 69 | 0.07 | 0.55 NA |
| TPS | FCE | 69 | 0.01 | 0.87 NA |
| FGP | FCE | 63 | 0.03 | 0.81 NA |
| FIP | FCE | 63 | 0.06 | 0.59 NA |
| FGS | FCE | 63 | 0.10 | 0.41 NA |
| FGM | FCE | 63 | 0.01 | 0.97 NA |
| P1LC (Anterior) | FCE | 60 | 0.12 | 0.32 NA |
| P1MC (Anterior) | FCE | 60 | 0.19 | 0.14 NA |
| P1LP (Anterior) | FCE | 60 | –0.07 | 0.55 NA |
| P1MP (Anterior) | FCE | 60 | 0.00 | 0.97 NA |
| P1PA (Anterior) | FCE | 60 | 0.18 | 0.15 NA |
| P1DA (Anterior) | FCE | 60 | –0.04 | 0.76 NA |
| P1LC (Posterior) | FCE | 59 | 0.33 | 0.00 ** |
| P1MC (Posterior) | FCE | 59 | 0.03 | 0.80 NA |
| P1LP (Posterior) | FCE | 59 | 0.28 | 0.03 * |
| P1MP (Posterior) | FCE | 59 | 0.24 | 0.06 NA |
| P1PA (Posterior) | FCE | 59 | 0.04 | 0.72 NA |
| P1DA (Posterior) | FCE | 59 | 0.19 | 0.14 NA |
| P2LP (Posterior) | FCE | 62 | 0.12 | 0.32 NA |
| P2MP (Posterior) | FCE | 62 | 0.05 | 0.67 NA |
| P2LC (Anterior) | FCE | 62 | 0.09 | 0.46 NA |
| P2MC (Anterior) | FCE | 62 | 0.14 | 0.24 NA |
| P2ED (Anterior) | FCE | 62 | 0.12 | 0.34 NA |
| P2LP (Posterior) | FCE | 59 | 0.19 | 0.14 NA |
| P2MP (Posterior) | FCE | 59 | –0.01 | 0.90 NA |
| P2LC (Posterior) | FCE | 59 | 0.25 | 0.04 * |
| P2MC (Posterior) | FCE | 59 | 0.18 | 0.15 NA |
| P2ED (Posterior) | FCE | 59 | 0.22 | 0.08 NA |

Codes for the enthesis refer to Table 5.6. FCE = fibrocartilaginous enthesis; FE = fibrous enthesis. *** = very highly significant ($P \leq 0.001$), ** = highly significant ($P \leq 0.01$), * = significant ($P \leq 0.05$), NS = non-significant ($P > 0.05$).

### 5.7.4 Variations between fore- and hindlimbs

As the number of entheses recorded in each anatomical element differs, the results may not be directly comparable. Z-score normalisation was applied to all data to transform them onto a common scale with a mean of 0.

Forelimb elements, including the humerus and radius-ulna, have a higher median score than the hindlimb elements, while the tibia shows a higher maximum value (Figure 5.38). Conversely, the posterior phalanges show a slightly higher median than the anterior phalanges, with the latter displaying more outliers with higher scores.

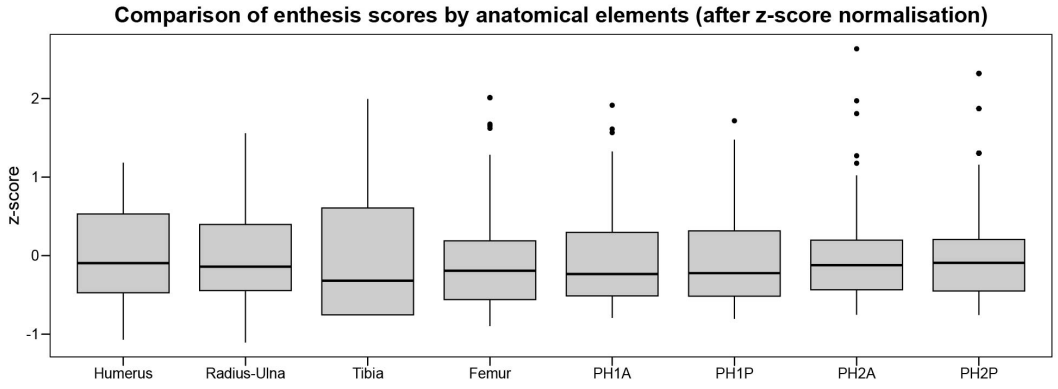



Figure 5.38: Comparison of enthesis scores by anatomical elements (after z-score normalisation). PH1A = Anterior first phalanx; PH1P = Posterior first phalanx; PH2A = Anterior second phalanx; PH2P = Posterior second phalanx.

When examining the scores of entheses from the first phalanges individually, it becomes evident that the anterior phalanges mostly have the highest maximum values, with the exception of the distal digital annular ligament (P1DA) (Figure 5.39A). Nonetheless, the median values from the anterior are not always higher than the posterior first phalanges.

The distribution of scores is consistent across the entheses on second phalanges, as evidenced by the closely aligned median values in Figure 5.39B. The posterior second phalanges show a greater number of outliers with significant alterations.

Table 5.48 indicates that only the lateral collateral metacarpophalangeal/ metatarsophalangeal ligament (P1LC) significantly between the anterior and posterior first phalanges variations based on the Wilcoxon signed-rank test. Similarly, the medial interphalangeal proximal collateral ligament (P2MP) of the second phalanges shows a statistical difference between the anterior and posterior.

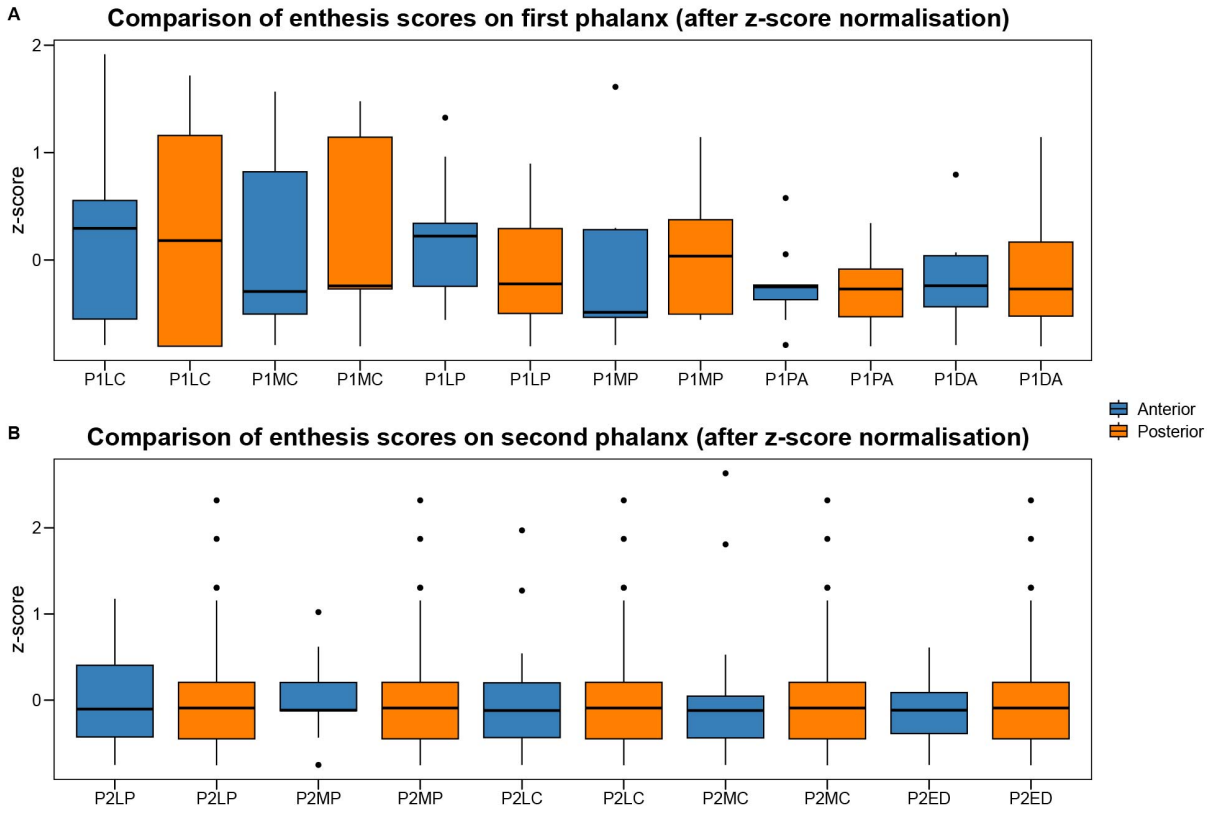



Figure 5.39: Comparison of enthesis scores on phalanges (after z-score normalisation). Codes for the enthesis refer to Table 5.6.

Table 5.48: Summary of Wilcoxon signed-rank test on the EC anterior vs. posterior.

| Anatomical element | Enthesis | P |
|---|---|---|
| First phalanx (Number of pair = 58) | P1LC | 0.03 * |
| | P1MC | 0.17 NA |
| | P1LP | 0.73 NA |
| | P1MP | 0.72 NA |
| | P1PA | 0.82 NA |
| | P1DA | 0.77 NA |
| Second phalanx (Number of pair = 61) | P2LP | 0.87 NA |
| | P2MP | 0.04 * |
| | P2LC | 0.28 NA |
| | P2MC | 0.64 NA |
| | P2ED | 0.65 NA |

Codes for the enthesis refer to Table 5.6. * = significant ($P \leq 0.05$), NS = non-significant ($P > 0.05$).

### 5.7.5 Discussion: Entheseal changes in modern non-draught cattle

Reconstructing activity patterns through the analysis of entheseal changes has been a longstanding interest in studying human remains. Recent research has explored entheseal changes in reindeer and equids to gain insights into their human-related activities, including domestication and mobility patterns (Niinimäki and Salmi, 2016; Bindé et al., 2019; Salmi et al., 2020). However, the validity of using entheseal changes in humans remains as a method to reconstruct past activities has been challenged due to the influence of confounding factors, including age, body size, sex, and trauma (Benjamin et al., 2002; Mariotti et al., 2007; Niinimäki, 2011; Weiss et al., 2012; Henderson et al., 2013). This section revealed the impact of biological factors on entheseal changes in modern non-draught cattle, suggesting that these confounding factors may exert varying effects on entheses.

Overall, old-aged cattle tended to show more pronounced changes than younger animals. This positive correlation is well-studied in humans (Weiss, 2004; Cardoso and Henderson, 2009; Niinimäki, 2011; Villotte and Santos, 2023). Similar trends have also been noticed in equids (Bendrey, 2008; Bindé et al., 2019) and sheep (Liu, 2021). Ageing is widely considered a significant causal factor for entheseal

modifications, and one plausible explanation is that entheseal scores increase with age due to the accumulation of mechanical stresses over an individual's lifetime (Robb, 1998; Wilczak, 1998; Yonemoto, 2016). Another hypothesis suggests osteoblast production may slow down with age, reducing cortical thickness and a rougher bone surface (Weiss, 2004).

Regardless of the reason, it is worth noting that although higher scores were generally observed in older modern cattle, not all entheses show significant correlations with age. Previous analyses of human remains indicate that age is likely the only causative factor for the morphological differences in fibrous insertions (Mariotti et al., 2007; Niinimäki, 2011). In the present study, twelve of the 42 entheses examined showed strong correlations with age, two of which were fibrous entheses. Although the sample size could potentially reduce the statistical power of the study, the analysis on cattle indicates that fibrous entheses are solely related to age. Notably, one particular fibrous site, the deltoideus on the humerus, showed a highly significant correlation with age. This result aligns with the observations in equids (Bindé et al., 2019) and sheep (Liu, 2021: 24). The consistency of these results across different species suggests that the deltoideus site should be excluded in for analysing draught use in archaeological materials.

Sexual variations were observed in both fibrocartilaginous and fibrous entheses, with bulls displaying more pronounced changes than cows. It is important to clarify that these sex variations cannot be attributed to uneven age distributions among the two groups, as the cows had a higher mean age than the bulls. Similar results have been widely identified in studying human entheseal changes. Nevertheless, the underlying reasons for these variations remain a subject of ongoing debate. It has been suggested that sexual variations in entheseal changes are potentially related to the division of labour. Males had higher chances of engaging in physically demanding activities; thus, they tended to show greater modifications (Hawkey and Merbs, 1995; al-Oumaoui et al., 2004; Mazza, 2019). This reason, however, cannot account for the observed variations in the modern cattle used in this study, as they were non-draught animals.

The second hypothesis suggests that the more pronounced modifications observed in males may be due to hormonal influences on muscle and bone growth throughout their life cycles. Estrogen and androgens influence endosteal and periosteal bone deposition. Males typically display greater periosteal apposition compared to females, which enhances bone size and helps prevent bone loss in later years (Seeman, 2001), while androgens enhance muscle growth in males (Niinimäki, 2011). Although the direct connection between hormonal activities and entheseal modifications in humans remains incompletely understood, variation in sex hormones could partly explain the observed differences between bulls and cows in this study.

Comparative results occur in equids and sheep, where males exhibit significantly higher modifications in several entheses. However, these differences have been attributed to the imbalanced age distribution between the two sex groups (Bindé et al., 2019; Liu, 2021: 43). If age were the sole factor contributing to the observed variation in entheseal changes, it would be expected that variation between sexes would not occur, given that cows, on average, were older than bulls in this study. Thus, significant differences in entheseal changes between males and females suggest that sex likely influences the morphology at the attachment sites. The interrelations between different biological factors may not be easy to disentangle, particularly sex and body size. Bulls are generally larger than cows because of the sexual size dimorphism in mammals. However, the entheses that exhibited significant variations between sexes were not entirely identical to those strongly associated with the size proxy. This finding suggests that both sex and body size likely contributed to the observed modifications to some extent, although their effects may differ.

Entheses from the forelimbs showed higher levels of morphological changes than hindlimbs in the present study. However, reversed trends were observed in the phalanges, where the posterior phalanges displayed slightly higher median scores than the anterior phalanges. A prior study on modern sheep found that modifications on the forelimbs are more prominent than those on the hindlimbs

(Liu, 2021: 40). Additionally, it has been noted that draught reindeer exhibit higher entheseal scores in their front limbs, likely as a result of increased load-bearing (Niinimäki and Salmi, 2016). However, as only two working reindeer are in the sample, this result may not show a conclusive link between entheseal changes in hindlimbs and draught work.

The variation of entheseal changes between the front and back legs could be related to the weight distribution in quadrupedal locomotion. Similar trends have been presented in the Pathological Index and discussed in the previous section. The higher modification level in the forelimb elements of non-draught cattle could be attributed to the weight distribution. The pattern, however, does not appear to hold entirely true for the phalanges. Although the highest scores from the first and second phalanges are both anterior, the median values were slightly higher in the posterior. Nonetheless, the connection between weight distribution and the variation in entheseal morphology between body parts has yet to be widely explored.

This study demonstrates the significant impact of age, sex, and body weight on entheses in modern cattle. Entheseal changes in non-human animals have not been thoroughly investigated. However, like other skeletal pathologies and modifications, entheses changes are a multifactorial process. Particularly, habitat is another critical factor to consider in the archaeological context. Animals inhabiting rugged terrain may experience elevated levels of repeated locomotor stress, leading to more pronounced modifications (Bartosiewicz and Gál, 2013; Holmes et al., 2021c). Like for the Pathological Index, identifying draught individuals might not be possible based only on their entheses morphology. As demonstrated by modern non-draught cattle, captive animals can also show pronounced entheseal changes on certain insertion sites. Nonetheless, this method could be a new tool for exploring the overall trend changes between sites. The dataset generated in this study from modern non-draught cattle can serve as a helpful baseline for comparison.

## 5.8 Distinguishing anterior and posterior phalanges

As discussed in the previous sections, the separation of anterior and posterior phalanges is important for identifying draught cattle. The classifications are less effective when anterior and posterior phalanges are mixed because of their morphological differences. Variations in the Pathological Index and entheseal changes between phalanges could also be informative about draught exploitation. Thus far, the separation of phalanges has mainly been based on the morphological criteria posited by Dottrens (1946). It is suggested that the anterior phalanges are generally stockier than the posterior (Plate 5.14). While this method has been useful, individual variations in cattle could lead to ambiguous distinctions based on visual assessments, especially for archaeological materials. This section attempts to distinguish the phalanges through biometry and investigate the level of agreement between Dottrens' method and the biometrical approach.

The materials used in this analysis were modern non-draught cattle. Most of the phalanges were labelled. For those lacking labels to distinguish between anterior and posterior, Dottrens' method was applied. Since the study dealt with complete skeletons, a full set of phalanges was available, making Dottrens' attribution more likely to be accurate.

Plate 5.14: Morphological variations between anterior and posterior phalanges of the same individual. [**A**] Lateral views of the first phalanges. The anterior phalanx, on the whole, is more robust, while the posterior is gracile. [**B**] Palmar view of the first phalanges. The groove between the proximal articular foveae is shallower in the anterior phalanx, whereas this groove is deep and narrow in the posterior. [**C**] Lateral views of the second phalanges. The anterior phalanx is shorter and more massive compared to the posterior phalanges.

### 5.8.1 Biometry approach in classifying anterior and posterior phalanges

Figure 5.40 presents the shape ratios of the first phalanges displayed in bivariate plots. Although overlap can be observed between the anterior and posterior phalanges, Figures 5.40C and 5.40D demonstrate reasonably good separation, with the anterior phalanges concentrated in the right area. The anterior phalanges tend to have a higher Bp/Dp ratio (Figure 5.40C). This observation implies that the breadth of the proximal end is generally longer than the depth, resulting in a more robust shape for the anterior phalanges. Similarly, in Figure 5.40D, most anterior phalanges are centralised in the top-right region, with only a few outliers from the posterior phalanges. This clustering further confirms not only that the Bp/Dp ratio is higher in anterior phalanges but also that the Bp/GLpe ratio is generally higher. Results from this study illustrate that the anterior phalanges are mostly stockier than the posterior phalanges.

Conversely, the ratios in Figure 5.40B overlap entirely. The fact that the Dp/GLpe ratio is similar between the anterior and posterior phalanges suggests that their distinction is mainly due to the anterior phalanges exhibiting a wider breadth rather than a longer depth compared to the posterior phalanges.

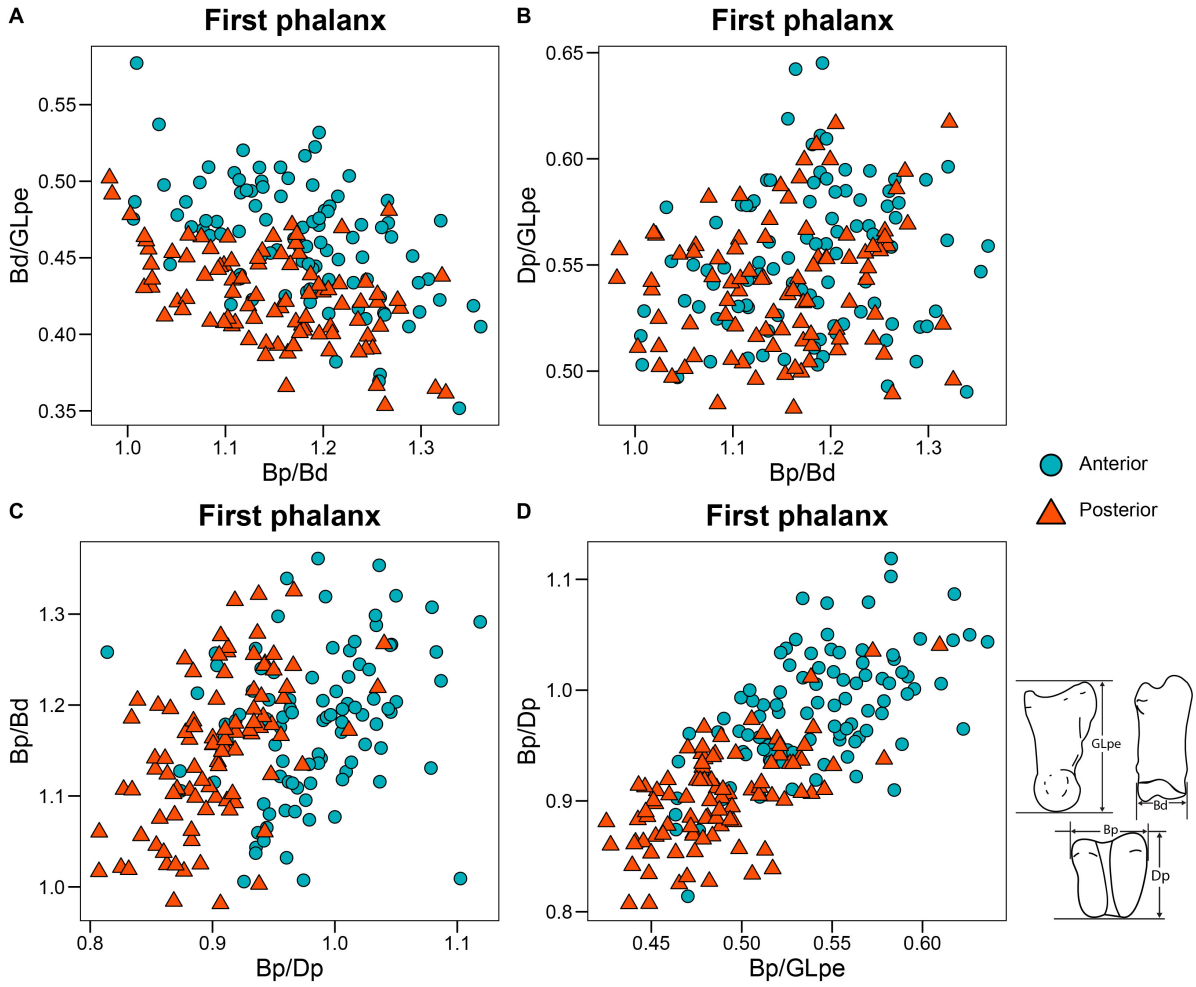



Figure 5.40: Shape ratios comparing anterior and posterior second phalanges. [**A**] The greatest breadth of the proximal end (Bp) to the greatest breadth of the distal end (Bd) against the greatest breadth of the distal end (Bd) to the greatest length of the peripheral (abaxial) half (GLpe); [**B**] The greatest breadth of the proximal end (Bp) to the greatest breadth of the distal end (Bd) against the depth of the proximal end (Dp) to the greatest length of the peripheral (abaxial) half (GLpe); [**C**] The greatest breadth of the proximal end (Bp) to the depth of the proximal end (Dp) against the greatest breadth of the proximal end (Bp) to the greatest breadth of the distal end (Bd); [**D**] the greatest breadth of the proximal end (Bp) to the greatest length of the peripheral (abaxial) half (GLpe) against the greatest breadth of the proximal end (Bp) to the depth of the proximal end (Dp).

Fair classifications of the second phalanges are displayed in Figure 5.41. The anterior and posterior second phalanges are uniform in terms of shape, with the data points more closely clustered. In Figure 5.41A, a group of anterior second phalanges in the top left is observed to have a high Bd/GLpe ratio. This pattern

indicates that the anterior phalanges have a broader distal end in relation to their greatest length. Likewise, in Figure 5.41D, it can be observed that although there is significant overlap, the anterior phalanges can have a greater Bp/GLpe ratio than the posterior. This finding further reinforces the previous suggestion that the anterior phalanges typically have a robust shape.

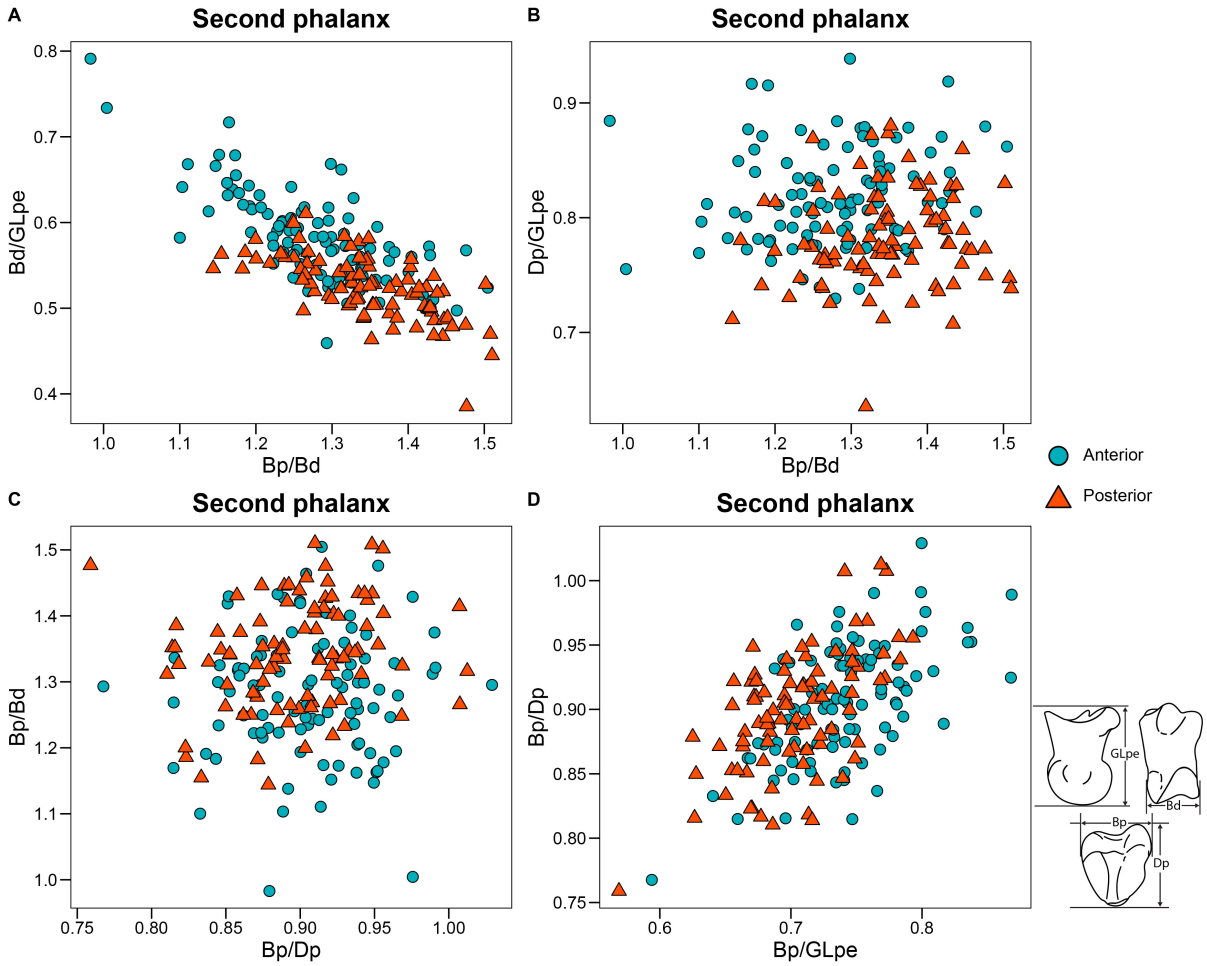



Figure 5.41: Shape ratios comparing anterior and posterior first phalanges. [**A**] The greatest breadth of the proximal end (Bp) to the greatest breadth of the distal end (Bd) against the greatest breadth of the distal end (Bd) to the greatest length of the peripheral (abaxial) half (GLpe); [**B**] The greatest breadth of the proximal end (Bp) to the greatest breadth of the distal end (Bd) against the depth of the proximal end (Dp) to the greatest length of the peripheral (abaxial) half (GLpe); [**C**] The greatest breadth of the proximal end (Bp) to the depth of the proximal end (Dp) against the greatest breadth of the proximal end (Bp) to the greatest breadth of the distal end (Bd); [**D**] the greatest breadth of the proximal end (Bp) to the greatest length of the peripheral (abaxial) half (GLpe) against the greatest breadth of the proximal end (Bp) to the depth of the proximal end (Dp).

The PCA analysis based on the ratios of the first phalanges indicates that the first two components explain $80.9\%$ of the total variance (PC 1 = $52.66\%$ and PC2 = $28.23\%$) (Figure 5.42A). PC1 is negatively related to all shape ratios, particularly Bp/GLpe ($-0.63$) and Bd/GLpe ($-0.46$). Anterior first phalanges tend to have negative PC1 scores. This implies that they are represented by a broader proximal (Bp) and distal end (Bd) in relation to the greatest length of the peripheral (abaxial) half (GLpe) compared to the posterior phalanges. However, there are several posterior phalanges with equally negative PC1 scores.

The main variations along the PC2 axis are characterised by a negative relationship with Bp/Bd ($-0.77$) and a positive relationship with Bd/GLpe (0.53). Despite some overlap between the two types of phalanges, the anterior first phalanges were more likely to have higher Bp/Bd ratios and Bd/GLpe ratios than the posterior phalanges.

For the second phalanges, the first two components account for $73\%$ of the total variance (PC1 = $45.57\%$ and PC2 = $27.41\%$) (Figure 5.42B). PC1 values are negatively associated with Bd/GLpe ($-0.60$) and Bp/GLpe ($-0.56$). Accordingly, more anterior second phalanges had negative PC1 scores, indicating wide distal and proximal ends relating to the greatest length of the peripheral (abaxial) half.

Conversely, the posterior second phalanges are plotted towards a more positive pole of PC1. Specifically, they exhibit higher Bp/Bd ratios than anterior phalanges. This pattern suggests that posterior phalanges tend to have a broader proximal end in relation to the distal end, which concurs well with Dottrens' (1946: 753) description of posterior second phalanges resembling the shape of a champagne cork.

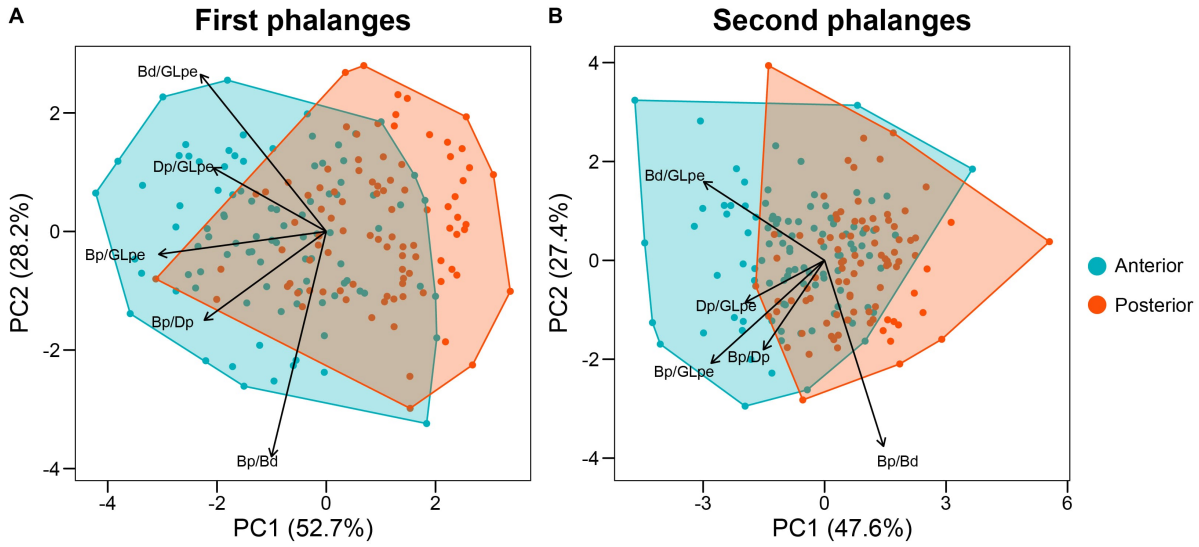



Figure 5.42: Principal component analysis of shape variation between anterior and posterior phalanges in modern non-draught cattle.

The separation of anterior and posterior phalanges on bivariate plots based on two shape ratios demonstrates satisfactory results; however, significant overlaps are present. Therefore, the modelling approach using multiple shape ratios was adopted to improve classification performance. First, a Random Forest was used for feature selection. Figure 5.43A illustrates the results for the first phalanges, indicating that the Bp/Dp ratio is the most important feature for separation. While Bd/GLpe is considered the most important for the second phalanges (Figure 5.43B).

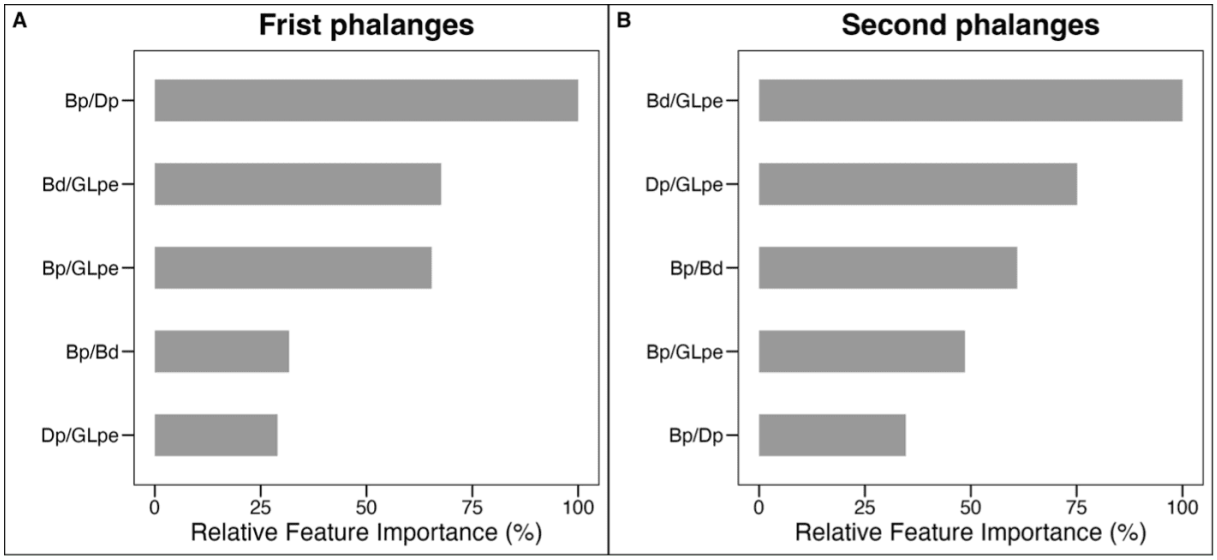



Figure 5.43: Relative feature importance of phalanges shape ratios obtained with Random Forest.

Next, the top three important ratios of each phalanx were integrated into the Support Vector Machine (SVM) model with 10-fold cross-validation for further evaluation (Table 5.49). Surprisingly, despite considerable overlap, as indicated previously on the bivariate plots, the SVM model has yielded a balanced accuracy of $80\%$ in the first phalanges (Table 5.50). Alongside a good F-score of 0.80, these results suggest a reasonably accurate classification of anterior and posterior first phalanges. Satisfactory classification results were achieved in the second phalanges, with a balanced accuracy of $64\%$ (Table 5.50). The higher specificity than sensitivity indicates that the model is better at correctly identifying the posterior second phalanges.

Table 5.49: Variables included in the SVM model.

| **Anatomical element** | **Shape ratio** |
|---|---|
| First phalanx | Bp/Dp, Bd/GLpe, Bp/GLpe |
| Second phalanx | Bd/GLpe, Dp/GLpe, Bp/Bd |

Table 5.50: Performance of the Support Vector Machine model in classifying anterior and posterior phalanges.

| Anatomical element | Accuracy | Sensitivity | Specificity | Balanced Accuracy | F-score |
|---|---|---|---|---|---|
| First phalanx | 80% | 0.75 | 0.85 | 80% | 0.80 |
| Second phalanx | 63% | 0.57 | 0.72 | 64% | 0.65 |

### 5.8.2 Level of agreement between Dottrens' criteria and shape ratios

Promising results for the classification of anterior and posterior phalanges were achieved through the SVM model. However, it is essential to acknowledge that neither the Dottrens' method nor the biometry approach is perfect. The following section examines the level of agreement between the two approaches.

The test sample used here consists of 17 first and 20 second phalanges. These materials are unknown archaeological specimens without any pathological conditions housed in the Zooarchaeology Laboratory of the University of Sheffield. Both methods were used to determine whether a phalanx is from the anterior or posterior.

There were three cases of mismatch in the first phalanges, where they were classified as anterior by Dottrens' method but suggested to be posterior by the SVM model (Table 5.51). Cohen's kappa test was employed to evaluate the agreement between the two methods. The first phalanges presented a kappa value of 0.65. According to Landis and Koch (1977: 165), a value between 0.61 and 0.80 indicates a substantial agreement.

Table 5.51: Comparison of classification results of first phalanges from two methods with Cohen's Kappa test for agreement.

| Method | Anterior | Posterior | Cohen's kappa |
|---|---|---|---|
| Dottrens' method | 9 | 8 | 0.65 |
| SVM model | 6 | 11 | (substantial agreement) |

SVM = Support Vector Machine model.

Classification results of the two methods for the second phalanges are presented in Table 5.52. Four cases of disagreement were identified, three of which were classified as posterior by the visual criteria, yet, they were predicted as

anterior in the SVM model. The Cohen's kappa value is 0.47 for the second phalanges, showing a moderate level of agreement between the two methods. It can be expected that the agreement will be lower in the second phalanges than in the first phalanges, given that the accuracy in the SVM model was not high. Nonetheless, the value of 0.47 suggests that the agreement is not entirely due to chance.

Table 5.52: Comparison of classification results of second phalanges from two methods with Cohen's Kappa test for agreement.

| Method | Anterior | Posterior | Cohen's kappa |
|---|---|---|---|
| Dottrens' method | 14 | 6 | 0.47 |
| SVM model | 16 | 4 | (moderate agreement) |

SVM = Support Vector Machine model.

The accuracy of separating anterior and posterior phalanges is fundamental to the analyses of archaeological materials. This section has presented the results of using biometry for classification, indicating a better result in the first phalanges. The results highlight that shape ratios, particularly the Bp/GLpe and Bp/Dp show a good separation in the bivariate plot. The anterior phalanges generally showed a more robust shape than the posterior. The findings in this study align with prior work by Bartosiewicz (1993), suggesting that the first phalanges have higher classification accuracy than the second phalanges.

The PCA results reveal that the anterior first phalanges show significant expansion at both their proximal and distal ends compared to the overall length of the peripheral half. This suggests that the anterior phalanges are generally thicker and shorter than the posterior phalanges, which appear more gracile and elongated.

Similarly, the anterior second phalanges display substantial width at the proximal and distal ends relative to the greatest length of the peripheral half. In contrast, the posterior second phalanges show a broader proximal end compared to the distal end. These patterns concur neatly with Dottrens' (1946: 753) observations, indicating that the anterior second phalanges are squat, flattened, and wider than high.

This section demonstrated the substantial agreement in classifying the first phalanges using the Dottrens' and biometry methods. Despite the SVM model being less effective in classifying the second phalanges, it still achieved an acceptable level of agreement. Dottrens (1946) suggests that the anterior phalanges tend to show greater robustness, whereas the posterior phalanges appear slenderer. These observations can be supported by the biometrical results obtained in this study. Nonetheless, ambiguity can occur when different individuals are mixed. The results demonstrated that comprehensive classification of anterior and posterior phalanges can be achieved by adopting a mixed approach.

## 5.9 Conclusion: Identifying draught cattle from osteological data

This chapter addresses the first sub-question in this thesis: *How can draught animals be identified in archaeological assemblages?* It focuses on the method for identifying draught animals in archaeological assemblages through analyses of limb bone morphology in modern draught and non-draught cattle. Five different aspects that may have a potential for the identification of draught animals have been analysed on modern material—spavin, asymmetry of the distal metapodials, biometry, Pathological Index, and entheseal changes. The small sample of modern draught cattle data has been the main problem in assessing potential differences between draught and non-draught cattle. Nonetheless, a wide range of modern non-draught cattle data has helped to develop a baseline for the analysis of archaeological materials. Five main conclusions have been reached in this chapter:

1. Skeletal modification and pathology are mostly multifactorial processes. Despite significant morphological variations observed between draught and non-draught cattle, none of the studied osteological changes was diagnostic of traction. Concurring with prior research, results in this study revealed the influence of confounding variables, particularly ageing and sex, which

tend to have a substantial effect on skeletal morphology. As demonstrated by the biometrical analysis, non-draught bulls may show a robust structure comparable to draught animals. Additionally, breeds may affect limb bone morphology; for example, the metapodial shape of Chartley bulls is similar to that of the draught herd. Old animals are more likely to show a high PI value and entheseal changes, even when they have not been used for traction. Thus, it is imperative to emphasise that no single ratio or pathology can be regarded as an absolute indicator of traction use.

2. Since no single method is perfect for identifying draught cattle, using a combination of approaches is encouraged when studying archaeological materials. Spavin and asymmetry of the metapodial distal ends may be associated with draught exploitation. However, these conditions may lead to misinterpretations in archaeological contexts as they are very likely to occur also in non-draught individuals. The Pathological Index and entheseal changes could be useful but several non-draught cattle in the current study presented high PI values and entheseal change scores, which could be related to old age or pathology rather than their past activity patterns. These results highlight that focusing on one bone with high PI values and entheseal change scores to infer the presence of traction cattle may lead to spurious identification. Nonetheless, the constant low average scores presented in the modern non-draught cattle can serve as a helpful baseline for comparing the overall trend observed in archaeological assemblages.

3. Entheseal change has been explored in this study on cattle. The results from this study are consistent with previous research on humans, equids and reindeer, indicating that age, sex, and body size could affect entheseal modifications. The fibrous attachment sites tend to be strongly associated with biological factors; therefore, they should be omitted in further applications. Although the validity of this method to study past activities remains debatable, prior research on humans and other ungulates demonstrates its

potential application. The analysis of cattle presented in this study suggests that not all of these show a significant association with the tested biological factors. This method has not been widely used in non-human animals to study past activity patterns. However, the relatively low gradings observed in the non-draught cattle in this study indicate the potential applicability of entheseal changes to archaeological materials.

4. The new biometric approach developed in this chapter provided the most effective tool in distinguishing draught and non-draught cattle, particularly through shape ratios of the distal ends of the metapodials and phalanges. This chapter uses bivariate plots and logistic regression models to illustrate the shape ratio differences between the two cattle groups. Notably, the first phalanx exhibits the highest Balanced Accuracy among all tested anatomical elements, which has not previously been recognised in the literature. In contrast to the Pathological Index and entheseal changes that rely on subjective scoring, the biometric method is a more objective approach. Based on these results, this biometric approach represents the most effective method for investigating the presence of traction use at the population level in archaeological assemblages.

5. When feasible, separate analyses of anterior and posterior phalanges are recommended. In general, anatomical elements from the forelimbs in non-draught cattle show higher deformation than those from the hindlimbs. Entheseal changes were slightly more pronounced in the anterior than the posterior phalanges. The overall trend could be attributed to the fact that the front legs support a larger proportion of the body weight. Based on this observation, if the modifications are higher in the back legs compared to the front legs, it could potentially indicate draught animals.

   However, although the accuracy for classifying draught and non-draught cattle was higher when the phalanges were separated, the distinction between fore and hind limb phalanges based on the visual method proposed by

Dottrens can be ambiguous. This chapter has analysed the shape variations between anterior and posterior phalanges through biometry. The biometric results are largely consistent with Dottrens' observations; nonetheless, there are considerable overlaps in the shape ratios between the two, particularly on the second phalanx. This indicates the need for caution when relying solely on Dottrens' criteria to distinguish fore and hind limb phalanges in archaeological material.

Identification of draught animals through osteological data is inherently challenging due to the complexity of pathological and morphological changes. The new biometric method developed in this study, when combined with the Pathological Index and entheseal changes, offers the most robust approach for identifying draught cattle in archaeological assemblages.Integrating these multiple lines of evidence enables us to gain a more holistic understanding of the use of animal traction and the significant role that draught cattle played in shaping past human societies and economies.

# 6

# ANIMAL TRACTION IN PREHISTORIC BRITAIN: AN OSTEOLOGICAL APPROACH

## Contents


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## 6.1 Introduction

This chapter addresses the second research question:*When did animal traction begin in Britain?* To explore this, the study focuses primarily on sites dating from the Early Neolithic to the Late Bronze Age in order to explore the origins and earliest development of animal traction in Britain. Current speculation regarding the earliest use of animal traction places it within this timeframe, as highlighted in Section 2.5. A hypothetical Neolithic origin is supported by findings such as the plough marks from South Street (Mercer, 1981: x) and a pathological pelvis from Etton (Armour-Chelu and Clutton-Brock, 1985: 300–1). In contrast, evidence for a Late Bronze Age/Early Iron Age origin derives from the remains of ploughing tools(C. W. Bishop, 1936; Curwen, 1927). The most concrete evidence of draught

animal use in Britain comes from the yoke remains found at Loch Nell in Argyll, dated to 1950-1525 cal. BC (Hedges et al., 1995).

## 6.2 The archaeological sites

Data from 14 later prehistoric sites across Britain, dating from the Early Neolithic to the Late Bronze Age, were collected (Figure 6.1 and Table 6.1). These sites were selected for three reasons. First, they are within chronologies where early traction might have been adopted. Second, they have produced a relatively large quantity of well-preserved cattle limb bones. Third, the materials were available for access.

Additionally, eight comparative sites from the Iron Age, Roman, and Medieval periods were recorded. While this study focuses on the pre-Iron Age farming period, these later sites provide valuable comparative data, as draught animals were known to have been used during the Roman and Medieval periods. A brief background of the recorded sites is provided in the following section. The chronological framework used in this study is outlined in Table 1.1. However, the sub-division of periods may vary between publications; related discrepancies are addressed in the site-specific discussions below.

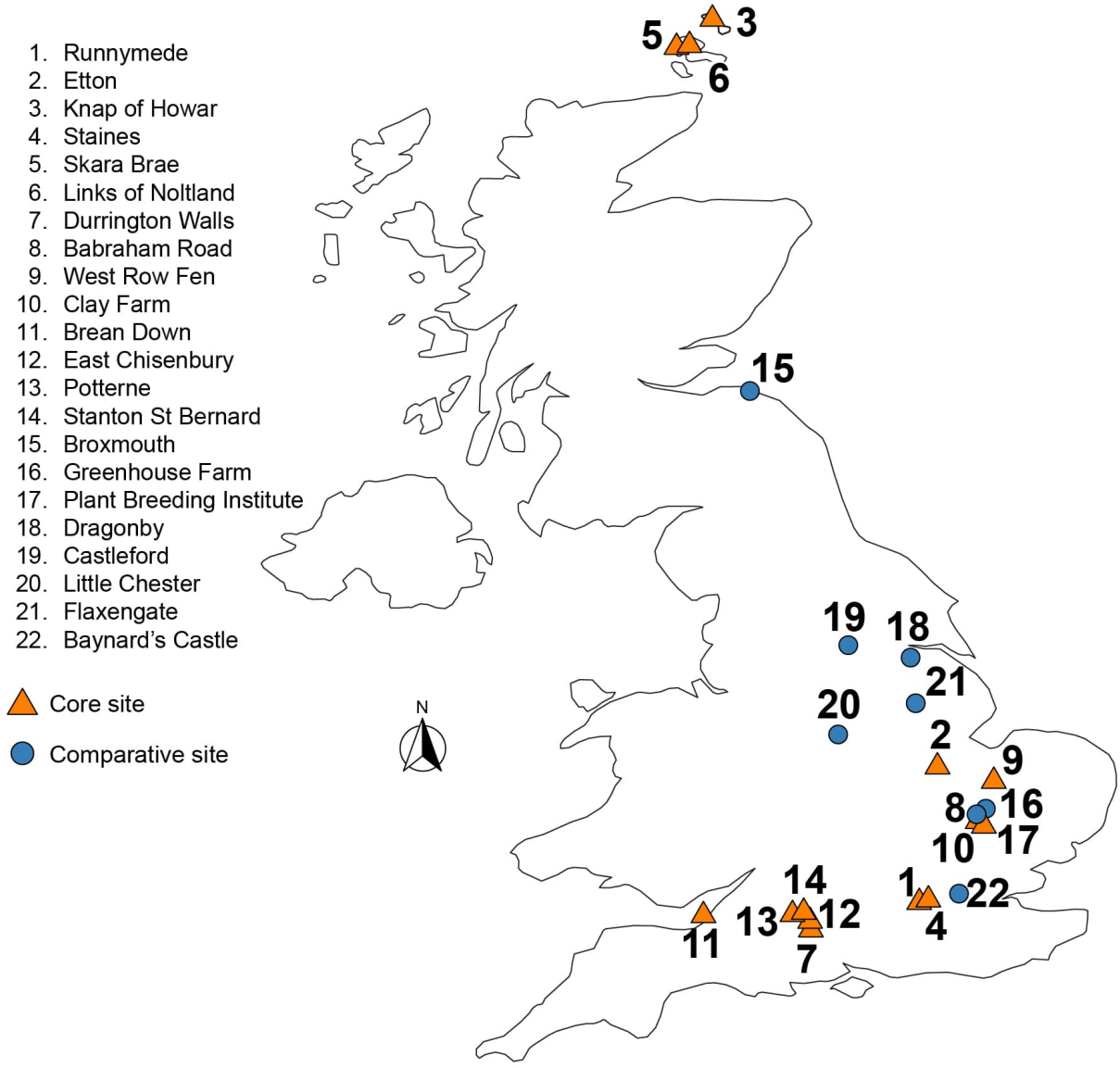



Figure 6.1: Location of the archaeological sites included in this study.

Table 6.1: The archaeological sites included in this study.

| Type | No. | Site | County | Chronology |
|---|---|---|---|---|
| Core site | 1 | Runnymede | Surrey | Early Neolithic; Late Bronze Age |
| | 2 | Etton | Cambridgeshire | Early Neolithic |
| | 3 | Knap of Howar | Orkney | Early Neolithic |
| | 4 | Staines | Surrey | Early Neolithic |
| | 5 | Skara Brae | Orkney | Late Neolithic |
| | 6 | Links of Noltland | Orkney | Late Neolithic |
| | 7 | Durrington Walls | Wiltshire | Late Neolithic |
| | 8 | Babraham Road | Cambridgeshire | Late Neolithic/Early Bronze Age; Mid/Late Bronze Age |
| | 9 | West Row Fen | Suffolk | Early Bronze Age |
| | 10 | Clay Farm | Cambridgeshire | Mid Bronze Age |
| | 11 | Brean Down | Somerset | Mid and Late Bronze Age |
| | 12 | East Chisenbury | Wiltshire | Late Bronze Age |
| | 13 | Potterne | Wiltshire | Late Bronze Age |
| | 14 | Stanton St Bernard | Wiltshire | Late Bronze Age |
| Comparative site | 15 | Broxmouth | East Lothian | Iron Age |
| | 16 | Greenhouse Farm | Cambridgeshire | Iron Age |
| | 17 | Plant Breeding Institute | Cambridgeshire | Iron Age |
| | 18 | Dragonby | Lincolnshire | Roman |
| | 19 | Castleford | Yorkshire | Roman |
| | 20 | Little Chester | Derbyshire | Roman |
| | 21 | Flaxengate | Lincolnshire | Saxon-Norman; Medieval |
| | 22 | Baynard's Castle | Greater London | Medieval; Post-Medieval |

### 6.2.1 Core sites

1. **Runnymede**

   Runnymede, located in northwest Surrey, underwent major excavations during the 1970s (Longley, 1980; Needham, 1991, 1996, 2000). These excavations yielded a large quantity of animal bone from the Middle Neolithic and Late Bronze Age periods. Nonetheless, only materials from Area 4, and 6 (Done, 1991) and 16 East (Serjeantson, 1996) have been analysed and published. Therefore, this study includes assemblages solely from these three areas.

   Dating from Area 4 and 6 suggests that Middle Neolithic activities in Runnymede commenced between c. 4000 and 3500 cal. BC (Leese, 1991: 352). While the original publications attributed the Neolithic phase of Runnymede to the Middle Neolithic, the radiocarbon dates of this phase are contemporary to Hambledon Hill and Windmill Hill; it should therefore be attributed to the Early Neolithic, though to its latest phase to the Neolithic (for discussion, see Albarella, 2019: 37). The Late Bronze Age settlement was dated to the c. 900 to 790 cal. BC (Leese, 1991: 353).

2. **Etton**

   The Etton causewayed enclosure is located in Maxey, Cambridgeshire. Pryor (1998: 351) identified five phases of activity at the site. This study, however, includes only materials recovered from Phase 1 (Middle Neolithic). The later dating program indicates that the Neolithic activities at Etton commenced in 3775–3650 cal. BC (95% probability), while the primary use of the enclosure ceased in 3330–3095 cal. (95% probability) (Healy et al., 2011a: 324–5). Like Runnymede, the original publications suggested Phase 1 as Middle Neolithic.

   The initial animal bone reports from Etton document the presence of osteoarthritis in cattle acetabula and scapulae, which was interpreted as a potential result of draught work (Armour-Chelu and Clutton-Brock, 1985:

300–2; Armour-Chelu, 1998: 273–88). The Etton faunal assemblage was re-analysed in 2014 in a PhD thesis, focusing on the taphonomic changes (Parmenter, 2014). While the thesis did not address the pathological aspects, it highlighted that the report from the 80s only analysed one-third of the material in the archive (Armour-Chelu, 1998: 273–88).

3. **Knap of Howar**

   Knap of Howar, located on Papa Westray Island of Orkney, is an Early Neolithic settlement containing two house structures. The site was first excavated in 1929 (Traill and Kirkness, 1937), with further investigations conducted in 1973 and 1975 (Ritchie et al., 1984). Two major periods of activity were identified; however, Ritchie et al. (1984: 44) suggest no significant chronological differences between the two periods. More recent studies proposed the start of activity at 3635–3370 cal. BC and the end of activity at 3305–2835 cal. BC at the site (Griffiths, 2021: 280; Bayliss et al., 2017: Fig. S17).

4. **Staines**

   Staines (Surrey) is an Early Neolithic causewayed enclosure in the lower Thames Valley. The original publication does not provide definite dating for the site due to the absence of reliable radiocarbon dates (Robertson-Mackay et al., 1987: 60) . However, more recent analysis suggests that the construction of the inner circuit dates to 3525–3380 cal. BC (89% probability), while the outer ditch is dated to 3465–3375 cal. BC (55% probability) (Healy et al., 2011b: 393).

5. **Skara Brae**

   The Late Neolithic settlement of Skara Brae is located on the Bay of Skaill in western Mainland Orkney. Radiocarbon dating of the settlement suggests three phases of occupation from c. 3400–2500 cal. BC, where the earliest phase began around 3400 cal. BC and ended around 3200 cal. BC, followed by the establishment of the nucleated settlement around 2900 cal. BC,

and the site was re-occupied between approximately 2750 and 2500 cal. BC (Bayliss et al., 2017). Animal bones recorded for this study came from excavations conducted in 1972-73 and 1977.

6. **Links of Noltland**

   Links of Noltland is a Late Neolithic settlement on the north coast of Westray, Orkney. The materials recorded in this study were from excavations conducted between 1979 and 1981, focusing on the northeast corner of the Links of Noltland (Clarke and Sharples, 1985). The deposits from this excavation were dated to the Late Neolithic period, during which the settlement was contemporary with Skara Brae (Moore and Wilson, 2011: 14). The latest dating programme indicates that the estimated date of activity at the Links of Noltland falls between 3160 and 2870 cal. BC (Clarke et al., 2017).

   Recent analyses of the specimens excavated in 2007–2015 suggest that cattle could have been used for traction at Neolithic Links of Noltland, based on pathological alterations on the phalanges (Fraser, 2011: 45, 2015: 313).

7. **Durrington Walls**

   The Late Neolithic henge of Durrington Walls in Wiltshire was first excavated in 1951–1952 (Stone et al., 1954), with subsequent excavations in 1966–1967 (Wainwright and Longworth, 1971). The settlement began in the 2525–2470 cal. BC and ended in 2480–2440 cal. BC, and is associated with Grooved Ware pottery (Parker Pearson et al., 2011). The materials recorded in this study derive from excavations conducted between 2004 and 2007 by the Stonehenge Riverside Project.

8. **Babraham Road**

   Babraham Road in Cambridge shows evidence of human activity from the Late Neolithic period through to the Iron Age. This study focuses only on materials from Phase 1 (Late Neolithic/Early Bronze Age) and Phase 2 (Early/Middle Bronze Age). The Late Neolithic/Early Bronze Age is represented by radiocarbon dates ranging from c. 2205–1895 cal. BC, while

the Early/Middle Bronze Age is dated from 1755 to 1415 cal. BC (Baxter, 2007, 2002).

9. **West Row Fen (Mildenhall 165)**

   The Early Bronze Age settlement site of West Row Fen in Suffolk was excavated from 1982 to 1986, revealing a large and well-preserved assemblage of fauna (E. Martin and Murphy, 1988; Olsen, 1994). Radiocarbon dating places the Early Bronze Age component in the time frame of 2290 to 1780 cal. BC (Olsen, 1994: 116).

   At this site, domestic cattle appear as the predominant livestock, and most of these cattle were kept beyond the age of six years. Considering the high survival rate of adult cattle and the pathological conditions observed in the ischium and phalanges, the potential use of cattle for traction was suggested (Olsen, 1994: 144).

10. **Clay Farm**

    Clay Farm is located in Trumpington, on the southern fringes of Cambridge (Phillips and Mortimer, 2012). This site contains archaeological remains from multiple periods, but this study primarily focuses on Period 3, the Middle Bronze Age (c. 1600–1150 cal. BC). The full publication of this site was unavailable at the time of writing this thesis.

11. **Brean Down**

    Brean Down (Somerset) is a Bronze Age settlement that contains four main prehistoric occupational layers. The cattle bones recorded for this study are derived from Unit 7 (Beaker), 5b (Mid-Bronze Age), and 4 (Late Bronze Age) (Walker, 1990: 108).

12. **East Chisenbury**

    East Chisenbury is also a Late Bronze Age site in the Vale of Pewsey, Wiltshire. A recent Bayesian program suggests that this site could have been

occupied from the late 10th or early 8th century cal. BC to the 5th century cal. BC (Waddington, 2009, as cited in Madgwick et al., 2023).

13. **Potterne**

    The Late Bronze Age to Early Iron Age midden of Potterne in the Vale of Pewsey, Wiltshire, produced over 130,000 animal bones. The primary excavation occurred between 1983 and 1985, where most of these bones came from zone 4–14 of the Cuttings 12 (Locker, 2000). A precise chronological range has not been established due to the significant reworking of the site. Nonetheless, it is suggested that the early occupation commenced by the late 12th century cal. BC, whereas the deposit was accumulated between the beginning of the 10th century and the end of the 6th century cal. BC (Lawson et al., 2000a: 261).

14. **Stanton St Bernard**

    This site is located close to Potterne on the chalk downs of Wiltshire. The dating of this site is unavailable. Nonetheless, analyses of human bones from Stanton St Bernard have produced dates ranging from 800 to 700 cal. BC (Booth and Brück, 2020).

### 6.2.2 Comparative sites

Data were collected from three Iron Age, three Roman, and two Medieval sites for comparison. Based on current evidence of ploughs and the wheeled vehicle remains, animal traction was likely practised in the Iron Age, whereas the use of draught cattle is well-documented in the Roman and Medieval periods. Analysing the Iron Age and historical assemblages can, therefore, aid in interpreting results from prehistoric sites.

15. **Broxmouth**

    Broxmouth is an Iron Age hill fort in East Lothian, Scotland. The site is divided into seven phases (Armit and McKenzie, 2013: 18–9):

- Phase 1: 640/570–490 cal. BC
- Phase 2: 490/430–395/375 cal. BC
- Phase 3: 395/375–295/235 cal. BC
- Phase 4: 295/235–235/210 cal. BC
- Phase 5: 235/210–100/60 cal. BC
- Phase 6: 100/60 cal. BC–AD 155/210
- Phase 7: AD 420-540

The majority of the animal bones derive from Phases 3 and 5, while no materials from Phase 7 were included in this study. Nonetheless, given the small sample size for each phase, the analysis will combine all phases to represent a general Iron Age context.

16. **Greenhouse Farm**

    The Early to Late Iron Age settlement of Greenhouse Farm is located on Newmarket Road in Cambridge (Mould, 1996).

17. **Plant Breeding Institute**

    The Iron Age site of Plant Breeding Institute is located in Trumpington, Cambridgeshire (Davidson and Curtis, 1973). The material recorded was from the excavation in 2001.

18. **Dragonby**

    The Iron Age and Early Roman settlement site of Dragonby is in North Lincolnshire near the River Humber (May, 1996). The cattle bones analysed in this study derive from the Roman contexts.

19. **Castleford**

    Castleford was occupied by the military from AD 80 to AD 150, while residents continued living in the settlement after the Roman army left (Abramson et al., 1999). Materials studied were from the vicus and derived from the following phases:

- Phase 1: AD 71/4 to AD 86
- Phase 2: AD 85–90 to AD 135–40
- Phase 4: AD 180+ to AD 400

20. **Little Chester**

    Little Chester is located within the town of Derby and is a Roman settlement and fort whose origins date to the late first or mid-second century AD (Brassington, 1996). The animal bones predominantly date from the mid-third to late fourth century.

21. **Flaxengate**

    This site in Lincoln lies between Flaxengate and Grantham Street (O'Connor, 1982). The bones recorded for this study are from the Saxon-Norman period (c. 1060–1140), the Early Medieval period (c. 1140–1200), and the High Medieval period (c. 1200–1400).

22. **Baynard's Castle**

    The Medieval site of Baynard's Castle in London produced a large quantity of animal bones dated from the 13$^{th}$ to 16$^{th}$ century (Armitage, 1977). Cattle bones recorded for this study cover all phases.

## 6.3 Materials and methods

### 6.3.1 Materials

The analyses were taken on the cattle metapodials, the first and second phalanges. Table 6.2 shows the number of anatomical elements recorded at each site.

Table 6.2: Number of elements recorded for each site.

| | Site | Metacarpal | Metatarsal | 1st phalanx | 2nd phalanx | Total |
|---|---|---|---|---|---|---|
| Core site | Runnymede (ENEO) | - | 1 | 7 | 4 | 12 |
| | Etton | 13 | 12 | 22 | 12 | 59 |
| | Knap of Howar | 11 | 2 | 23 | 21 | 57 |
| | Staines | 5 | 5 | 1 | - | 11 |
| | Skara Brae | 18 | 20 | 180 | 199 | 416 |
| | Links of Noltland | 15 | 7 | 32 | 7 | 61 |
| | Durrington Walls | 13 | 11 | 87 | 93 | 204 |
| | Babraham Road (LNEO/EBA) | 2 | 5 | 3 | 2 | 12 |
| | West Row Fen | 6 | 6 | 27 | 21 | 60 |
| | Babraham Road (E/MBA) | 1 | - | 3 | - | 4 |
| | Clay Farm | 20 | 23 | 43 | 16 | 102 |
| | Brean Down (MBA) | - | - | 5 | 3 | 8 |
| | Runnymede (LBA) | 6 | 3 | 27 | 17 | 53 |
| | Brean Down (LBA) | 3 | - | 12 | 4 | 18 |
| | East Chisenbury | - | - | 5 | 3 | 8 |
| | Potterne | 18 | 31 | 128 | 81 | 258 |
| | Stanton St Bernard | - | 2 | 7 | 1 | 10 |
| Comparative site | Broxmouth | 38 | 41 | 153 | 71 | 303 |
| | Greenhouse Farm | 4 | 4 | 7 | 3 | 18 |
| | Plant Breeding Institute | 10 | 6 | 16 | 6 | 38 |
| | Castleford | 11 | 20 | 35 | 2 | 66 |
| | Dragonby | 12 | 12 | 50 | 31 | 105 |
| | Little Chester | 8 | 15 | 42 | 10 | 75 |
| | Flaxengate | 44 | 20 | 92 | 29 | 185 |
| | Baynard's Castle | 50 | 55 | 192 | 67 | 364 |

ENEO = Early Neolithic; LNEO = Late Neolithic; EBA = Early Bronze Age; MBA = Mid-Bronze Age; LBA = Late Bronze Age.

### 6.3.2 Methods used for the archaeological materials

The analyses of the archaeological assemblages employed the same methods as those applied to modern materials, including the Pathology index, biometry, and entheseal changes (see Section 5.3). Considering the uncertainty in distinguishing between anterior and posterior phalanges in archaeological assemblages, the analysis of the two phalanges is combined. Section 5.8 indicates that the separation may be aided by biometry; however, there is significant overlap. Therefore, a decision has been made not to separate the phalanges to avoid potential errors and maximise the sample size.

#### 6.3.2.1 Kill-off patterns

Ageing data from several sites were extracted from the literature, and only sites containing more than 10 samples were considered in this study (Table 6.3). In the absence of published ageing data, age was assessed according to tooth eruption

and wear for dP4, P4 and molars. Mandibular tooth wear stages were recorded following Grant (1982) and allocated into the five age categories proposed by O'Connor (1988). Tooth wear stages were recorded when at least two recordable teeth were present in a mandible.

Table 6.3: References used for age data of archaeological sites.

| Site | Reference |
|---|---|
| Runnymede | Done, 1991; Serjeantson, 1996, 2006 |
| Skara Brae | Recorded by the author |
| Links of Noltland | Recorded by the author |
| Durrington Walls | Personal data from U. Albarella |
| West Row Fen | Olsen, 1994 |
| Clay Farm | Recorded by the author |
| Potterne | Locker, 2000 |

#### 6.3.2.2 Pathological Index

The Pathological Index (PI) method introduced by Bartosiewicz et al. (1997) was adopted to assess pathological alterations in metapodials and phalanges (see Section 5.3.2 for details). However, to account for the fragmentary nature of the archaeological specimens, the PI value was calculated using the modified approach proposed by Carlson Dietmeier (2018). Thus, the PI is calculated for the proximal and distal metacarpals, proximal and distal metatarsals, first phalanx, and second phalanx.

A mean PI is first calculated for each anatomical part across all specimens from a given site. Then, the overall mean PI for the site is obtained by averaging the mean values of all anatomical parts, providing a single representative PI value for each site. The overall mean PI is calculated only when the recorded elements exceed five.

#### 6.3.2.3 Biometry

The biometric analysis of the archaeological materials follows the method developed in Section 5.6.2.4, focusing on the morphological variations in cattle

metapodials and first and second phalanges. Measurements taken on archaeological specimens are listed in Table 5.5.

#### 6.3.2.4 Entheseal changes

The recording of entheseal changes in archaeological specimens follows the method established in modern materials (see Section 5.3.4). However, the sample size was limited due to the fragmentation of long bones from archaeological sites. Therefore, entheseal changes were only recorded for the first and second phalanges (Plates 5.8 and 5.9).

## 6.4 Archaeological results

### 6.4.1 Cattle kill-off patterns

The age data in this study primarily support the interpretation of the results presented later in this section; therefore, the age composition of individual sites will not be discussed in detail. Nonetheless, the kill-off patterns provide a broad idea of animal exploitation for various purposes. If cattle traction was practised, it should be expected that some animals used for this purpose would be culled at a mature stage to maximise their utility, as time and effort are required to train them to perform draught work efficiently.

Figure 6.2 shows the distribution of cattle at different age stages in sites with at least ten recorded samples. A notable pattern is the high percentage of young animals culled at the juvenile and immature stages in the two Neolithic sites in Orkney, Skara Brae and Links of Noltland. The high mortality rate of young calves may be related to an emphasis on milk production. Similarly, the intensive use of cattle for milk is also suggested at Runnymede in the Early Neolithic context, where over $20\%$ of the animals were culled before six months (Serjeantson, 2011: 24).

The two Early and Middle Bronze Age sites, West Row Fen and Clay Farm, are dominated by older cattle, with adults and elderly individuals comprising

over $60\%$ of the population. In contrast, an even distribution of ages is indicated at Potterne, which could suggest that the animals were potentially exploited for diverse purposes, including meat and secondary products.

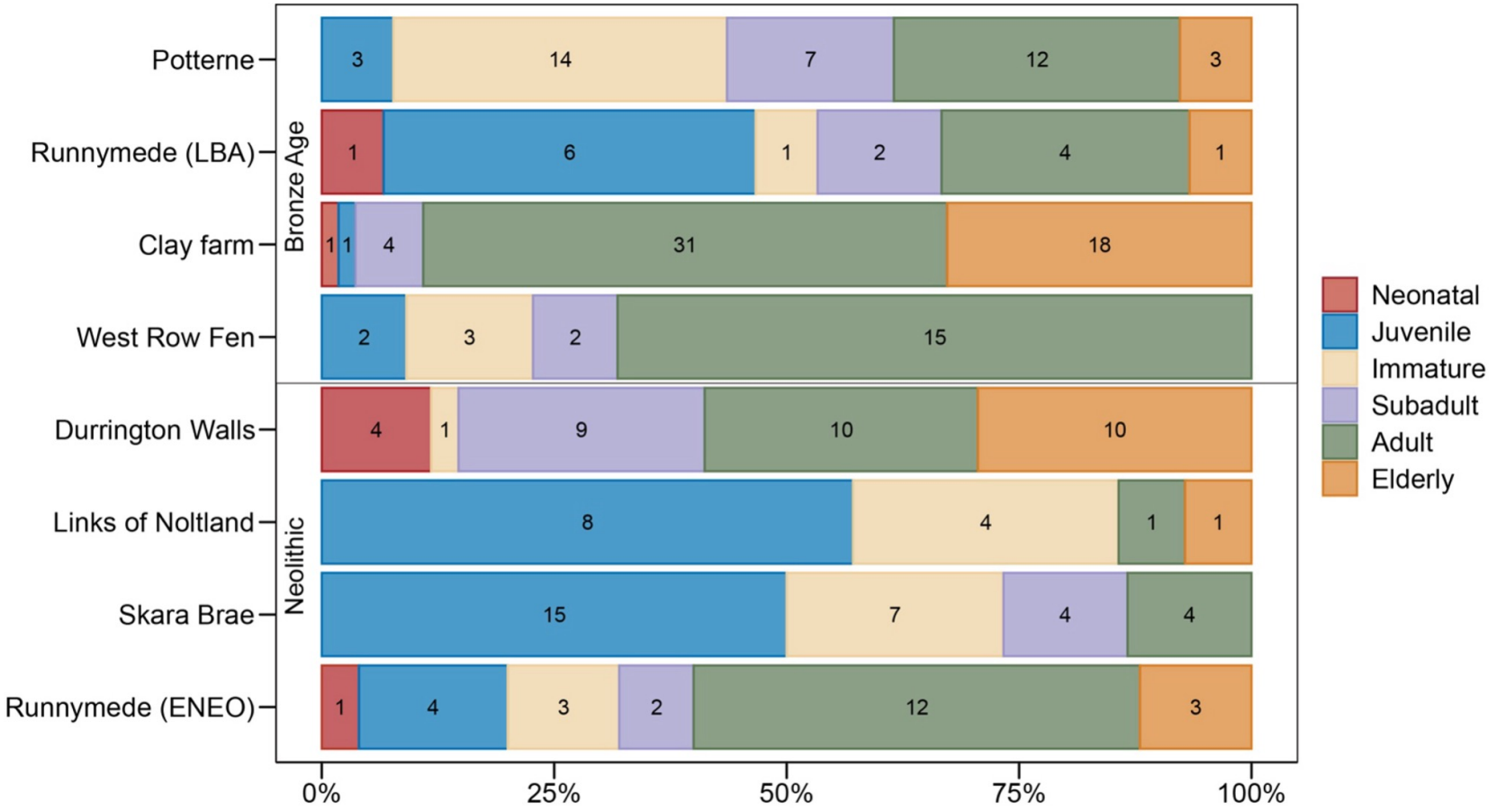



Figure 6.2: Distribution of cattle mandibles by age stage at the core sites. Only include sites with more than ten samples (the sample size is marked inside the bar). The age stages follow O'Connor (1988).

### 6.4.2 Pathological Index

Pathological alterations are generally minimal at the core sites (Table 6.4). Notably, most sites show no pathological conditions in the proximal metapodials, as indicated by a PI value of 0. The only site displaying pathological changes in the proximal metacarpal is the Late Bronze Age site of Potterne, which presents conditions comparable to those observed at the Late Medieval site of Baynard's Castle.

Although the Early/Mid Bronze Age context at Babraham Road shows the highest PI value for the distal metacarpal (Table 6.4), this elevated value is based on a single sample and can, therefore, be considered insignificant. Exostosis is rare in the distal metapodials among the core sites, while distal broadening is commonly recorded (Plate 6.1). West Row Fen and Potterne display relatively high PI values in the distal metapodials, particularly in the metacarpals. Both sites exhibit PI values for the distal metacarpals that exceed those of comparative sites, including Little Chester (Roman) and Baynard's Castle (Medieval).

Figure 6.3 shows the mean PI values calculated by combining the proximal and distal ends of the metacarpals and metatarsals (including only sites with more than five recorded specimens). The results indicate that bones from Neolithic sites generally exhibit minimal or no pathological conditions, whereas the PI values substantially increase in the Bronze Age, particularly in the metacarpals (Figure 6.3A).

Table 6.4: Mean Pathological Index values of the archaeological sites.

| | Site | MC (Proximal) | MC (Distal) | MT (Proximal) | MT (Distal) | 1st phalanx | 2nd phalanx |
|---|---|---|---|---|---|---|---|
| Core site | Runnymede (ENEO) | - | - | - | - | 0.013 | 0 |
| | Etton | - | 0 | - | 0 | 0 | 0.008 |
| | Knap of Howar | 0 | 0 | 0 | 0 | 0 | 0.02 |
| | Staines Enclosure | 0 | 0 | 0 | 0 | - | - |
| | Skara Brae | 0 | 0.01 | 0 | 0.006 | 0.007 | 0.02 |
| | Links of Noltland | 0 | 0 | 0 | 0 | 0.006 | 0.04 |
| | Durrington Walls | 0 | 0.03 | 0 | 0.02 | 0.004 | 0.005 |
| | Babraham Road (LNEO/EBA) | 0 | 0 | - | 0 | 0 | 0.05 |
| | West Row Fen | 0 | 0.09 | 0 | 0.02 | 0.03 | 0.01 |
| | Babraham Road (E/MBA) | 0 | 0.1 | - | - | 0.06 | - |
| | Clay Farm | 0 | 0.04 | 0.01 | 0.005 | 0.02 | 0.02 |
| | Brean Down (MBA) | - | - | - | - | 0.04 | 0.03 |
| | Runnymede (LBA) | 0 | 0.08 | 0 | 0 | 0.02 | 0.02 |
| | Brean Down (LBA) | 0 | 0 | 0 | 0 | 0 | 0.03 |
| | East Chisenbury | - | - | - | - | 0.07 | 0 |
| | Potterne | 0.02 | 0.09 | 0.03 | 0.04 | 0.03 | 0.04 |
| | Stanton St Bernard | - | - | - | 0 | 0.03 | 0.09 |
| Comparative data | Broxmouth | 0.01 | 0.02 | 0 | 0.003 | 0.02 | 0.03 |
| | Greenhouse Farm | 0 | 0.03 | 0 | 0.06 | 0.04 | 0.06 |
| | Plant Breeding Institute | 0 | 0.03 | 0 | 0 | 0.03 | 0.09 |
| | Little Chester | - | 0.03 | 0 | 0.05 | 0.02 | 0.05 |
| | Baynard's Castle | 0.02 | 0.09 | 0.06 | 0.05 | 0.07 | 0.07 |
| | Modern Non-draught (Halle) | 0.1 | 0.06 | 0.1 | 0.05 | 0.05 | 0.05 |

MC = Metacarpal; MT = Metatarsal; LNEO = Late Neolithic; EBA = Early Bronze Age; MBA = Mid-Bronze Age; LBA = Late Bronze Age.

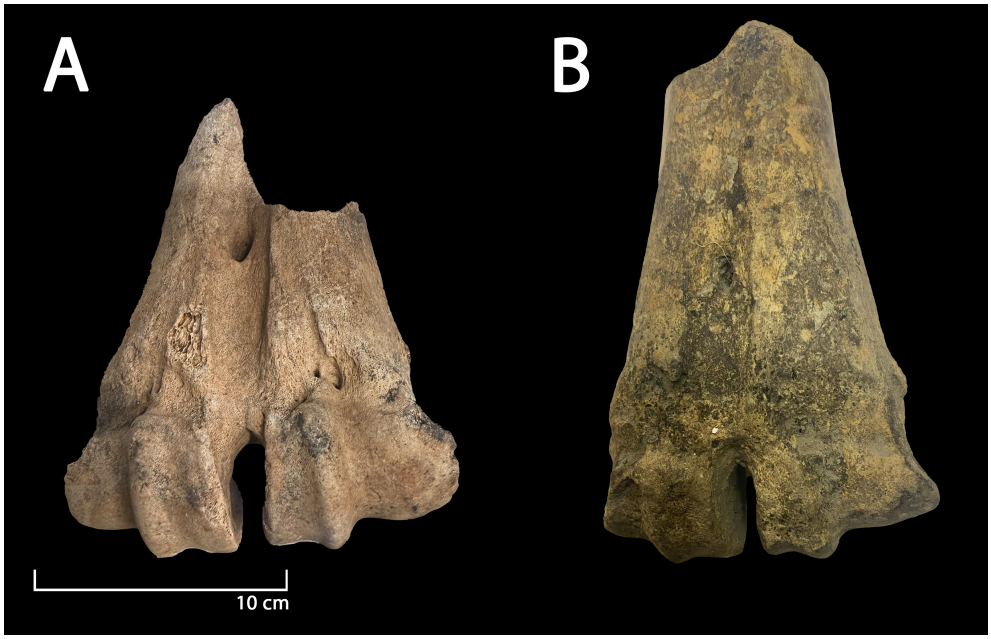



Plate 6.1: Distal broadening of the distal metatarsal from [**A**] Clay Farm and [**B**] Potterne.

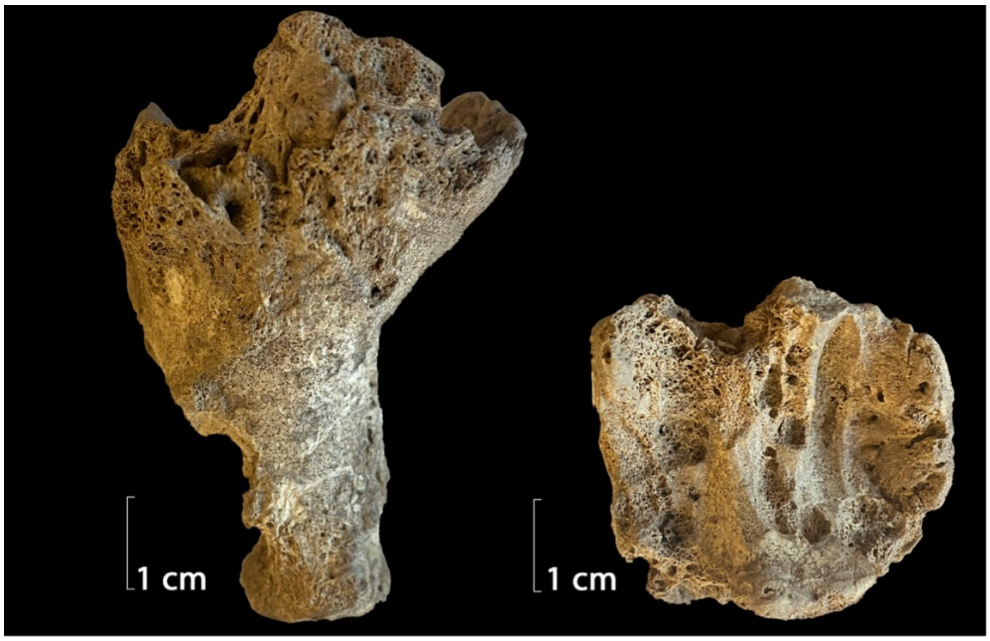



Plate 6.2: First phalanx from Brean Down (Unit 5b, Mid-Bronze Age) showing extensive exostosis on the proximal end.

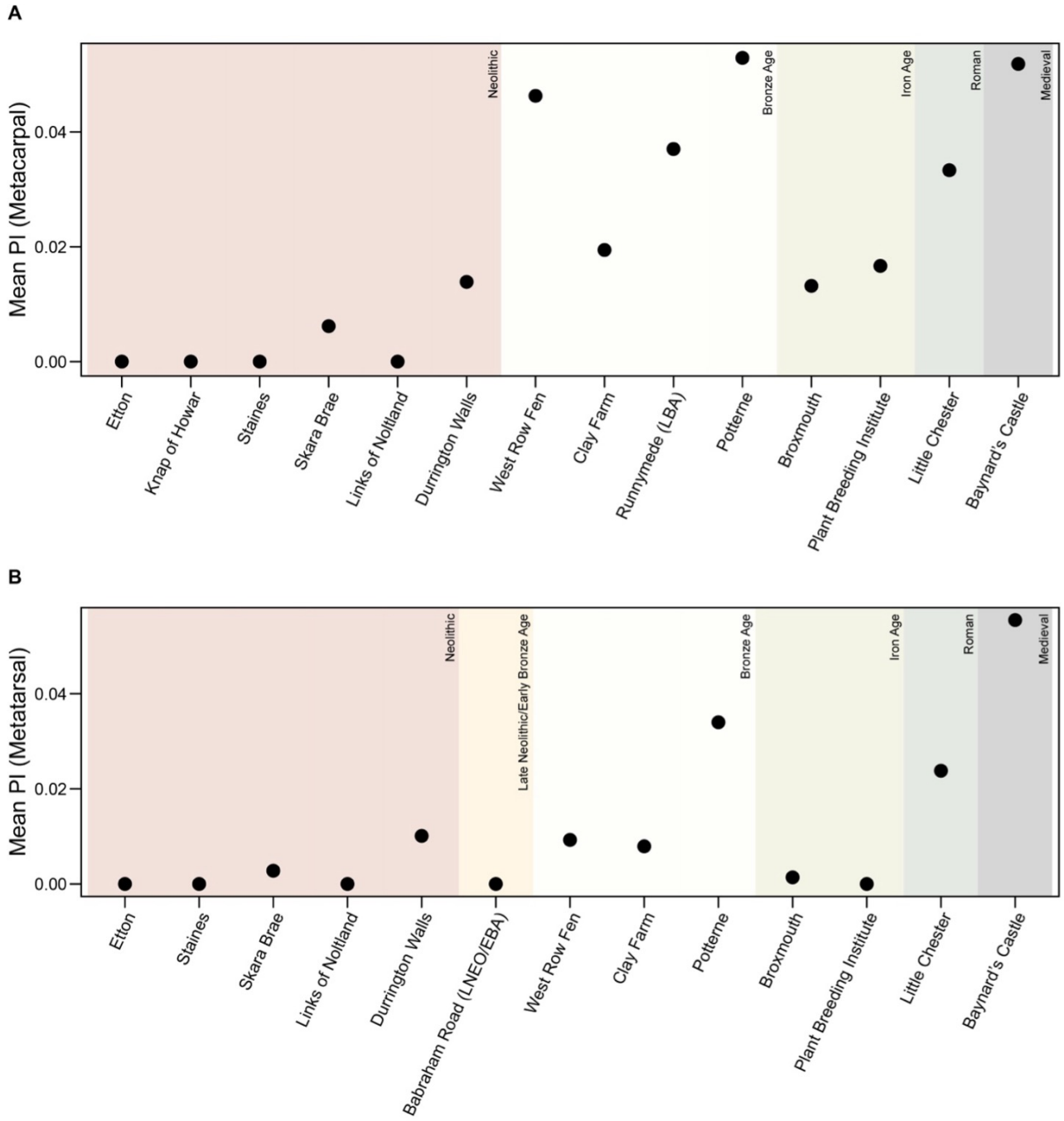



Figure 6.3: Mean Pathological Index (PI) values of [**A**] metacarpal and [**B**] metatarsal from archaeological sites.

Pathological changes were commonly recorded on the first and second phalanges; however, they were rare in Neolithic specimens. In contrast, Bronze Age sites demonstrate increased PI values, with Grade 2-3 proximal lipping and exostosis frequently recorded. Notably, one first phalanx from a Mid-Bronze Age

context at Brean Down displayed substantial new bone growth at the proximal end (Plate 6.2). Eburnation, while relatively rare, has been observed on the first phalanx at a limited number of sites — specifically at only one core site, Potterne (Plate 6.3), and two comparative sites (Broxmouth and Baynard's Castle). The mean PI values in the first and second phalanges (Figure 6.4) align with those of the metapodials (Figure 6.3), indicating a marked increase in pathological changes from the Neolithic to the Bronze Age.




Plate 6.3: First phalanx from Potterne, exhibiting proximal and distal exostosis and distal eburnation. The circled area highlights the location of the eburnation.

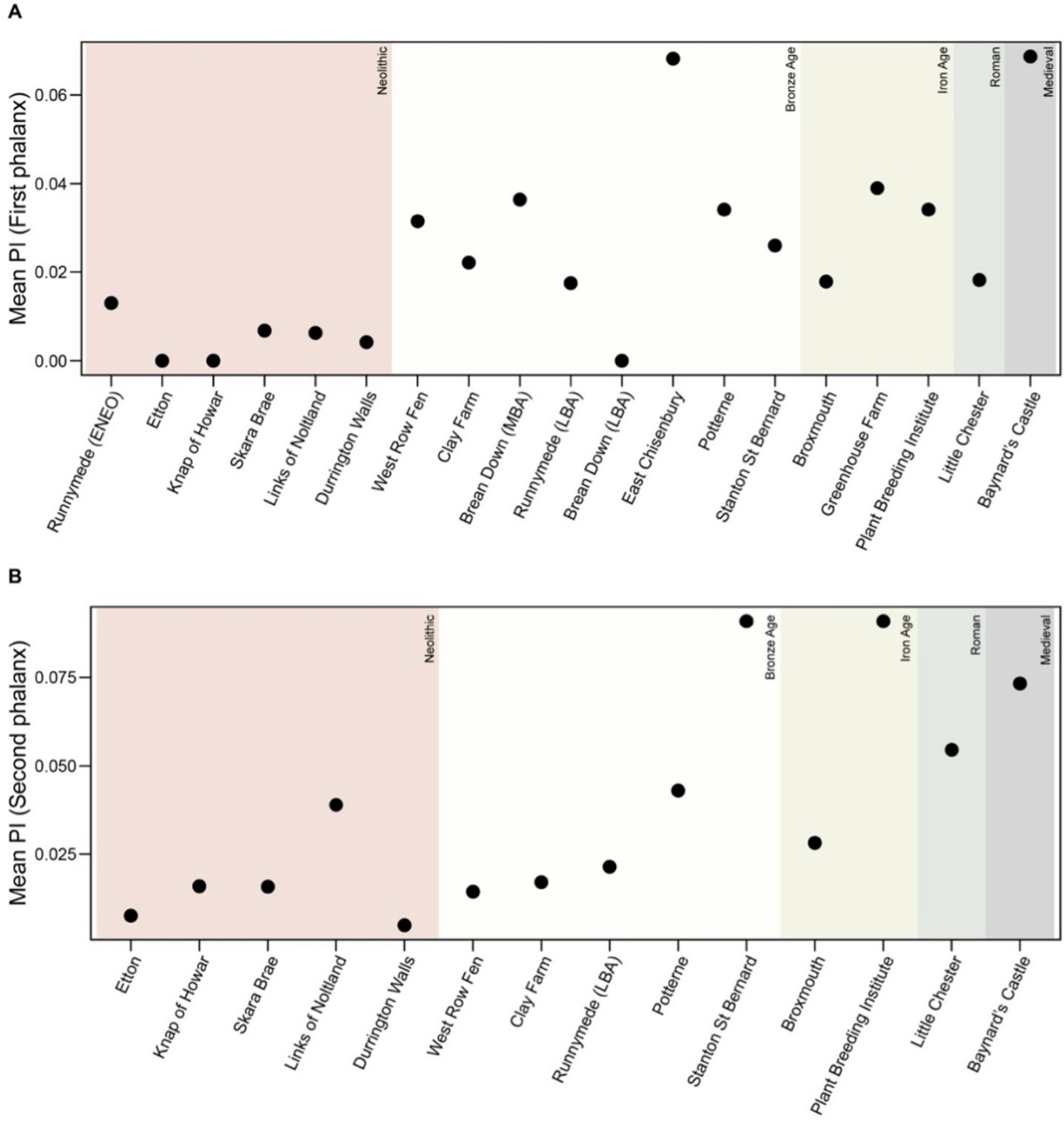



Figure 6.4: Mean Pathological Index (PI) values of [**A**] first phalanx and [**B**] second phalanx from archaeological sites.

The overall mean PI values of the archaeological sites demonstrate a clear trend, with pathological alterations beginning to surge from the Bronze Age (Figure 6.5). The Early/Mid Bronze Age context at Babraham Road is excluded here due to the total number of recorded specimens being fewer than five. The

overall increase in mean values by the Bronze Age is unlikely to be attributed solely to heightened pathological conditions in specific anatomical parts, as the same trend is consistently observed across all recorded anatomical elements (Figures 6.3 and 6.4). However, it is important to emphasise that the mean PI value for modern non-draught cattle from Halle (as discussed in Section 5.5) is 0.075, which exceeds any values recorded for the archaeological sites. This complicates the determination of which specific site may have included draught cattle, as non-draught cattle could also exhibit high PI values. Nonetheless, comparing sites at a broad regional and/or chronological scale may reveal underlying trends in the data.

As demonstrated by the modern non-draught cattle in Section 5.5, several pathological traits show a strong positive correlation with age, indicating that older animals tend to develop more severe pathological conditions. Based on this finding, the increased PI value observed for the Bronze Age sites could be attributed to changes in the age composition of cattle herds between the Neolithic and Bronze Age. Figure 6.6 (extracted from Figure 6.2) illustrates the percentage of adult and elderly cattle at each site in relation to the overall mean PI value. Undoubtedly, age influences pathological conditions (see Section 5.5), which may explain the low PI value at the two Neolithic Orcadian sites, where the proportions of adult and elderly cattle are also low. Similarly, the slightly higher mean PI value at Durrington Walls among the Neolithic sites may be related to the greater proportion of elderly cattle present.

However, age is not the sole factor contributing to this increasing trend. Although the percentages of older cattle are high at the Neolithic sites of Runnymede and Durrington Walls, these sites also show low PI values, comparable to those found at the Orcadian sites. In contrast, the Late Bronze Age site of Potterne displays the highest PI value among all the core sites, despite having a lower proportion of older cattle compared to Runnymede and Durrington Walls. This suggests that factors beyond age contributed to the increased PI value in the Bronze Age, with the use of cattle for draught purposes being a likely explanation.

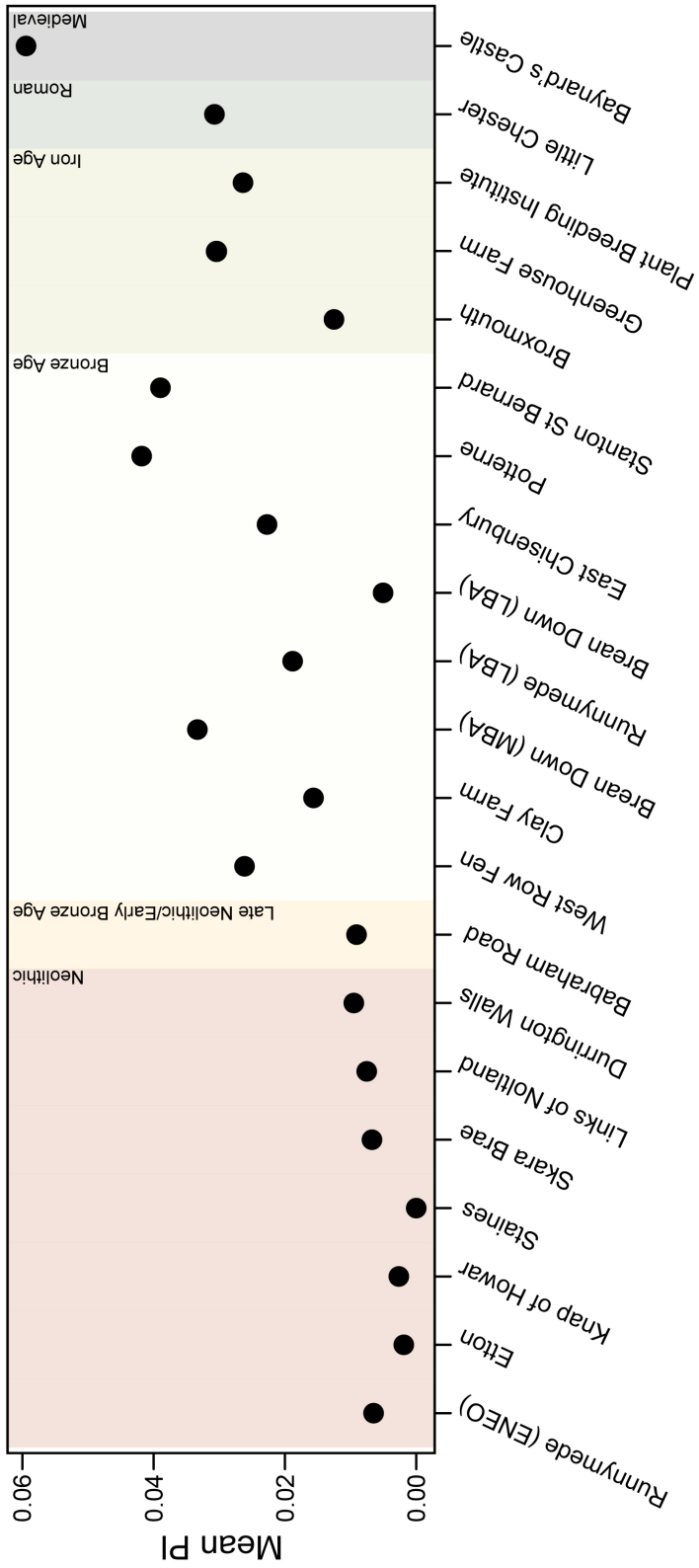



Figure 6.5: Overall mean Pathological Index (PI) values of the archaeological sites, illustrating trends in pathological changes from the Bronze Age onwards. Note that the Early/Mid Bronze Age context at Babraham Road is excluded due to the total number of recorded specimens is fewer than five. ENEO = Early Neolithic; MBA = Mid-Bronze Age; LBA = Late Bronze Age.

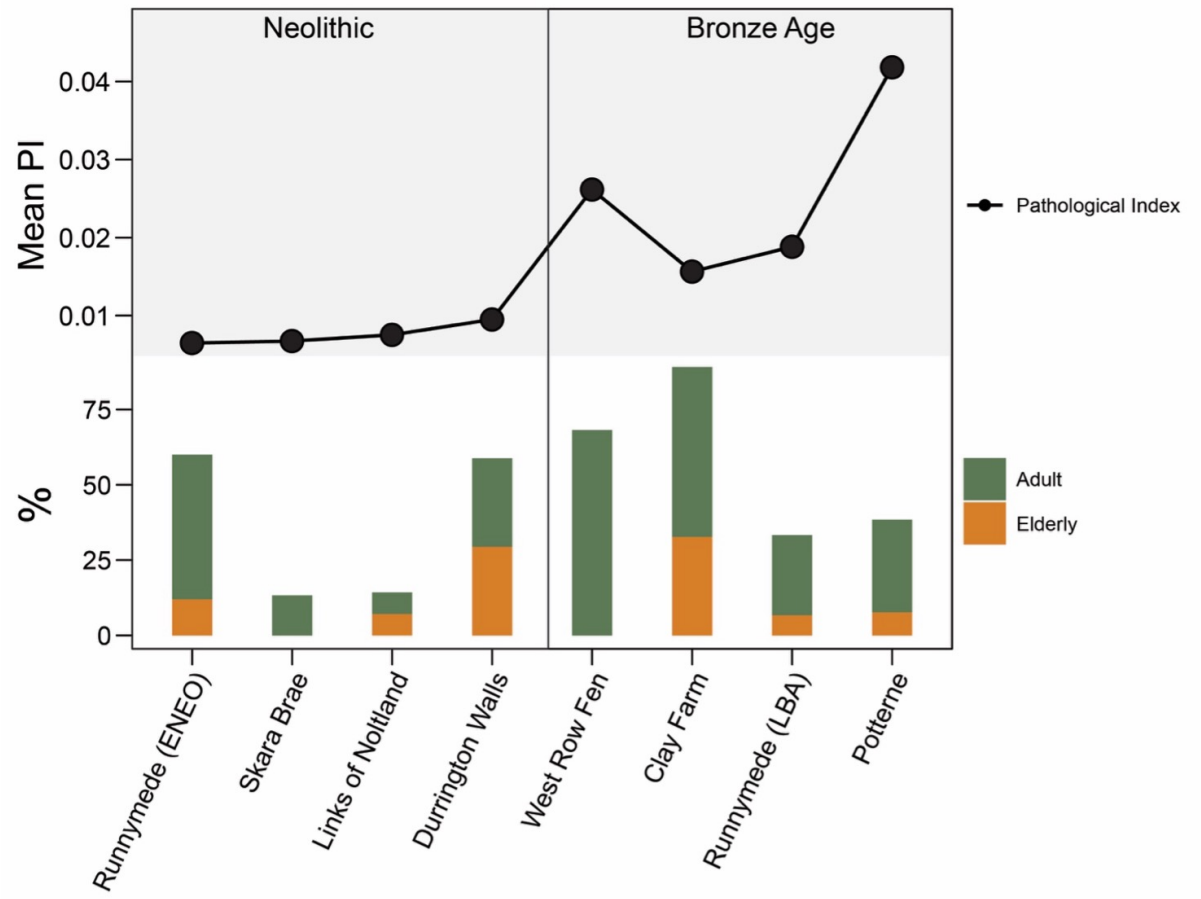



Figure 6.6: Percentage of adult and elderly cattle in archaeological sites [bottom] and the overall mean Pathological Index (PI) [top]. Age data only include sites with more than ten mandibles. The overall mean PI is only for sites with more than five recorded elements. ENEO = Early Neolithic; LBA = Late Bronze Age.

### 6.4.3 Entheseal changes

Figure 6.7 shows the distribution of scores for six entheses recorded on the first phalanx. Overall, most specimens show no modification, as indicated by the higher percentage in Grade 1, particularly for P1LP (lateral collateral proximal interphalangeal ligament) (Figure 6.7C). Grade 2 modifications are more prevalent at Bronze Age sites, while Grade 3 modifications are generally rare, primarily occurring at some Bronze Age sites. Durrington Walls is the only Neolithic site exhibiting Grade 3 modifications, which may be associated with the higher percentage of older-age cattle at this site (Figure 6.2). The mean scores from

the six entheses recorded on the first phalanx further confirm that all the Early Neolithic sites exhibit low mean values, particularly at Etton, suggesting that all specimens from this site show no modifications (Figure 6.8).

Contrary to the Neolithic sites, the mean score at the three Bronze Age sites of West Row Fen, Clay Farm, and Potterne is notably high. As discussed in Chapter 5, age positively correlates with entheseal changes in cattle, similar to the Pathological Index. This correlation may partly explain the relatively high mean values from West Row Fen and Clay Farm, where the proportion of adult and elderly cattle is substantial (Figure 6.2). However, this explanation may not fully account for the high value at Potterne, as the percentage of older-age cattle is lower than at West Row Fen and Clay Farm.

Most second phalanges from the core sites were recorded as Grade 1 (Figure 6.9). Notably, Potterne exhibits a higher percentage of Grade 2 and Grade 3 modifications compared to the other sites. The distribution of scores aligns with the overall mean score (Figure 6.10), where specimens from the Neolithic sites generally show no alterations.

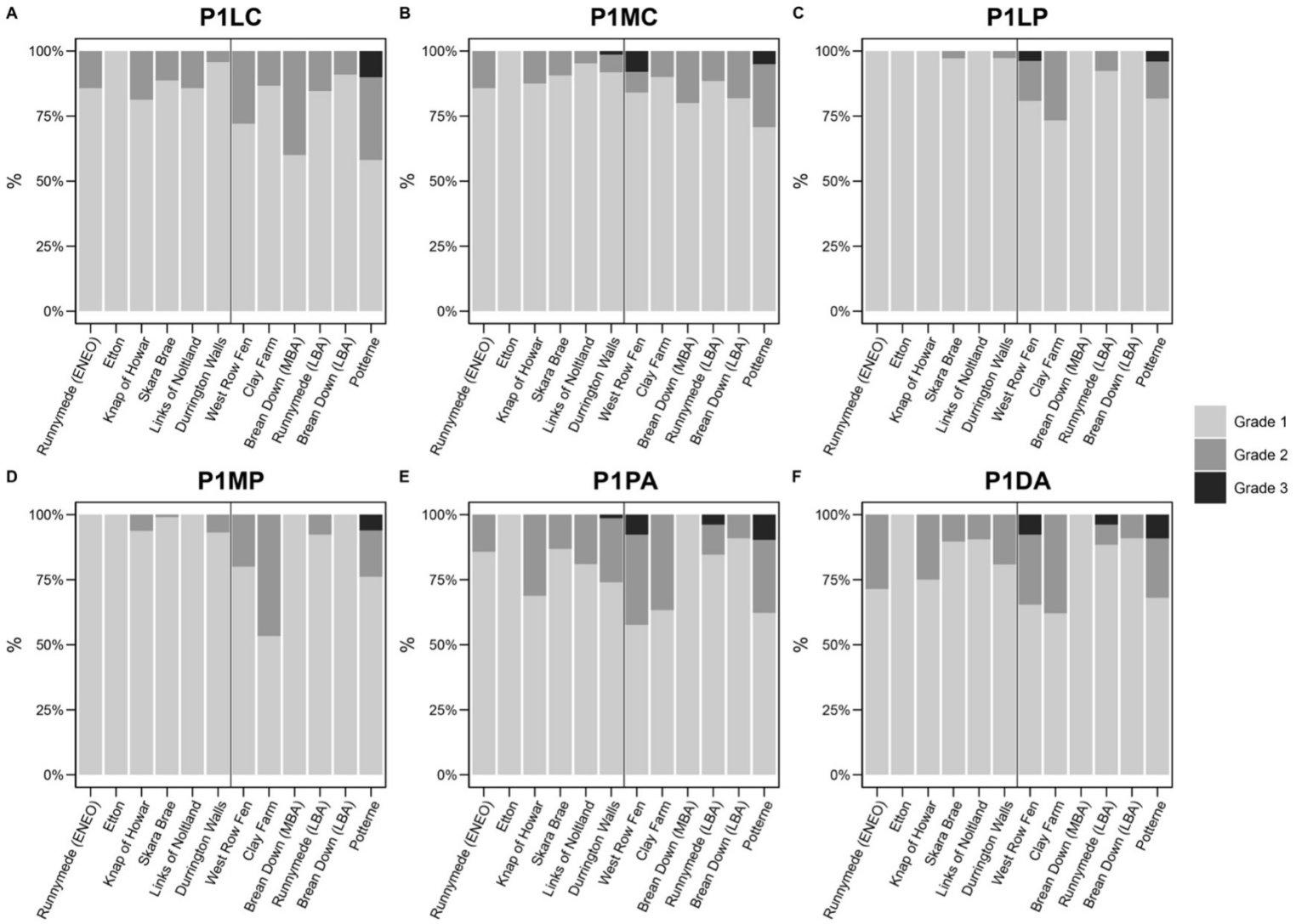



Figure 6.7: Distribution of scoring of entheses on the first phalanx. Grade 1 indicates no change (see Appendix C for the grading). [**A**] Lateral collateral metacarpophalangeal/metatarsophalangeal ligament; [**B**] Medial collateral metacarpophalangeal/ metatarsophalangeal ligament; [**C**] Lateral collateral proximal interphalangeal ligament; [**D**] Medial collateral proximal interphalangeal ligament; [**E**] Proximal digital annular ligament; [**F**] Distal digital annular ligament.

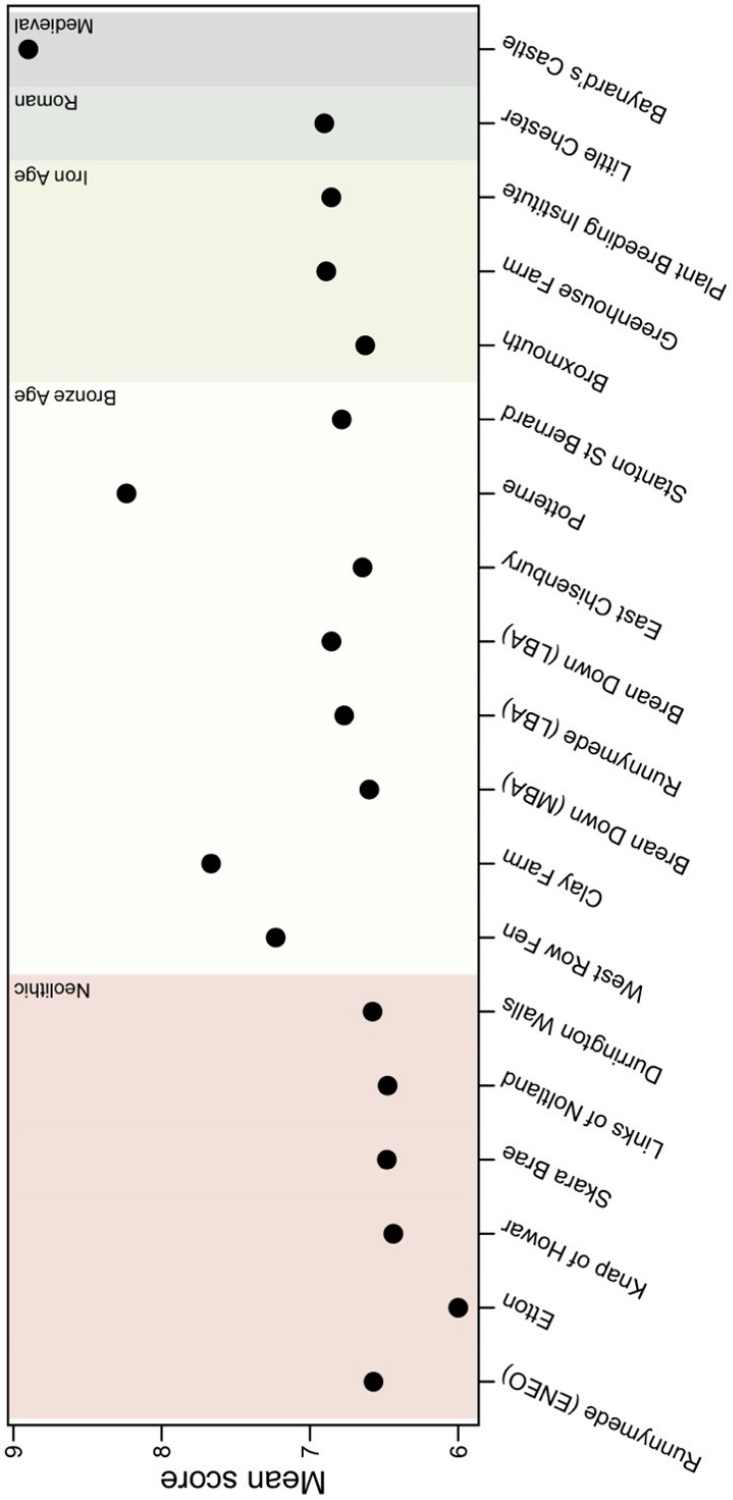



Figure 6.8: Overall mean score for the six entheses on the first phalanx. A minimum value of 6 indicates no change. ENEO = Early Neolithic; MBA = Mid-Bronze Age; LBA = Late Bronze Age.

Figure 6.9: Distribution of scoring of entheses on the second phalanx. Grade 1 indicates no change (see Appendix A for detailed descriptions). [**A**] Lateral interphalangeal proximal collateral ligament; [**B**] Medial interphalangeal proximal collateral ligament; [**C**] Lateral interphalangeal distal collateral ligament; [**D**] Medial interphalangeal distal collateral ligament; [**E**] Extensor digitorum communis.

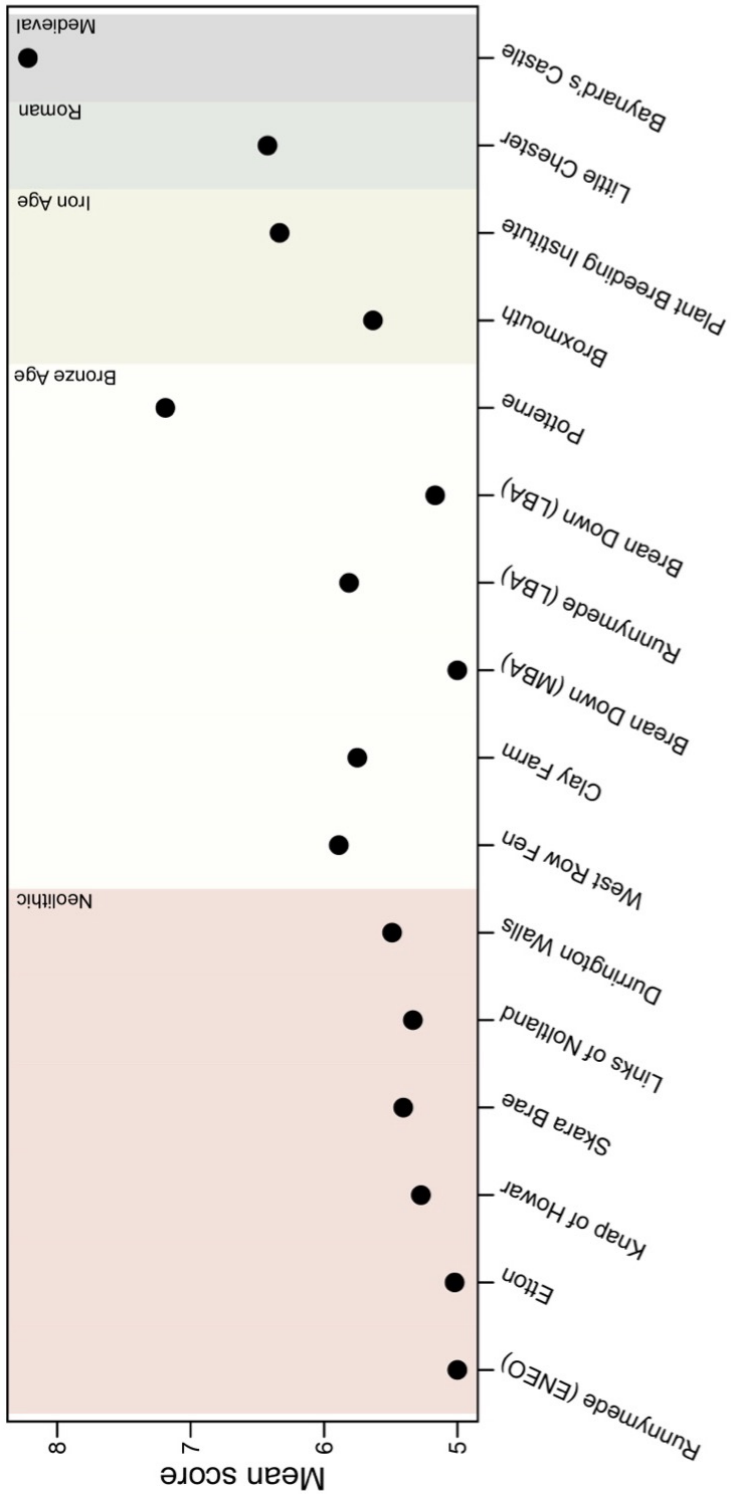



Figure 6.10: Overall mean score for the five entheses on the second phalanx. A minimum value of 5 indicates no change. ENEO = Early Neolithic; MBA = Mid-Bronze Age; LBA = Late Bronze Age.

### 6.4.4 Biometric analyses

Figures 6.11 to 6.14 present the biometric results from all archaeological sites studied, accompanied by a comparison with modern data (discussed in Chapter 5) to facilitate the interpretation of changing trends. Only those combinations of anatomical elements that yielded the highest balanced accuracy and demonstrated the most distinct clusters between the modern draught and non-draught groups are included here (see Section 5.6.2.4). Individual graphs for each site can be found in Appendix D.

**Metacarpals**

Overall, the metacarpals from the core sites are consistent with modern non-draught cattle, exhibiting low values in the distal condyle ratios f/4 and e/1 (Figure 6.11). Notably, all specimens from the Early Neolithic sites show low values for the f/4 ratio. Two metacarpals from Durrington Walls, however, display high values for both f/4 and e/1, plotting toward the draught area. As modern data indicate, bulls may often exhibit similar robust features on their distal metacarpal condyles, even if they have not been employed for draught work. Like the specimen from West Row Fen, it is likely that these robust metacarpals represent bulls rather than traction animals, given the limited number of specimens that align with the draught cattle pattern and their large size.

The modern data in Chapter 5 show that draught cattle often exhibit overlapping characteristics with non-draught cattle. The overlap may contribute to the ambiguous patterns observed in the analysis of metacarpals from archaeological sites.

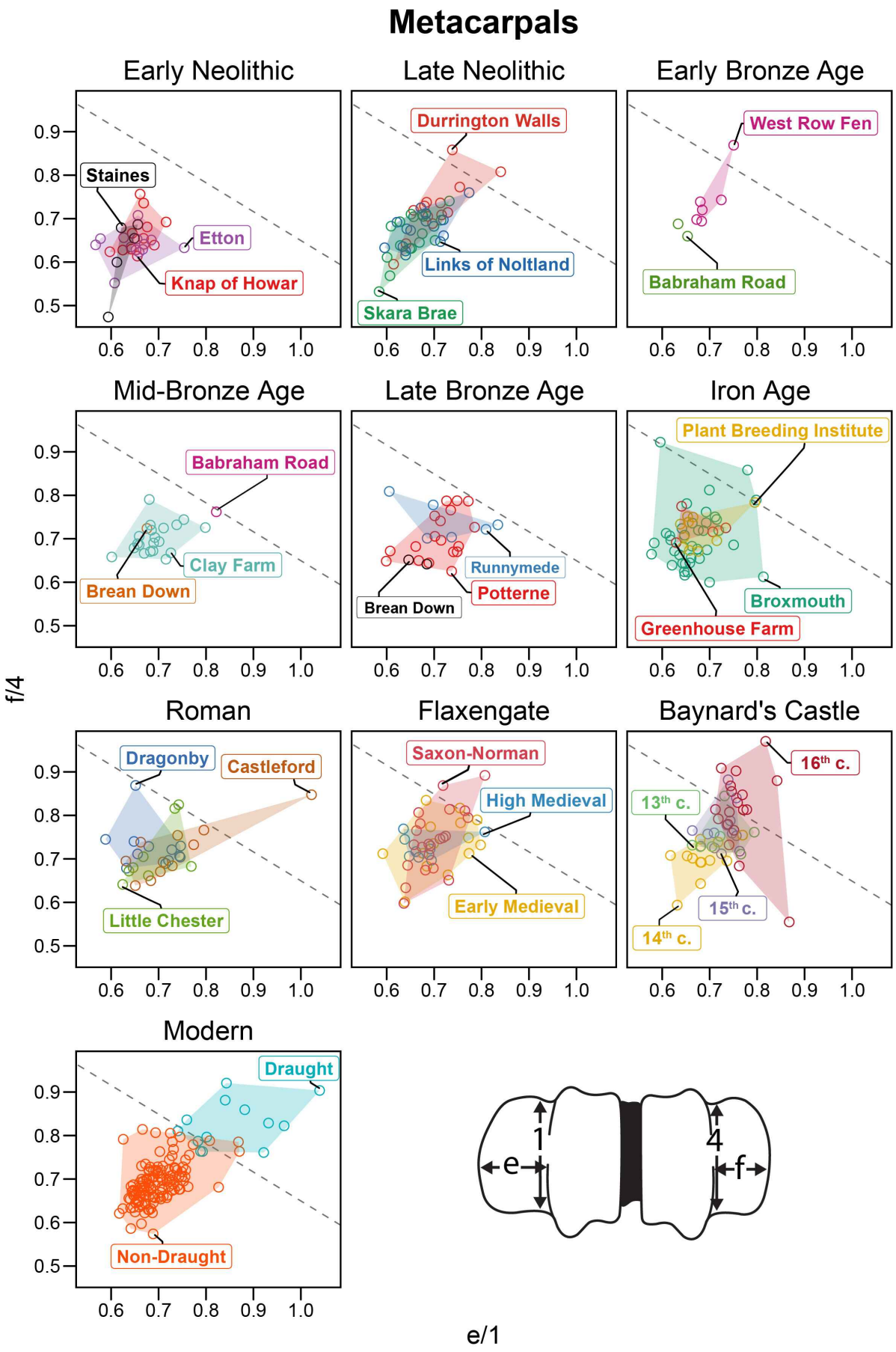



Figure 6.11: Shape ratios of the metacarpal condyles of cattle from archaeological sites with comparisons with modern data (Continued on the following page).

Figure 6.11: 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 $P = 0.5$.

### Metatarsals

Figure 6.12 presents the biometric analysis of distal metatarsals, which closely resembles that of the metacarpals. Notably, specimens from the Early Neolithic sites cluster in the bottom left corner, indicating a morphology consistent with modern non-draught cattle. The only core site that aligns with the comparative sites and may suggest the use of cattle for traction is Potterne. However, it is important to note that only two specimens from Potterne exhibit a high value in the e/1 ratio, which does not provide sufficient evidence for conclusive interpretations.

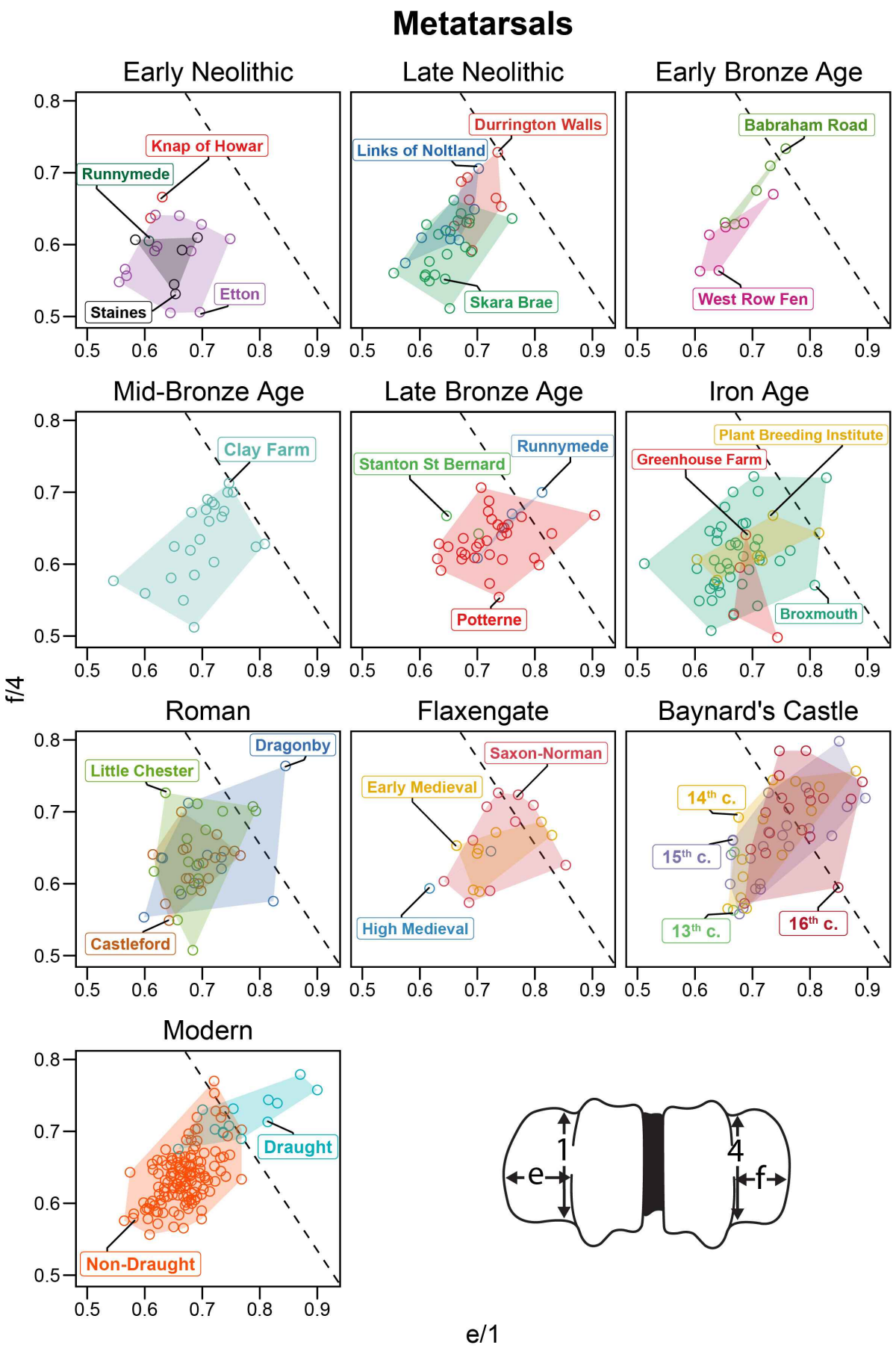



Figure 6.12: Shape ratios of the metatarsal condyles of cattle from archaeological sites with comparisons with modern data (Continued on the following page).

Figure 6.12: 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 $P = 0.5$.

**First phalanges**

The largest sample size of the first phalanges reveals a clear trend, indicating that morphological changes resembling those of modern draught cattle began to emerge from the Middle to Late Bronze Age (Figure 6.13). Although one specific specimen from Durrington Walls displays a slightly higher Bd/GLpe ratio, this may be a bull, as bulls tend to exhibit more robust features.

The trend toward more cattle exhibiting higher Bd/GLpe ratios in the first phalanges is particularly pronounced in the Middle and Late Bronze Age sites, notably at Clay Farm and Potterne. The presence of deformed first phalanges at Potterne indicates that some of these animals may have been used for draught work, with similar practices likely occurring at Clay Farm. The results from these two later Bronze Age sites align closely with those from Flaxengate and Baynard's Castle, where most cattle appear to have been non-draught animals, but a smaller but sizeable proportion may have been exploited for draught use. This pattern reflects a realistic scenario, as it is improbable for an entire herd to be exclusively used for traction.

Another critical point highlighted in Figure 6.13 is that the pattern observed at Clay Farm and Potterne is not evident in other contemporary Later Bronze Age sites. This suggests that the use of draught animals may have been restricted to specific locations rather than being widespread across all communities during the same period.

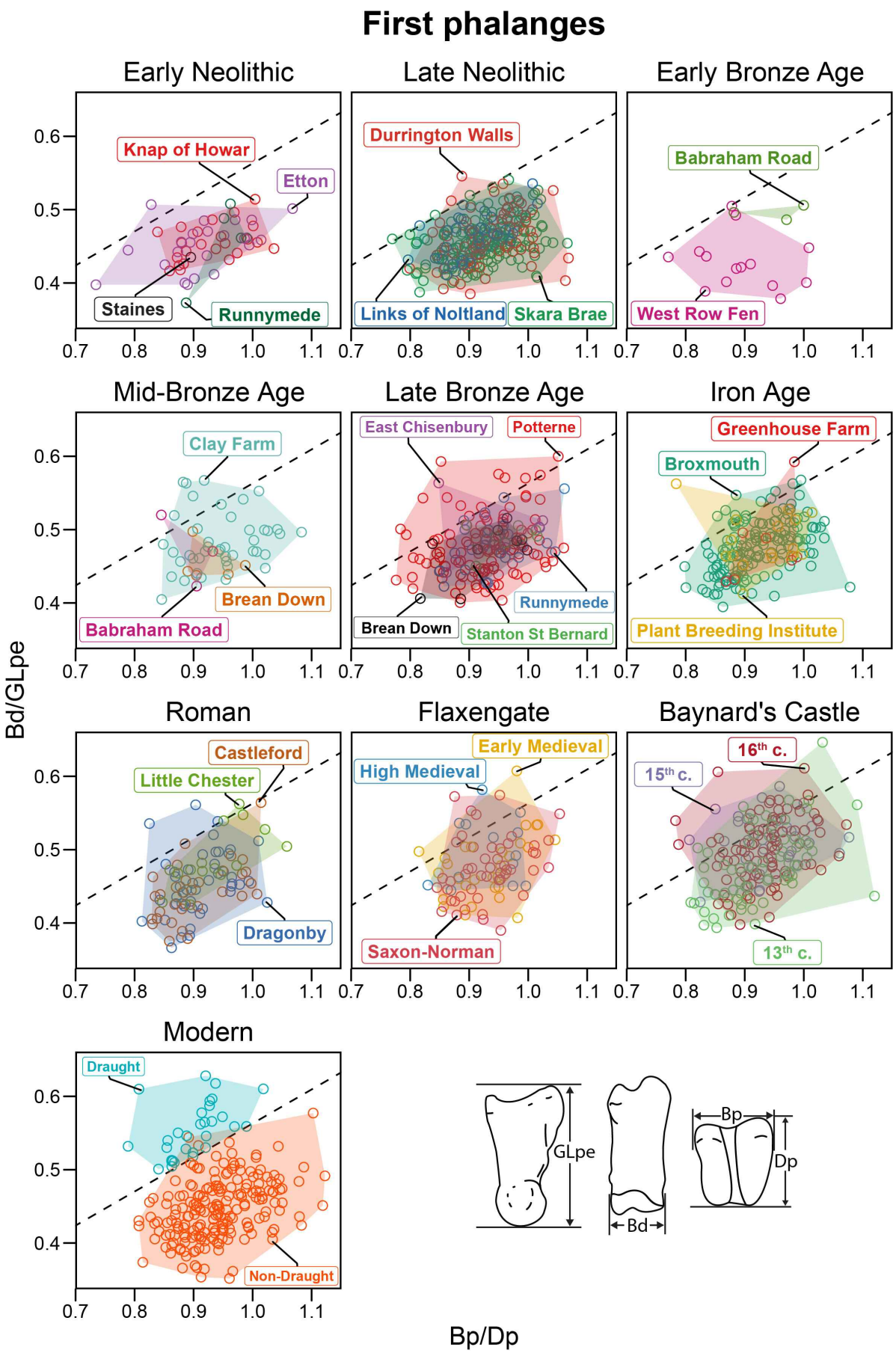



Figure 6.13: Shape ratios of the first phalanx of cattle from archaeological sites with comparisons with modern data (Continued on the following page).

Figure 6.13: 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 $P = 0.5$.

### Second phalanges

In line with the results from the first phalanges, the second phalanges from the Neolithic sites generally conform to the morphology of modern non-draught cattle, showing minimal deformations (Figure 6.14). This suggests that the presence of draught cattle at these sites is unlikely. Potterne is the only core site that includes a relatively small proportion of second phalanges exhibiting higher values in the Bp/GLpe and Bd/GLpe ratio.

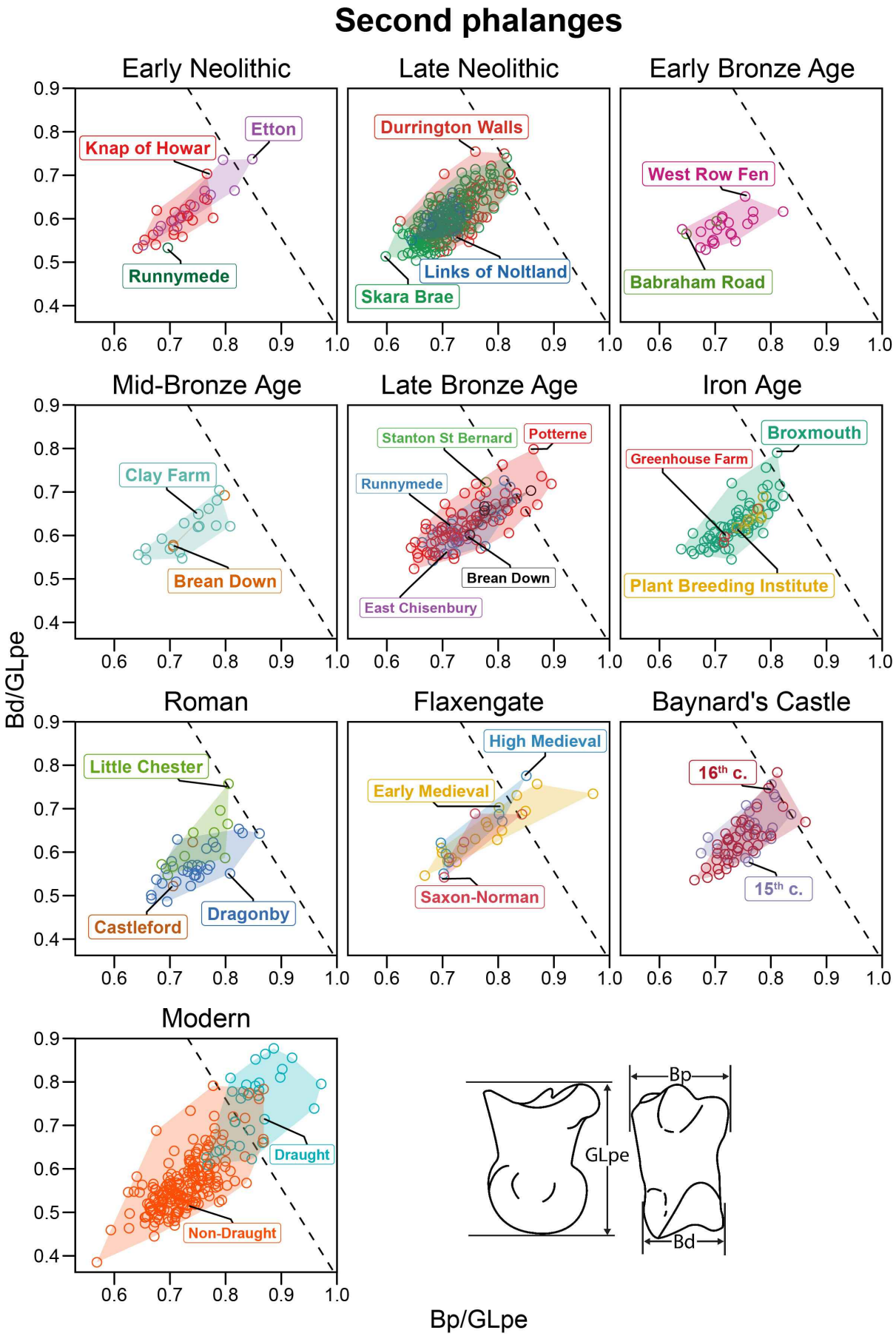



Figure 6.14: Shape ratios of the second phalanx of cattle from archaeological sites with comparisons with modern data (Continued on the following page).

Figure 6.14: 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 $P = 0.5$.

**Overall biometrical pattern**

As discussed, a few of the archaeological specimens exhibit a morphology similar to modern draught cattle. However, the analysis of modern data reveals that several factors, particularly sex, can influence limb morphology. While it is impossible to entirely rule out the possibility that these animals could be draught cattle, they may also be bulls.

Overall, the biometric analyses of the metapodials and phalanges suggest that the Late Bronze Age site of Potterne provides the first compelling evidence of cattle potentially being used for draught purposes. To some extent, the Middle Bronze Age site of Clay Farm also shows morphological features consistent with modern draught cattle, although this is only evident in the first phalanges. The biometric results imply that the emergence of draught cattle in Britain likely occurred from the Middle to Late Bronze Age, consistently with other lines of evidence presented in the previous sections, including the elevated PI values from the Bronze Age onwards (Figure 5.3) and the significant proportion of adult and elderly cattle at those sites (Figure 6.2). It is possible, if not likely, that earlier populations were familiar with animal traction but did not practice it regularly or intensively, therefore leaving only undetectable signs on the cattle bones.

### 6.4.5 Revisiting the pathological pelves from Etton

Essentially, pelvic pathology is not considered in this study. However, eburnation observed on the pelves from Etton represents the most frequently cited evidence—possibly the only osteological evidence—of potential draught cattle use in Early Neolithic Britain to date. The pictures provided in the original report (Armour-Chelu and Clutton-Brock, 1985, Pl. XLV) are in black and white, making it difficult to discern the pathological conditions clearly. It is, therefore, worth revisiting these pathological pelves from Etton.

Two pelves (ID: 155 and 4643) from the waterlogged level are reported to exhibit 'extensive eburnation' on the acetabulum (Armour-Chelu and Clutton-Brock, 1985: 301, Tab. 1). However, as illustrated in Plate 6.4, the observed con-

ditions are not as pronounced as originally described. There are also questions concerning the validity of relying on a single pathological condition as discussed in Section 3.2.1. Considering the analyses presented in previous sections, there is no conclusive evidence to suggest that cattle were used for traction in Etton.

Despite the uncertainty regarding the connection between this type of eburnation and draught use, one particularly interesting observation is that both pelves exhibit eburnation localised to a specific area on the lunate surface. This pattern of bone alteration is also noted in a cow from Early Neolithic Knossos (Isaakidou, 2006: 104, Fig. 8.5), as well as in specimens from Clay Farm and Flaxengate (examined by the author). The interpretation of this pattern remains unclear, but its potential regularity warrants further investigation.

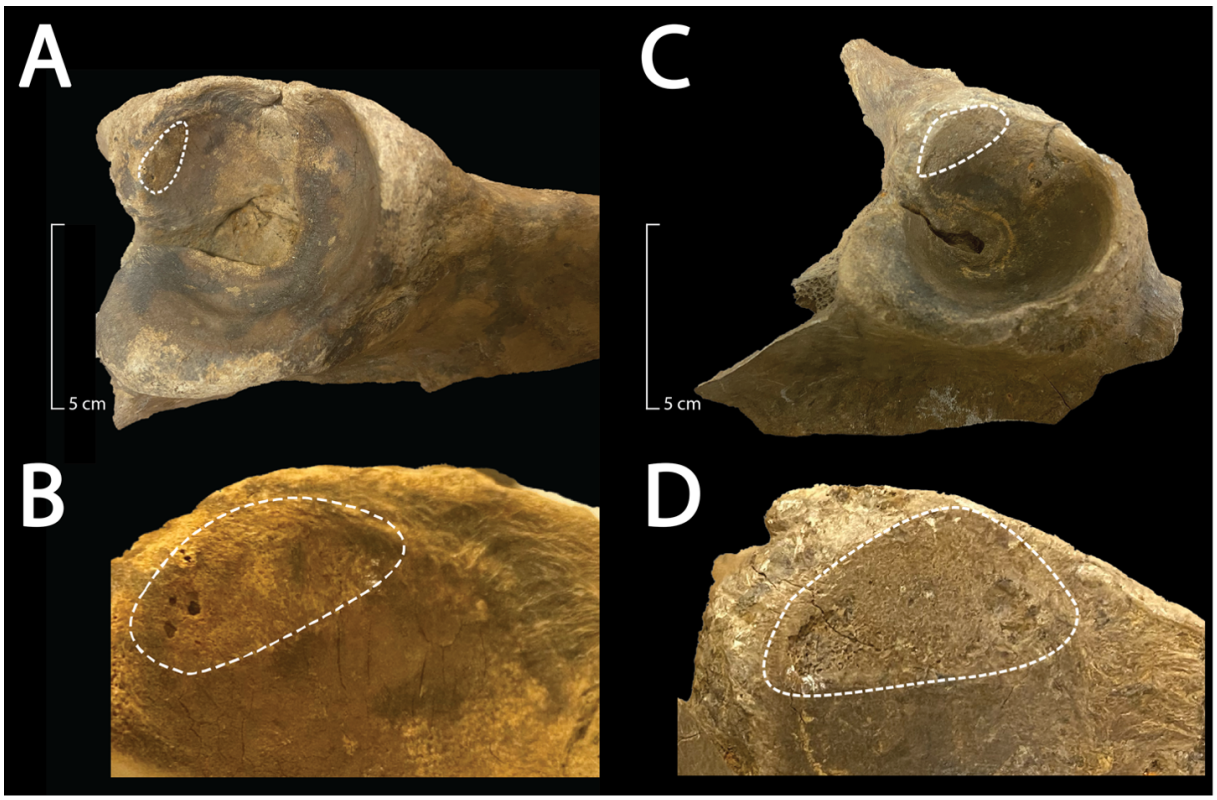



Plate 6.4: Two pelves from Etton showing eburnation on the acetabulum: [**A**] Specimen 1557; [**B**] Close-up of eburnation on Specimen 1557; [**C**] Specimen 4643; [**D**] Close-up of eburnation on Specimen 4643.

## 6.5 Discussion: Synthesising osteological evidence for animal traction

This section integrates findings from osteological methods to understand the timing of the emergence of animal traction in Britain. Three osteological methods were used to analyse cattle limb bones from Early Neolithic to Late Bronze Age sites. Both osteological assessments and kill-off patterns point to a coherent conclusion: the earliest clear evidence for the use of cattle for traction in Britain dates to the Middle to Late Bronze Age.

The Pathological Index (PI) shows a clear increase in values starting in the Bronze Age, indicating that pathologies became more prevalent in cattle limb bones compared to those from Neolithic sites. A similar trend is also evident in the entheseal changes observed on the first and second phalanges, where the animals from Neolithic sites show minor to no modification.

More detailed results are revealed by the biometric methods developed in Chapter 5. Not all recorded anatomical elements provide equally clear indications of draught use, but metapodials and phalanges from the Neolithic sites largely align morphologically with modern non-draught cattle. In contrast, a sizeable proportion of animals from the Middle Bronze Age site of Clay Farm and the Late Bronze Age site of Potterne exhibit morphological features like those of modern draught animals. These morphological characters are most evident in the first phalanx, which also provides the best accuracy in distinguishing between modern draught and non-draught cattle (see Chapter 5).

The same osteological modifications are noted at some of the comparative sites, especially at the two Medieval sites of Flaxengate and Baynard's Castle, where historical records document the use of cattle for draught work. A prior study reveals a high PI value at Flaxengate, further supporting the interpretation of this practice at the site (Holmes and R. Thomas, 2022: 67). Thus, the biometric results indicated at these comparative sites support the argument that the deformation of the first phalanges in the Later Bronze Age sites likely reflects draught

use. Nonetheless, another factor to consider is sex, as the analysis of modern animals shows that it can influence cattle bone morphology. Bulls are more likely to exhibit robust features that are compatible with draught animals. Therefore, it is possible that some specimens from the Later Bronze Age sites plotting close to the draught area may indeed be bulls, although it is unlikely that all of them are.

The kill-off patterns further enhance the interpretation of the osteological analyses, particularly regarding the sudden rise in PI values during the Bronze Age. As discussed in Chapter 5, there is a well-established correlation between old age and pathological changes in cattle. This relationship helps explain the low PI values observed at the Late Neolithic sites of Skara Brae and Links of Noltland, where the proportion of adult and elderly cattle remains significantly low.

The predominance of immature cattle in Neolithic Orcadian sites is a well-documented phenomenon. In addition to Skara Brae and Links of Noltland, at Knap of Howar, Noddle (1979: 94) reported that $50\%$ of the cattle died in their first year, with only $20\%$ surviving to maturity. This high mortality rate among young animals is thought to be associated with an emphasis on milk production (Serjeantson, 2007: 206). Interestingly, the relatively high proportion of adult and elderly cattle at Durrington Walls and Runnymede (Early Neolithic context) is associated with a surprisingly low PI, consistent with other contemporary sites. Such patterns could indicate that these populations were also engaged in secondary product use, but it is more likely to be milk production rather than traction. The interpretation is further supported by the presence of ruminant dairy fats on sherds from both Durrington Walls (Craig et al., 2015) and Runnymede (Copley et al., 2005).

Figure 6.6 reveals that while older cattle likely contributed to the elevated PI in the Bronze Age sites, it cannot fully account for the high values observed, particularly at Potterne. This result suggests that the increased PI values in cattle result from their use for traction. The even distribution of age classes at Potterne indicates, however, that such a use was not the product of a specialised economy. While part of the herd was dedicated to work in the fields,

an equally sizeable proportion was specifically bred for meat production and possibly other purposes too.

Although the kill-off pattern provides important complementary data for interpreting other findings, it might be problematic if used in isolation. This limitation is illustrated by the case at West Row Fen, where the initial interpretation of the kill-off pattern suggested that cattle were primarily used for meat or draught purposes rather than for milk production (Olsen, 1994: 144). It should be noted that only 22 mandibles were available from this site, and this rather small sample size might not provide conclusive evidence. While the PI value at West Row Fen is high, as indicated by the modern data in Chapter 5, non-draught cattle can also exhibit elevated values. Furthermore, the biometric results from West Row Fen show no morphological changes associated with draught use. Thus, although the possibility of cattle being used for short-term or low-intensity draught work cannot be entirely ruled out, it is also plausible that these older animals were primarily culled at a later stage for meat.

Conversely, while Potterne provides the strongest biometric evidence of cattle being used for traction, its kill-off pattern does not align with typical expectations for draught work, as young and old cattle distribution is relatively even. In fact, evidence from Medieval sites such as Flaxengate and Baynard's Castle indicates that cattle used for traction constituted only a relatively small portion of overall herds. These discrepancies between age data and biometric evidence from West Row Fen and Potterne highlight the importance of interpreting age data alongside other findings. The integrated approach demonstrated in this study provides comprehensive conclusions on the emergence of animal traction in prehistoric societies.

The Early Neolithic site of Etton has been suggested to indicate the draught use of animals (Armour-Chelu and Clutton-Brock, 1985); however, the pathological and entheseal changes observed in cattle bones from this site are minimal, and the morphological features of the limb bones closely align with modern non-draught cattle. Although the eburnation on the pelves is noteworthy, the

association with draught use requires further investigation. While it is possible that prehistoric communities in Britain may have attempted to harness cattle for hauling loads as early as the Neolithic, the evidence for animal traction during this period remains weak. In contrast, integrated results from various osteological methods indicate that the use of cattle for draught work became more pronounced in the Middle to Late Bronze Age, though, even then, this practice appears to have been limited to certain communities.

*Animal traction, however, is a truly revolutionary development which had significant implications for the household labour supply and the ability of individual households to manage their accumulation strategies. Perhaps the 'Secondary Products Revolution' might be recast as the 'Animal Traction Revolution' to capture the sense of the impact that this development had on prehistoric European society.*

— Bogucki (2000: 228)

# 7

# THE ORIGINS OF ANIMAL TRACTION IN BRITAIN

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## 7.1 Introduction

Animal traction for ploughing and carting represents the earliest use of external motive power to reduce human labour, potentially marking the most transformative development in later prehistory. Recognising its significance, Bogucki (2000: 228) suggested that the 'Animal Traction Revolution' should replace the concept of the 'Secondary Products Revolution', as formulated by Andrew Sherratt. This would emphasise the profound impact it had on prehistoric communities. Despite its fundamental importance, the emergence of animal traction remains less comprehensively studied compared to other secondary products like milk and wool. This knowledge gap is particularly pronounced in Britain due to the absence of iconography and sparse non-osteological evidence related to the draught use of animals.

This chapter aims to integrate the results presented in Chapters 5 and 6 in order to address the broader themes of timing, motivation, and socio-economic

impact related to the adoption of animal traction in later prehistoric Britain. Sub-research question 1 (*How can draught animals be identified in archaeological assemblages?*) was explored in Chapter 5, and question 2 (*When did animal traction begin in Britain?*) was addressed in Chapter 6. This chapter will first summarise those findings before turning to sub-research questions 3 and 4: *What motivated the use of animal traction in later prehistoric Britain?* and *What social and economic changes did this technology bring to prehistoric societies in Britain?* Given the scattered nature of artefactual evidence, osteological analysis remains the most promising approach for advancing our understanding of how and why this technology emerged and evolved.

## 7.2 Studying animal traction in archaeological context

Identifying animal traction in the archaeological record presents significant challenges. Unlike other secondary products like milk and wool, which leave distinct material traces such as lipid residues and textile fibres, traction produces power, which is intangible. Recent studies have focused on osteological changes in cattle limb bones as a method for identifying potential draught animals. Specifically, Lin et al. (2016) have demonstrated biometric differences between modern draught and non-draught cattle based on metapodial measurements. However, a systematic application of these findings to archaeological materials remains underdeveloped. This methodological limitation underlies the first objective of this study. To address it, a new biometric method was developed using a large comparative dataset of modern non-draught and draught cattle, with logistic regression applied for classification. Notably, this new method reveals that the first phalanx is the best anatomical element for the identification of traction, a finding that was not previously recognised. The new biometric method represents a significant methodological advancement, offering a data-driven tool to enhance the identification of draught cattle in the archaeological record.

The main challenge in developing an osteological method is the limited availability of modern draught cattle skeletons. As an alternative, materials from Roman and Medieval sites—periods with documented evidence of draught use—were incorporated into the analysis. The findings of the Medieval sites reveal patterns consistent with those of modern draught cattle, demonstrating the potential of this new biometric approach when applied to archaeological specimens. However, the results from the Roman sites are less clear, which could be related to the types of sites and smaller sample sizes. Further research expanding the analysis would be valuable, particularly on villa sites where draught cattle were likely kept, as these were agriculturally productive areas (Lodwick, 2023). It is important to acknowledge that the intensity and duration of draught use significantly influence the degree of skeletal modification. As such, it would be unrealistic to expect this method, or any current osteological approach, to detect short-term or sporadic draught use in animals.

Previous studies have emphasised the importance of analysing anterior and posterior phalanges separately when studying draught cattle due to differences in weight distribution across the body (Holmes et al., 2021b; R. Thomas et al., 2021). The results from this study of modern cattle support this idea, as the accuracy in identifying draught cattle improves when anterior and posterior phalanges are analysed independently. To date, the separation of cattle phalanges has primarily relied on the morphological criteria established by Dottrens (1946). While this method has proven useful, individual variations among cattle can lead to ambiguous distinctions when relying on visual assessments, particularly in archaeological contexts. Breakage and pathological conditions further complicate these assessments. Although confidently distinguishing anterior and posterior phalanges would be the optimal approach, this study demonstrates that a combined analysis of both can also produce effective results in identifying draught use of cattle. The lack of greater anatomical resolution in the combined analysis is unfortunate, but the potential misidentification of anterior and posterior phalanges would confuse the analysis to a more serious degree.

In addition to the biometric approach, this study also examines the use of entheseal changes in cattle. Entheseal analysis has been widely applied to human remains to study past activities and has also been successfully used in animals such as horses (Bendrey, 2008; Bindé et al., 2019; Niskanen and Bindé, 2021) and reindeer (Hull et al., 2020; Niinimäki and Salmi, 2016; Salmi and Niinimäki, 2016). Its application to modern non-working bovids was explored in prior work (Liu, 2021), demonstrating its potential for studying draught use in cattle. This study has further investigated this method, applying it to archaeological materials. Overall trends in entheseal changes on the first and second phalanges are noticeable and align with the results from biometric methods and the Pathological Index. However, a significant concern with this method is the fragmented nature of archaeological specimens, which limits its application to elements that are prone to poor preservation, such as the proximal humerus. Additionally, the erosion of bone surfaces complicates the assessment of entheseal changes, potentially reducing the accuracy of the analysis.

Kill-off patterns are a fundamental method for studying husbandry goals in zooarchaeological research. However, the discrepancies between kill-off patterns and the biometric results presented here highlight the need for caution in relying on either method alone to infer the draught use of animals. Ageing data have also proven valuable with the Pathological Index, particularly as the modern data indicated strong positive correlations between age and severity of pathological conditions. Although pathological conditions could be related to factors unrelated to draught use, the Pathological Index is useful for analysing broad-scale variation between sites. This is demonstrated by the increasing PI values observed at Bronze Age sites compared to the Neolithic sites, which align with other osteological results. The integrated approach adopted in this thesis demonstrates the strength of combining these methods to address the complexities of identifying animal traction in archaeological records.

## 7.3 Integrating lines of evidence: artefactual and osteological

This study integrates the new biometric approach with previously established methods for the detection of traction and applies it to 14 later prehistoric sites in Britain. The results indicate that the earliest substantial evidence for cattle traction dates to the Middle to Late Bronze Age.

The osteological evidence is consistent with the existing artefactual evidence. The most conclusive non-osteological evidence of animal traction comes from the yokes found at Loch Nell, dated 1950-1525 cal. BC (Hedges et al., 1995). Similar finds from England include those from the Late Bronze Age sites of Flag Fen and Must Farm (Pryor et al., 1986: 15; Tyers et al., 2024: 1280). The yokes found in England align with the osteological evidence presented in this study, although the evidence from Scotland suggests that animal traction may have been used slightly earlier. However, the development of this technology did not need to be uniform across different regions. The results from this study indicate that, even when animal traction was adopted, it appears to have been restricted to certain communities rather than being a widespread phenomenon. Different economic needs, agricultural practices, and social structures likely influenced the degree of its adoption.

Animal traction might have developed concurrently with wheeled vehicles in Britain, as evidenced by the earliest known wooden disc wheel discovered at Flag Fen in Cambridgeshire, dating to approximately 1300 BC (Taylor, 2001: 213–4). Similar wooden discs were found at Blair Drummond Moss in Scotland, dated to 1255-815 cal. BC (Cowie and Shepherd, 2003: 156). The convergence of osteological and artefactual evidence provides a coherent understanding of the development of animal traction during the Middle to Late Bronze Age. While the current analysis suggests the potential origins of animal traction during this period, it is important to acknowledge that lower-intensity use may

have occurred prior to the Mid-Late Bronze Age but did not produce detectable skeletal modification.

## 7.4 Animal traction in Neolithic Britain?

As discussed in Chapter 2, animal traction serves both cultivation and transportation purposes. Ploughing was likely the primary use before the advent of wheeled vehicles, though animals could also have been used to drag logs and stones. Speculations about Neolithic animal traction in Britain are primarily based on plough marks at South Street long barrow (Mercer, 1981: x) and skeletal pathologies from Etton (Armour-Chelu and Clutton-Brock, 1985). However, the osteological results in this study challenge these earlier interpretations, revealing limited evidence for using cattle for traction in the Neolithic. It has also been discussed that the evidence from those two sites is far from being definitive, particularly at Etton (see Section 3.2).

One key aspect of a productive agricultural system is the effective management and movement of soil to support plant growth. Ploughing with animals is more efficient in cultivation compared to manual methods, enabling the extensive cultivation of larger areas in a shorter time. Thus, the ability to expand arable land through animal traction is often considered a characteristic feature of extensive agricultural systems. Although cereal cultivation was already practised in Britain from the onset of the Neolithic in the fourth millennium BC, it has been argued that it was operated as a small-scale but intensive system during the Early Neolithic (G. Jones and Bogaard, 2017; Rowley-Conwy et al., 2020: 414). These intensive small plots were restricted to a small scale, relying heavily on human labour input. Tools such as hoes and digging sticks could have cultivated these small, fixed plots (Rowley-Conwy, 2004).

The technical feasibility of using draught cattle in early farming systems depended on several critical factors, including animal selection and training. It has been suggested that intensive small-plot cultivation may have been compatible with the use of draught cows for ploughing (Bogaard, 2005a; Isaakidou, 2011). The

earliest timing of cattle castration practices in prehistoric Britain remains unclear, although several studies from Neolithic sites suggest the presence of potential oxen. Before the acquisition of specialised oxen, it would be reasonable to assume that cows, rather than intact bulls—known for their aggressive behaviour—would have been preferred for draught work. Osteological evidence from the Neolithic site of Knossos indicates that cows might have been used for non-specialised draught purposes (Isaakidou, 2011), a practice that continues in some modern agricultural contexts (Halstead, 2014). However, considerable time and resources are required to train and maintain draught animals, which would likely outweigh the potential advantages of small-plot cultivation. Early farmers may have found alternative cultivation methods more practical for these intensive systems.

Furthermore, cows were particularly important for milk production in Early Neolithic Britain. Lipid analyses of pottery reveal that dairy products from ruminant animals were already widely used in the Early Neolithic (Copley et al., 2005). The high mortality rate of young calves and the high ratio of cows to bulls at Neolithic sites in southern Britain led to the suggestion that cows were intensively milked during the Early-Middle Neolithic (Serjeantson, 2011: 25; Rowley-Conwy et al., 2020: 409). Using non-specialised cows for ploughing not only diminishes the quality of work but also reduces milk yield and calf productivity (Halstead, 1995; Johannsen, 2011). Nonetheless, as ploughing is generally a seasonal activity, it is plausible that cows were occasionally used for draught purposes. However, exploiting traction power from cows was unlikely to be a primary focus during this period. Despite the alleged pathological changes observed in the pelves of cows at Etton, this study indicates consistently low pathological alterations in the cattle limb bones from Early Neolithic sites. The morphological features of these bones also align more closely with those of modern non-draught cattle, suggesting that animal traction, if used, was not a primary function of cattle during this period.

Osteological analysis of Late Neolithic cattle reveals consistently low PI values and skeletal morphology closely aligned with modern non-draught cattle, indicating minimal evidence for animal traction. However, an analysis of more recent

excavations at Links of Noltland reveals pathological lesions on cattle pelves and phalanges, leading to speculation that some animals from this site were possibly involved in monumental constructions (Fraser, 2015: 315). Additionally, plough marks identified at Links of Noltland hint at arable activities, although it remains unclear whether animal traction was employed (Clarke and Sharples, 1985: 73–4). While it is possible that cattle were used for pulling loads, the current evidence remains inconclusive. Given the sandy soil in Orkney, it is plausible that ploughing could have been achieved through human labour with light ards, while perhaps cattle traction was limited to pulling weights.

The low intensity of cultivation during the Late Neolithic in Britain is compatible with the argument that animal traction was unlikely to have been used, or at least not widely adopted. Arable farming declined across Britain from around 3300 BC to 1500 BC in the Late Neolithic (M. Robinson, 2000; Stevens and Fuller, 2012). However, this decline appears regional, as arable farming remained significant in Scotland (R. R. Bishop, 2015). The absence of cereal cultivation at Grooved Ware sites, as suggested by Wainwright and Longworth (1971: 266) in their study of Durrington Walls, indicates a predominantly pastoral economy. Recent studies further support this shift, indicating reduced arable farming across southern England during the Mid to Late Neolithic (Worley et al., 2019). This greater emphasis on pastoralism concurs with the results of this study, which suggest that cattle were unlikely to have been used for traction, given the lack of necessity.

## 7.5 Emergence of animal traction in the Middle-Late Bronze Age

The emergence of animal traction in the Middle to Late Bronze Age, as revealed in this study, aligns with significant social transformations during this period. The latter part of the second millennium BC in Britain is marked by the intensification of agriculture, the adoption of field systems, and the development of an increasingly hierarchical society (Barrett, 1994; Champion, 1999; Ellison,

1981; Yates, 2007). Despite being smaller than their Neolithic counterparts, Bronze Age cattle would still have been effective for traction. Experimental work with a pair of Dexter cows demonstrated that ploughing could be carried out at a pace of 4 kilometres per hour, with the animals working for up to five hours (Reynolds, 1982). This would have enhanced cultivation efficiency and reduced manual labour. Previous research has predominantly focused on the consequences of adopting animal traction within prehistoric communities; however, understanding the motivations behind this shift is crucial for examining the origins and development of this new technology.

### 7.5.1 Motivations for the adoption of animal traction in the Middle-Late Bronze Age

Adapting a new technology is often driven by the need to overcome limitations imposed by existing tools or techniques. Sherratt (2006: 353) viewed animal traction for cultivation as a solution to address the fourth millennium BC crisis that European farming experienced in sustaining a stable mixed farming system. The strong cross-channel interactions and shifted emphasis on arable farming could have been the main reasons for adopting this technology in Britain. A large-scale migration during the Middle-Late Bronze Age (Patterson et al., 2022) could have introduced the technique of animal traction to Britain alongside the population movement. While osteological evidence for draught use is debatable (see Chapter 3), the pictorial evidence from continental Europe suggests that animal traction was well-established by the fourth millennium BC. Alternatively, increased cross-channel interactions during 1600-1100 cal. BC, particularly strong links between southern England and regions across the Channel (Bradley et al., 2016: 173), could have facilitated the spread of animal traction through cultural exchange. This period of heightened connectivity promoted the transfer of ideas and technologies, evidenced by shared pottery styles and burial rituals (e.g. Needham, 2009; Bradley et al., 2016: 192), and likely included the introduction of animal traction to Britain.

The significant investment required for maintaining draught animals likely demanded compelling motivating factors. A notable development in the Middle Bronze Age was the resurgence of arable farming after the Late Neolithic. The Later Bronze Age in Britain is particularly regarded as a period of agricultural intensification, characterised by the establishment of a balanced and settled mixed farming system (Barrett, 1980; Ellison, 1981; Stevens and Fuller, 2012). Using animal traction for ploughing would have allowed the cultivation of more extensive areas, in particular the heavy clay soil. This shift is suggested by evidence of land divisions extending into adjacent areas with heavier, less productive soils (Bradley and Yates, 2007).

During the Later Bronze Age, more permanent settlements emerged alongside the development of field systems. In contrast to the mobile lifestyle of the Early Bronze Age, settlements in the Middle Bronze Age demonstrated greater longevity (Brück, 2000: 288). These permanent farms likely reflected a shift toward more intensive arable cultivation, replacing the mobile pastoralist way of life previously dominant on the chalklands (Parker Pearson, 2005). The appearance of field systems during this period, particularly in southern England, has long been regarded as a sign of agricultural intensification to increase productivity aimed at generating a surplus (Barrett, 1994; Bradley, 1972; Yates, 2007). This emphasis on arable farming was a key driving force behind the adoption of animal traction. Barrett (1994: 149) indicated that the introduction of field systems, combined with new technologies such as animal traction and short-fallow systems, replaced the hoe-based cultivation practices of the preceding periods. However, field systems may not have been exclusively for arable farming; for example, it is suggested that they could also have been constructed for animal management (Pryor, 1996). Regardless of the function of the field system, the use of animal traction would have reduced labour and time input for tillage. This reduction in labour demands could have allowed farmers to focus on other tasks and encouraged shorter fallow periods.

Nonetheless, recent studies argue that the field system itself does not reflect the intensification of cereal cultivation but rather is associated with changing inter-group relationships (Brück, 2000; Carey et al., 2024). It is suggested that Middle Bronze Age field systems were not the work of a single household but rather the product of a communal effort undertaken by several neighbouring groups (Brück, 2000). This communal nature could have facilitated animal traction, particularly using oxen, by allowing the shared costs associated with maintaining draught animals. The barrier to adopting animal traction may not have been technological know-how but related to the costs (Halstead, 2014: 59). This is especially relevant for specialised draught oxen, which served a single purpose yet still required feeding during the off-season for ploughing. Sharing draught animals was practised in modern farming communities to reduce costs (Halstead, 2014). The Mid-Late Bronze Age is suggested to have been a time of strong communal actions and inter-group alliances (Ellison, 1981: 435; Barrett, 1988: 135; Brück, 2000; Whittle, 2002: 102). While the household was the primary unit of production in prehistoric communities, joint labour obligations between households may have been significant during times such as the harvest season (Brück, 2000: 288). It is possible that draught animals were shared between households to facilitate the labour-intensive tasks of agriculture, reflecting the solid communal ties of this period.

### 7.5.2 Animal traction and its socio-economic impact in Later Bronze Age Britain

Animal traction is closely tied to the most labour-intensive aspects of agricultural economies. The primary purpose of ploughing is to remove surface vegetation and create a suitable tilth for sowing seeds, facilitating fertilisation. Farmers can cultivate larger land areas by using draught animals for ploughing, thereby optimising land use and stabilising the mixed farming system (Sherratt, 2006: 356). The Middle Bronze Age is characterised by land-extensive and labour-intensive cereal cultivation (De Vareilles et al., 2023; Stevens and Fuller, 2012).

The improved ability to cultivate larger areas through animal traction had considerable socioeconomic impacts, potentially increasing social stratification by creating unequal access to productive resources and agricultural surplus.

Draught cattle, particularly oxen, could pull heavier ploughs, enabling the breaking of new ground on more compacted soils. Notably, it has been suggested that cultivation extended onto heavy clay soils during the Late Bronze Age (Murphy, 1987: 12; Bradley and Yates, 2007). By the Later Bronze Age, spelt had become a significant feature of arable economies in some sites in the south and east of England, likely linked to the expansion of farming on heavier soils (Murphy, 2013; de Carle, 2014: 159). This extensive arable regime of the Late Bronze Age would have been closely linked to the frequent use of draught cattle, as evidenced by prominent morphological changes. Expanding the arable land would have been particularly important during this time. Upland areas in southwest Britain were abandoned during the Late Bronze Age due to deteriorating climatic conditions (Turney et al., 2016). This likely forced population movements to the lowlands, increasing pressure on available arable land. Cultivation expanded onto previously challenging, heavier soils, facilitated by the use of animal traction.

The initial drivers for adopting animal traction may have been to replace human labour and expand land use. As the technology developed, its implications rapidly transcended mere agricultural efficiency. Animal traction could have become intricately linked with social stratification, with unequal access to plough oxen generating dependency relationships between households (Goody, 1977; Bogucki, 1993, 1988: 227–30). Sherratt (2006) argued that animal traction is an activity initially restricted to elites, serving as a means of resource concentration and the assertion of power. The ownership of specialised draught animals requires not only financial costs but also expertise in training the cattle. It is, therefore, unlikely to have been a widespread practice, which aligns with the results of this study, suggesting that this technology was likely confined to specific Later Bronze Age communities.

Increased agricultural surplus, achieved through the more intensive use of animal traction, facilitated the control of resources for exchange and contributed to the emergence of significant social changes. Although plough cultivation yields may have been lower per unit area compared to manual cultivation, the ability to cultivate a larger total area enabled the production of surplus (Halstead, 1995). During the Late Bronze Age, power became increasingly concentrated in the hands of elites (Bradley and Yates, 2007). Structures for storing cereals and fodder, associated with resource accumulation, became more common during the Later Bronze Age (Champion, 1999: 103). These new facilities, tied to formal land control and agricultural intensification, were likely connected to the growing complexity of social hierarchies established by the Middle Bronze Age. Specialised draught oxen, closely linked to large-scale agricultural overproduction, may have further exacerbated social inequality (Halstead, 2014: 58). By converting surplus into wealth and status through exchange, elites established a critical foundation for maintaining social power, particularly during the transition to the Earliest Iron Age (Barrett, 1980: 260; Barrett and Needham, 1988; Needham, 2007: 54). The emergence of animal traction was likely a driver of these social changes, enabling increased agricultural productivity while simultaneously reinforcing hierarchical structures.

Beyond cultivation, animal traction was crucial in transportation during the Mid-Late Bronze Age. The emergence of wheeled vehicles coincided with the use of draught animals, marking a significant development in mobility. This innovation facilitated the transport of goods over greater distances, thus supporting expanding trade and exchange networks. The increased cultivation of land, yielding higher agricultural outputs, likely necessitated using draught animals to transport harvested crops. However, as Bogucki (2000: 228) noted, while crops may have been a common cargo, other bulky items requiring regular transport into settlements might have been even more critical, including firewood and fodder. Storable food products, such as butter and cheese, were also significant

components of the Mid-Late Bronze Age economy in southern Britain (Serjeantson, 2007: 81). These products would have needed to be transported between settlements for trade and exchange. Moreover, considerations such as waste management, evidenced by substantial burnt stable refuse, including animal dung, at sites like Potterne (Lawson et al., 2000b: 268), further underscore the potential multipurpose utility of draught animals in Mid-Late Bronze Age societies.

While animal traction was evident in the Mid-Late Bronze Age, this technology remained a relatively restricted phenomenon. The scale of its adoption requires further analysis, particularly regarding its presence in northern England. Spade cultivation, used for turning soil, is also suggested to have been employed in Britain during this period. For example, plough and spade marks have been identified in well-preserved Mid-Late Bronze Age fields at Gwithian, Cornwall (A. Thomas, 1970; Nowakowski, 2017: 122). Similar practices could also have been employed in Scotland, particularly on the lighter soils of western Scotland (Cowie and Shepherd, 2003: 164). Despite its presence, the decision to use animal traction may have been influenced by various constraints, such as the ability to manage the demands of harvesting in extensive ox-ploughed fields or the significant resources required to maintain draught animals.

The biometric patterns indicating draught use are particularly prominent at Clay Farm and Potterne but are not observed at other contemporary sites, including Runnymede, East Chisenbury, and Stanton St Bernard. Unfortunately, the full publication of Clay Farm was unavailable at the time of writing this thesis, thus providing only a limited opportunity for the contextualisation of the evidence from the animal bones. It is known, however, that cereal cultivation at Clay Farm dates back to the Middle Bronze Age, with the construction of extensive field systems (Phillips and Mortimer, 2012).

Cereal cultivation at Potterne has also been identified, suggesting organised and systematic arable regimes that extended across a wide range of soil types in the area (Lawson et al., 2000b: 263). Potterne is suggested to have been a centre for feasting, exchange, and ritual activities for the surrounding areas, with its

influence stretching from the Vale of Pewsey to the Cotswolds (Lawson et al., 2000b: 270). The network connections across the Potterne region are further supported by recent isotope analysis of cattle bones. The results indicate that cattle at Potterne exhibited a broad range of sulphur isotope values, suggesting that animals may have originated from wider catchment areas and were brought to the site from elsewhere (Madgwick et al., 2023). This pattern differs from contemporary sites in Wiltshire, including East Chisenbury and Stanton St Bernard (Madgwick et al., 2023). Although no field systems have been identified at Potterne, these exist at several locations around the Vale of Pewsey (Tubb, 2011), an area characterised by heavy clay soils that were challenging to cultivate (Sharples, 2010: 52). It is possible that some draught animals were initially worked in the surrounding areas and brought to Potterne at the end of their working lives.

Animal traction emerged as a transformative technological innovation during the Middle to Late Bronze Age, reshaping agricultural practices and social structures in later prehistoric Britain. This study presents the first comprehensive osteological analysis of animal traction, revealing that this innovation was not a widespread practice, but a strategic technological adaptation confined to specific communities. By enabling the cultivation of previously uncultivated lands, particularly heavy clay soils, this technology facilitated agricultural expansion and intensification. Critically, animal traction was more than a mere technological tool—it catalysed social transformation, allowing resource concentration, control of surplus production, and the establishment of new power dynamics. Adopting animal traction reflects a socioeconomic response to environmental challenges and population pressures, marking a pivotal moment in the technological and social development of Later Bronze Age British societies.

# 8 CONCLUSION

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The first part of this chapter summarises the key findings presented in the previous chapters, while the second part outlines future directions for advancing the understanding of animal traction in the past.

## 8.1 Summary of the key results

**Methodological aspects:**

1. A new biometric approach for identifying draught cattle has been developed in this study, representing a significant advancement in zooarchaeological methodology. This method enables the reliable classification of archaeological specimens based on metapodials and phalanges, with the first phalanx yielding the highest predictive accuracy. It addresses a key gap in existing practices, where the identification of traction use has often relied on less quantifiable or more ambiguous indicators. The R scripts for the classification models are publicly available (`http://doi.org/10.17632/7722hz4z4x` and `https://github.com/Phoebe-WCLiu/draught_cattle_biometry`), providing an accessible and replicable tool for researchers working with archaeological assemblages.

2. The Pathological Index and entheseal changes are methods well-suited for identifying broad-scale trends across different sites or chronological periods at an assemblage level. However, it is unwise to make interpretations at the specimen level to infer potential draught use, as modern data clearly show that non-draught animals can also exhibit severe pathological conditions. For this reason, these methods are better used in combination with a biometric approach.

3. Kill-off patterns remain critical for studying the draught use of animals. They are particularly useful for clarifying results from the Pathological Index and entheseal changes, as advanced age positively correlates with the increased severity of pathological conditions. A high proportion of older animals can lead to elevated Pathological Index values, which may also be associated with milking rather than being solely a consequence of draught use. This study highlights that cross-checking findings using multiple methods is the most effective way to reach reliable interpretations.

4. The modern biometric data show improved results when analyses are conducted independently on the anterior and posterior phalanges. However, distinguishing archaeological phalanges based on visual criteria alone may not be reliable. Although the distribution of weight differs across body parts and can provide useful insights, this work has demonstrated that combining the analyses of these phalanges still yields reliable results.

**Archaeological aspects:**

5. Animal traction may have been used in the Neolithic; however, current evidence is weak. The lack of emphasis on cattle for draught use aligns with the present understanding of Neolithic agricultural practices, which predominantly involved small-scale, intensive cultivation systems unlikely to require animal traction. Additionally, the sharp decline in arable farming during Late Neolithic Britain, particularly in England, and the shift towards

pastoralism further support the notion that animal traction was not yet a central aspect of agricultural systems during this period.

6. Osteological results indicate the emergence of animal traction in Britain beginning in the Middle-Late Bronze Age, aligning with the artefactual evidence. It was unlikely to be a widespread practice when animal traction was adopted. Instead, it appears to have been restricted to certain communities, influenced by factors such as economic needs, agricultural practices, and social structures.

7. The social and economic changes during the Middle-Late Bronze Age offer motivations for adopting this new technology, which required significant effort. The shift towards more complex agricultural practices and the need for greater efficiency in cultivating larger areas likely motivated the adoption of animal traction. In Britain, this could have been influenced by continental Europe, as animal traction was likely used by the fourth millennium BC.

8. The use of animal traction could have further facilitated the significant socioeconomic developments of the Middle-Late Bronze Age. Enabling the cultivation of larger areas with less labour provided a more efficient arable strategy than manual ploughing. Consequently, this not only increased agricultural yields but also potentially intensified social stratification. The maintenance of specialised oxen required significant resources, leading to unequal access to productive assets and consolidating power among wealthier or more powerful groups. This likely contributed to the increasing complexity of social hierarchies in the Middle Bronze Age.

## 8.2 Future work

1. **Modern data**

   The key challenge in biometric studies of draught cattle is the lack of

sufficient data from modern draught animals. Addressing this gap may be difficult due to the decline in traditional draught practices in many regions. Alternatively, additional data from Roman or Medieval sites may compensate for this limitation. As demonstrated in this study, incorporating comparative sites from historical periods where animal traction was well established can strengthen the interpretation of draught-related osteological patterns. The risk of a circular argument must, however, be considered. That is, there is a risk of assuming that ploughing occurred at Roman and Medieval sites without first demonstrating it.

2. **Microstructure**

   Current osteological methods focus on macroscopic modifications. While these methods have shown promising results, the intensity required to trigger noticeable changes remains unknown. Histological analysis, particularly bone histomorphometrics, including osteon population density and diameter, is a promising avenue for further exploration. This method has already been applied to human skeletons with mobility and activity patterns (e.g. Miszkiewicz and Mahoney, 2016; Pitfield et al., 2019). The changing microstructure could potentially indicate more subtle modifications related to strain induced by draught use. The first step will be to analyse modern specimens with known life histories to confirm the variations between draught and non-draught animals. Preliminary histological analyses of the Romanian draught cattle have been conducted (Bartosiewicz et al., 1997b), but revisiting these specimens for further examination would be valuable.

3. **Sexing**

   Sex preference in choosing draught animals is an important area to explore, but it is currently constrained by methodological limitations. Using cows as draught animals is practised in modern societies and has been suggested for European prehistory, though the evidence remains inconclusive. Cattle sexing is typically achieved by measuring metapodials, particularly at the distal

end; however, draught use complicates this process, as external stresses appear to affect this region. Future work could involve first identifying phalanges indicative of draught use and then determining their sex through DNA analysis. This approach could further clarify the role of sex in selecting draught animals in prehistoric contexts.

4. **Bronze Age sites**
   Although the current study reveals that the adoption of animal traction in Middle-Late Bronze Age Britain appears to have been limited to specific regions, further investigations into sites in northern England and Scotland will refine insights into the spread of this new technology during its initial adoption. Large Bronze Age assemblages are rare in northern England; one potential site of interest is Thwing, an unpublished Late Bronze Age ringfort in East Yorkshire (Manby, 1980: 321). Unfortunately, the assemblage was unavailable for access during this project. Thwing likely contains one of the largest animal bone assemblages in the area, providing the best opportunity for further research.

5. **Broader contexts**
   Whether animal traction was adopted in continental Europe prior to the fourth millennium BC remains largely unresolved, although the possibility should not be dismissed. The current osteological evidence is inconclusive in supporting this idea. Further systematic analyses expanding to a broader European context may clarify the timeline of technological spread and whether it was introduced through cross-cultural interactions.

The debate on when secondary products were first exploited has largely been settled, with consensus reached on the timeline for milking and wool production. Animal traction, however, remains an unresolved issue. This technology was revolutionary, not only in enhancing cultivation capabilities but also in fostering a new dynamic between humans and animals. Animals actively participated in cooperative labour, reshaping agricultural practices and economic structures.

This study is a critical step toward advancing our understanding of animal traction in prehistoric Britain. The methodological approaches developed here offer new avenues for investigating osteological evidence for future research on the role of animal traction in past societies.

# Appendices

# A

# MODERN NON-DRAUGHT CATTLE

Table A.1 shows the general information of the modern non-draught cattle recorded for this thesis. Metric data can be downloaded from Mendeley Data (DOI: 10.17632/7722hz4z4x) and GitHub (github.com/Phoebe-WCLiu/draught_cattle_biometry).

Table A.1: General information of the modern non-draught cattle.

| | ID | Collection | Species | Breed | Sex | Age in year (Estimated age) |
|---|---|---|---|---|---|---|
| 1 | 1494 | SZL | *Bos taurus* | Jersey | F | (5.6) |
| 2 | 0078(b) | SZL | *Bos taurus* | Unknown | F | Adult |
| 3 | 0079 | SZL | *Bos taurus* | Unknown | F | (7.6) |
| 4 | 76 (Bbrtb3) | Halle | *Bos taurus* | Breitenburger | F | (3.8) |
| 5 | 220 (Bhld25) | Halle | *Bos taurus* | Holländer | F | (7.6) |
| 6 | 134 (Bfrsb2) | Halle | *Bos taurus* | Holstein Friesian | F | (7.6) |
| 7 | 135 (Bfrsb3) | Halle | *Bos taurus* | Holstein Friesian | F | (10.5) |
| 8 | 285 (Bfrr4) | Halle | *Bos taurus* | Holstein Friesian | F | - |
| 9 | 398 (Bwma6) | Halle | *Bos taurus* | Wilstermarscher | F | (6.8) |
| 10 | 216 (Bhld21) | Halle | *Bos taurus* | Holländer | M | (5.1) |
| 11 | 214 (Bhld19) | Halle | *Bos taurus* | Holländer | F | 3.3 |
| 12 | 218 (Bhld23) | Halle | *Bos taurus* | Holländer | F | (8.7) |
| 13 | 242 (Bjvl1) | Halle | *Bos taurus* | Jeverländer | F | 5 |
| 14 | 1035 | Halle | *Bos taurus* | Unknown | M | - |
| 15 | 83 (Bbtj2) | Halle | *Bos taurus* | Butjadinger | F | 17 |
| 16 | 397 (Bwma5) | Halle | *Bos taurus* | Wilstermarscher | F | - |
| 17 | 213 (Bhld18) | Halle | *Bos taurus* | Holländer | F | (8.1) |
| 18 | 74 (Bbrtb1) | Halle | *Bos taurus* | Breitenburger | F | (9.6) |
| 19 | 770 (Bsmr1*) | Halle | *Bos taurus* | Holstein Friesian | F | 18.8 |
| 20 | 182 (Bhdsl1) | Halle | *Bos taurus* | Haderslebener | F | - |
| 21 | 78 (Bbrtb5) | Halle | *Bos taurus* | Breitenburger | F | 4 |
| 22 | 19 (Bagl7) | Halle | *Bos taurus* | Angeln | F | 10.5 |
| 23 | 14 ( Bagl2) | Halle | *Bos taurus* | Angeln | F | - |
| 24 | 22 (Banstr1) | Halle | *Bos taurus* | Ansbach-Triesdorfer | F | 9.5 |
| 25 | 294 (Bpdstp2) | Halle | *Bos taurus* | Podolian | M | 13 |
| 26 | 293 (Bpdstp1) | Halle | *Bos taurus* | Podolian | F | (7.6) |
| 27 | 301 (Bprtg2) | Halle | *Bos taurus* | Prätigauer | F | 6.7 |
| 28 | 388 (Bwstw4) | Halle | *Bos taurus* | Westerwälder | F | (10.3) |
| 29 | 368 (Bwstw2) | Halle | *Bos taurus* | Westerwälder | F | (10.8) |
| 30 | 353 (Bsim5) | Halle | *Bos taurus* | Simmental | F | 5.6 |
| 31 | 126 (Bfrb2) | Halle | *Bos taurus* | Fribourgeoise | F | (5) |

**Table A.1 continued from previous page**

| | | | | | | |
|---|---|---|---|---|---|---|
| 32 | 188 (Bhrz6) | Halle | *Bos taurus* | Harzer | F | (6) |
| 33 | 315 (Bslrtv2) | Halle | *Bos taurus* | Silesian Red | F | 5.2 |
| 34 | 121 (Begl1) | Halle | *Bos taurus* | Egerländer | F | - |
| 35 | 322 (Bswyz4) | Halle | *Bos taurus* | Schwyzer | F | (12) |
| 36 | 380 (vgtl1) | Halle | *Bos taurus* | Vogtlander | F | - |
| 37 | 323 (Bswyz5) | Halle | *Bos taurus* | Schwyzer | F | - |
| 38 | 265 (Bmrbd2) | Halle | *Bos taurus* | Murbodener | F | 2.9 |
| 39 | 302 (prtg3) | Halle | *Bos taurus* | Prättigauer | F | - |
| 40 | 303 (prtg4) | Halle | *Bos taurus* | Prättigauer | F | - |
| 41 | 351 (Bsim13) | Halle | *Bos taurus* | Simmental | F | (7.3) |
| 42 | 379 (Bvjb3) | Halle | *Bos taurus* | Vogelsberg | F | 6.5 |
| 43 | 381 (Bvjb2) | Halle | *Bos taurus* | Vogelsberg | F | 19.6 |
| 44 | 328 (Bshh4) | Halle | *Bos taurus* | Shorthorn | F | (7.3) |
| 45 | 329 (Bshh5) | Halle | *Bos taurus* | Shorthorn | F | 6 |
| 46 | 335 (Bshh12) | Halle | *Bos taurus* | Shorthorn | F | 7.2 |
| 47 | 132 (Bdv1) | Halle | *Bos taurus* | Devon | F | (6) |
| 48 | 922 (Bdv6) | Halle | *Bos taurus* | Devon | F | (9.1) |
| 49 | 886 (Bbrtb1) | Halle | *Bos taurus* | Breitenburger | F | 7.8 |
| 50 | 289 (Bkry1) | Halle | *Bos taurus* | Kerry | F | (7.3) |
| 51 | 295 (Bkry2) | Halle | *Bos taurus* | Kerry | M | 6.9 |
| 52 | 760 (Bshh71*) | Halle | *Bos taurus* | Shorthorn | F | 4.5 |
| 53 | 763 | Halle | *Bos taurus* | Unknown | F | - |
| 54 | 766 | Halle | *Bos taurus* | Unknown | F | - |
| 55 | 629 (Bhld14*) | Halle | *Bos taurus* | Holländer | F | (3.3) |
| 56 | 912 | Halle | *Bos taurus* | Unknown | F | - |
| 57 | 254 (Bgrs1) | Halle | *Bos taurus* | Guernsey | F | (7.3) |
| 58 | 1338 (Bizb39*) | Halle | *Bos taurus* | Zebu | F | 3.3 |
| 59 | 1211 (Bsim5*) | Halle | *Bos taurus* | Simmental | F | 2.6 |
| 60 | 727 (Bglw4) | Halle | *Bos taurus* | Galloway | M | 5.1 |
| 61 | 727 (Bglw3) | Halle | *Bos taurus* | Galloway | F | 13.2 |
| 62 | 258 (Barsh2) | Halle | *Bos taurus* | Ayrshire | F | - |
| 63 | 5353 (Bjrs10) | Halle | *Bos taurus* | Jersey | M | 5.5 |
| 64 | 5325 (Blgh3) | Halle | *Bos taurus* | Longhorn | F | (8.1) |
| 65 | 513 (Bswdfj1) | Halle | *Bos taurus* | Fjäll | F | - |
| 66 | 5342 | Halle | *Bos taurus* | Unknown | F | - |
| 67 | 539 (Bshh57*) | Halle | *Bos taurus* | Shorthorn | M | (3) |
| 68 | 5226 (Bdv2) | Halle | *Bos taurus* | Devon | F | (5.6) |
| 69 | 744 (Blgh6) | Halle | *Bos taurus* | Longhorn | M | 4.4 |
| 70 | 253 (Bjrs2) | Halle | *Bos taurus* | Jersey | F | (7.6) |
| 71 | 1128 (Bopr1) | Halle | *Bos taurus* | Ostpreußisches Landrind | F | - |
| 72 | 257 (Blgh1) | Halle | *Bos taurus* | Longhorn | F | - |
| 73 | 1422 (Bjrs14) | Halle | *Bos taurus* | Jersey | F | 4.2 |
| 74 | 728 (Bjrs7) | Halle | *Bos taurus* | Jersey | F | 10.3 |
| 75 | 1423 (Bjrs11) | Halle | *Bos taurus* | Jersey | F | 7.1 |
| 76 | 633 (Bugstp4) | Halle | *Bos taurus* | Hungarian Grey | Castrated Male | - |
| 77 | 603 (Bjrs6) | Halle | *Bos taurus* | Jersey | F | (5.4) |
| 78 | 1520 (Bjrs13) | Halle | *Bos taurus* | Jersey | F | 3 |
| 79 | 1424 (Bjrs12) | Halle | *Bos taurus* | Jersey | F | 8.2 |
| 80 | 1200 (Bbrtb5) | Halle | *Bos taurus* | Unknown | F | (6.9) |
| 81 | 1573 (Bjrs7*) | Halle | *Bos taurus* | Jersey | M | - |
| 82 | 251 (Bshh4) | Halle | *Bos taurus* | Shorthorn | F | (7.3) |
| 83 | 594 (Bbtg6) | Halle | *Bos javanicus* | - | F | - |
| 84 | 255(Bhrfd1) | Halle | *Bos taurus* | Hereford | F | 9.5 |
| 85 | 256(Bdv4) | Halle | *Bos taurus* | Devon | F | (9.6) |

**Table A.1 continued from previous page**

| | | | | | | |
|---|---|---|---|---|---|---|
| 86 | 40 | Halle | *Bos taurus* | Watussi | F | - |
| 87 | 31 (Bfrr1) | Halle | *Bos taurus* | Holstein Friesian | F | - |
| 88 | 5330 (Blgh5) | Halle | *Bos taurus* | Longhorn | F | 5.6 |
| 89 | 5328 (Bw1) | Halle | *Bison bonasus* | - | F | - |
| 90 | 5320 (Bfrsb1) | Halle | *Bos taurus* | Holstein Friesian | F | (5.8) |
| 91 | 65 (Bawst10) | Halle | *Bison bison* | - | M | - |
| 92 | 612 (Bawst12) | Halle | *Bison bison* | - | F | - |
| 93 | 891 (Bnrm2) | Halle | *Bos taurus* | Normande | M | 3.9 |
| 94 | 476 (Bshh47*) | Halle | *Bos taurus* | Shorthorn | F | 7 |
| 95 | 1148 (Bpdstp4*) | Halle | *Bos taurus* | Podolian | M | 2.6 |
| 96 | 354 (Bshh26*) | Halle | *Bos taurus* | Shorthorn | M | 6.3 |
| 97 | 1157 (Bpdstp5*) | Halle | *Bos taurus* | Podolian | F | 8.4 |
| 98 | 195 (Bdv3*) | Halle | *Bos taurus* | Devon | M | 4.8 |
| 99 | 194 (Bdv2*) | Halle | *Bos taurus* | Devon | F | 7.2 |
| 100 | 700 (Bshh67*) | Halle | *Bos taurus* | Shorthorn | F | 8 |
| 101 | 415 (Bkry4*) | Halle | *Bos taurus* | Kerry | M | 12.2 |
| 102 | 298 (Bshh16*) | Halle | *Bos taurus* | Shorthorn | M | 6.8 |
| 103 | 657 (Bhld16*) | Halle | *Bos taurus* | Holländer | Castrated Male | 9.5 |
| 104 | 564 (Bshh6*) | Halle | *Bos taurus* | Shorthorn | F | 11.5 |
| 105 | 568(Bshh10*) | Halle | *Bos taurus* | Shorthorn | M | 5 |
| 106 | 586(Bshh32*) | Halle | *Bos taurus* | Shorthorn | M | 1.9 |
| 107 | 581 (Bshh24*) | Halle | *Bos taurus* | Shorthorn | F | 12.3 |
| 108 | 569 (Bshh11*) | Halle | *Bos taurus* | Shorthorn | M | 11.1 |
| 109 | 617 (Bshh60*) | Halle | *Bos taurus* | Shorthorn | F | 9.8 |
| 110 | 556 (Bkry3*) | Halle | *Bos taurus* | Kerry | F | 8 |
| 111 | 532 (Bgrs1) | Halle | *Bos taurus* | Guernsey | F | 4 |
| 112 | 555 (Bkry2*) | Halle | *Bos taurus* | Kerry | F | 18.3 |
| 113 | 579 (Bshh22*) | Halle | *Bos taurus* | Shorthorn | M | 3.6 |
| 114 | 110 | Halle | *Bos grunniens* | - | M | - |
| 115 | 590 (Bshh36*) | Halle | *Bos taurus* | Shorthorn | M | 10 |
| 116 | 576 (Bshh19*) | Halle | *Bos taurus* | Shorthorn | M | 4.7 |
| 117 | 540 (Bhld9*) | Halle | *Bos taurus* | Holländer | F | 4.3 |
| 118 | 547 (Bhld17*) | Halle | *Bos taurus* | Holländer | M | 6.8 |
| 119 | 327 (Bshh3*) | Halle | *Bos taurus* | Shorthorn | M | - |
| 120 | 592 (Bshh38*) | Halle | *Bos taurus* | Shorthorn | F | 10.3 |
| 121 | 619 (Bshh62*) | Halle | *Bos taurus* | Shorthorn | M | 5.2 |
| 122 | 537 (Bhld6*) | Halle | *Bos taurus* | Holländer | F | 16.7 |
| 123 | 583 (Bshh27*) | Halle | *Bos taurus* | Shorthorn | F | 2.9 |
| 124 | 566 (Bshh8*) | Halle | *Bos taurus* | Shorthorn | M | 6.9 |
| 125 | 565 (Bshh7*) | Halle | *Bos taurus* | Shorthorn | M | 7 |
| 126 | 580 (Bshh23*) | Halle | *Bos taurus* | Shorthorn | F | 4.6 |
| 127 | 612 (Bshh55*) | Halle | *Bos taurus* | Shorthorn | M | 7.3 |
| 128 | 215 (Bshh12*) | Halle | *Bos taurus* | Shorthorn | M | 3.5 |
| 129 | 572 (Bshh15*) | Halle | *Bos taurus* | Shorthorn | M | 3.6 |
| 130 | R671 | LZL | *Bos taurus* | Chillingham | F | 3.5 |
| 131 | R673 | LZL | *Bos taurus* | Chillingham | F | 3.5 |
| 132 | R672 | LZL | *Bos taurus* | Chillingham | F | 3.5 |
| 133 | R625 | LZL | *Bos taurus* | Chillingham | M | - |
| 134 | R760 | LZL | *Bos taurus* | Chillingham | M | - |
| 135 | 1953.4.22.6 | NHM | *Bos taurus* | Chillingham | M | (9.6) |
| 136 | 1953.4.22.5 | NHM | *Bos taurus* | Chillingham | M | (8.1) |
| 137 | 1953.4.22.4 | NHM | *Bos taurus* | Chillingham | F | (1.5) |
| 138 | 1953.4.22.9 | NHM | *Bos taurus* | Chillingham | - | - |
| 139 | 1953.4.22.9a | NHM | *Bos taurus* | Chillingham | - | - |

**Table A.1 continued from previous page**

| | | | | | | |
|---|---|---|---|---|---|---|
| 140 | 1953.4.22.9b | NHM | *Bos taurus* | Chillingham | - | - |
| 141 | 1953.4.22.1 | NHM | *Bos taurus* | Chillingham | - | - |
| 142 | 1953.4.22.2 | NHM | *Bos taurus* | Chillingham | - | - |
| 143 | 1981.984 | NHM | *Bos taurus* | Chillingham | F | 14 |
| 144 | 1981.989 | NHM | *Bos taurus* | Chillingham | F | 10 |
| 145 | 1981.986 | NHM | *Bos taurus* | Chillingham | F | 14 |
| 146 | 1981.985 | NHM | *Bos taurus* | Chillingham | F | 5 |
| 147 | 1924.4.28.1 | NHM | *Bos taurus* | Chartley | M | 12.35 |
| 148 | 1980.2665 | NHM | *Bos taurus* | Chartley | M | 10.47 |
| 149 | 1975.303 | NHM | *Bos taurus* | Chartley | M | - |
| 150 | 2002.118 | NHM | *Bos taurus* | Charolais | F | - |
| 151 | 2002.117 | NHM | *Bos taurus* | Jersey | Castrated Male | 3.75 |

SZL = Zooarchaeology Laboratory of the University of Sheffield
Halle = Museum für Haustierkunde Julius Kühn of the Martin Luther University of Halle-Wittenberg
LZL = Bone Laboratory of the University of Leicester
NHM = Natural History Museum (London)
*****Crossbred cattle, only the breed of sire was documented.

# B

# ADDITIONAL BIOMETRIC ANALYSES ON MODERN CATTLE

Figures B.1 and B.2 show the less effective ratios for separating between draught and non-draught cattle. Refer to Table 5.5 for the abbreviations of the measurements.

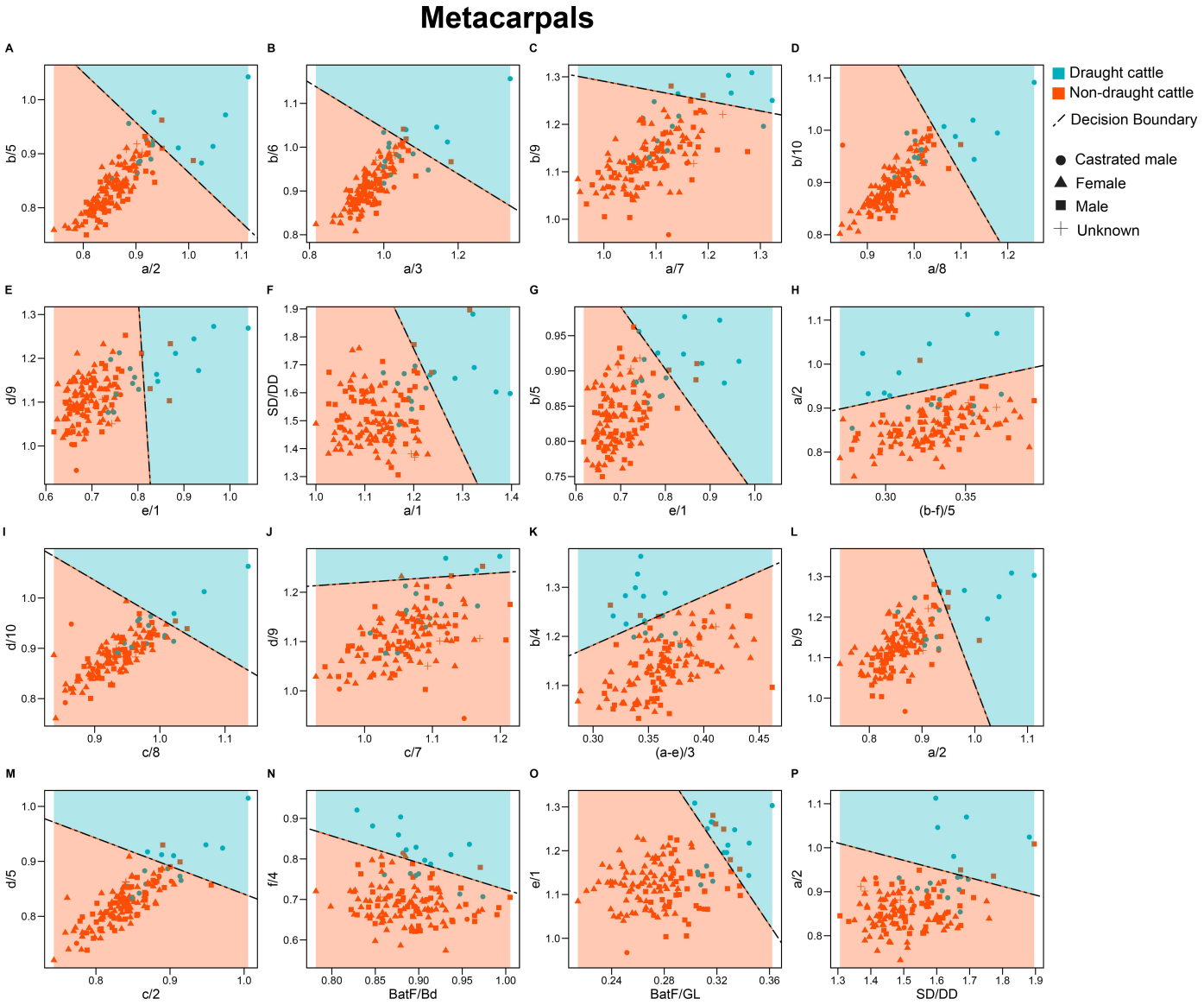



Figure B.1: Additional shape ratio analyses on modern cattle metacarpals.

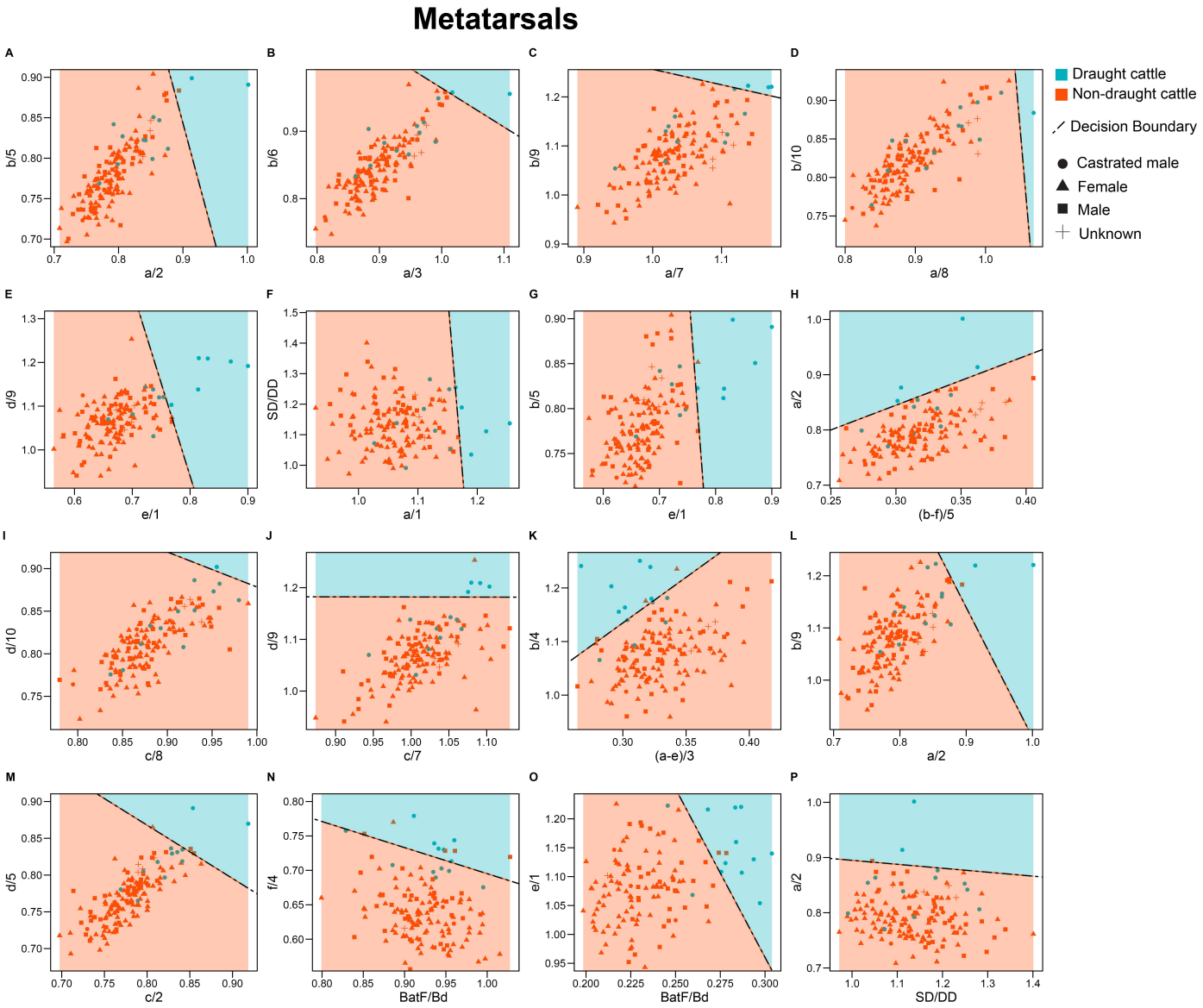



Figure B.2: Additional shape ratio analyses on modern cattle metatarsals.

# C

# GRADING SYSTEM FOR THE STUDIED ENTHESES

Three entheses are presented with incomplete grading illustrations due to the lack of suitable examples.

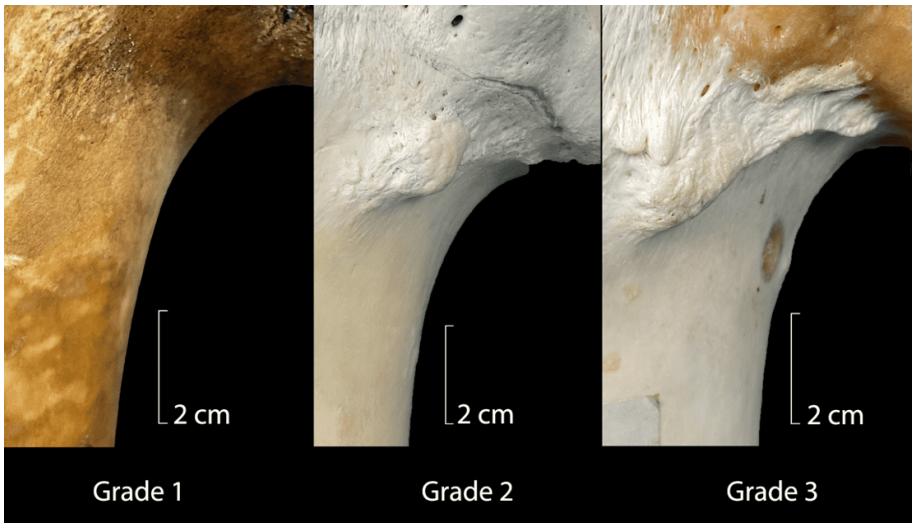



Plate C.1: Grading illustrations for the teres minor.

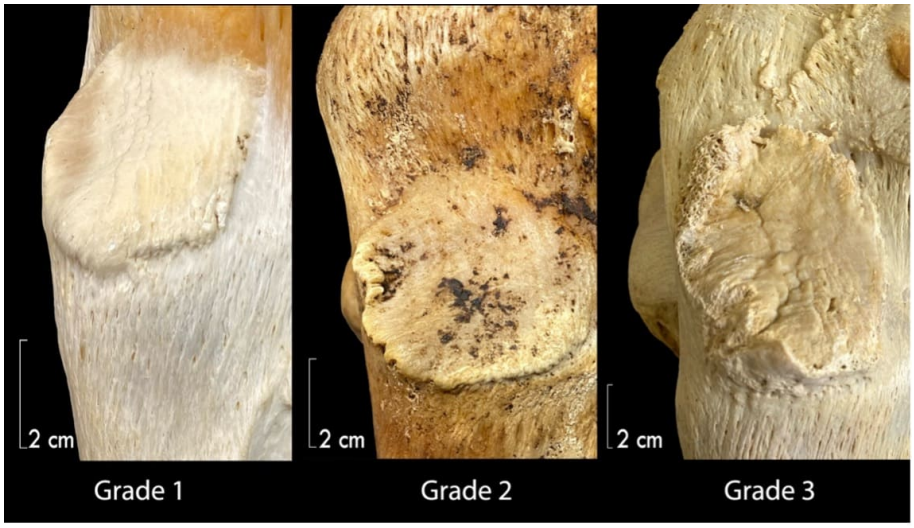



Plate C.2: Grading illustrations for the infraspinatus.

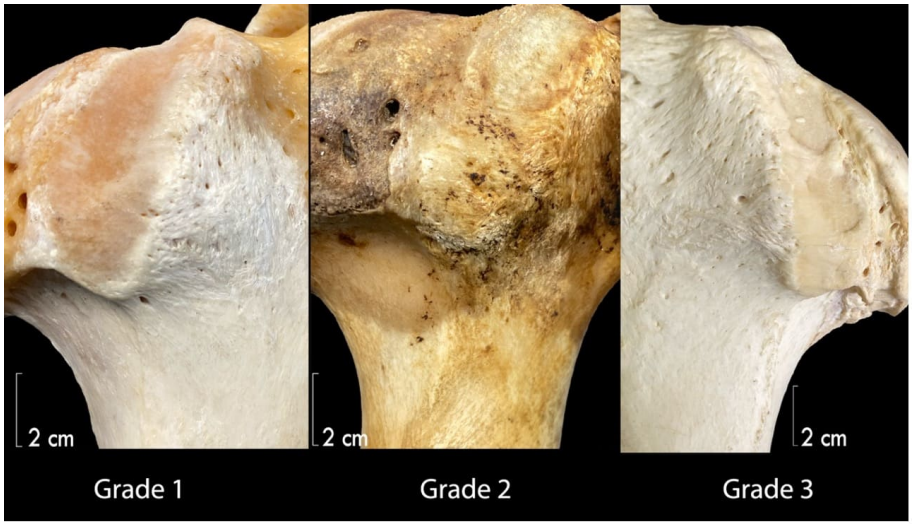



Plate C.3: Grading illustrations for the subscapularis.

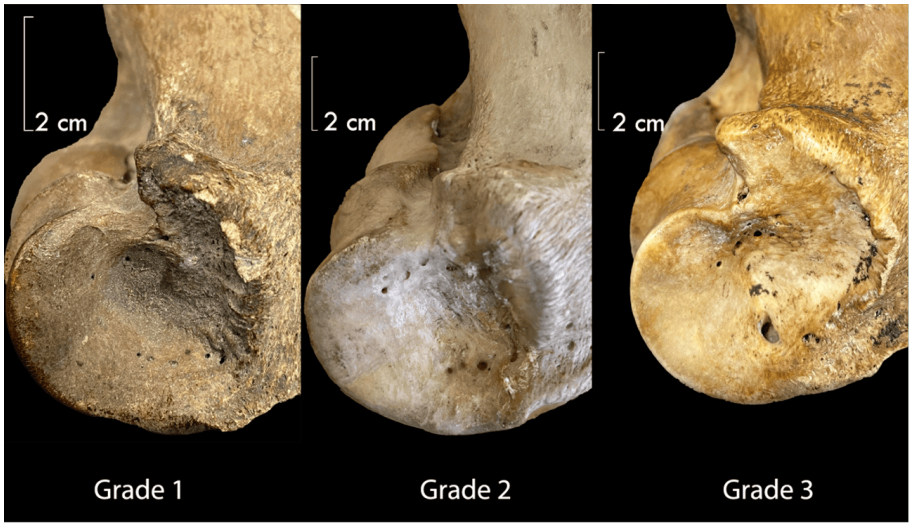



Plate C.4: Grading illustrations for the extensor digitorum communis.

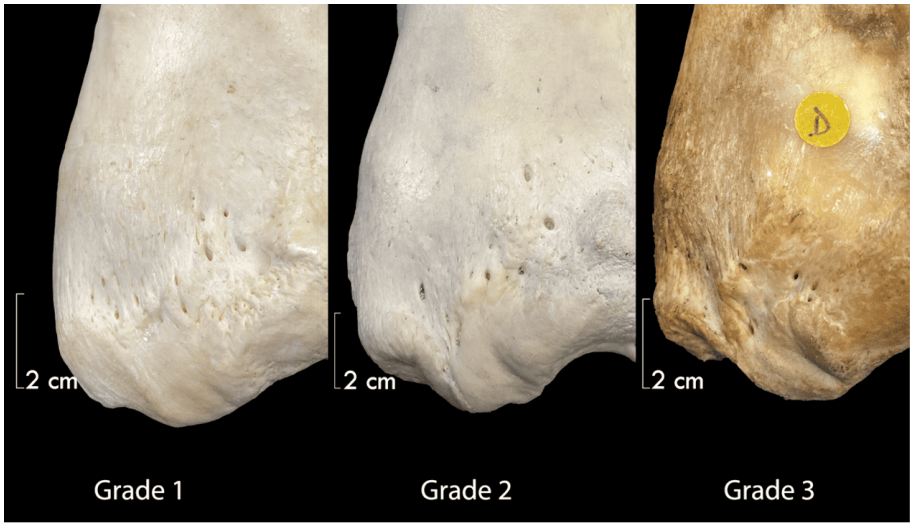



Plate C.5: Grading illustrations for the flexor digitorum profundus.

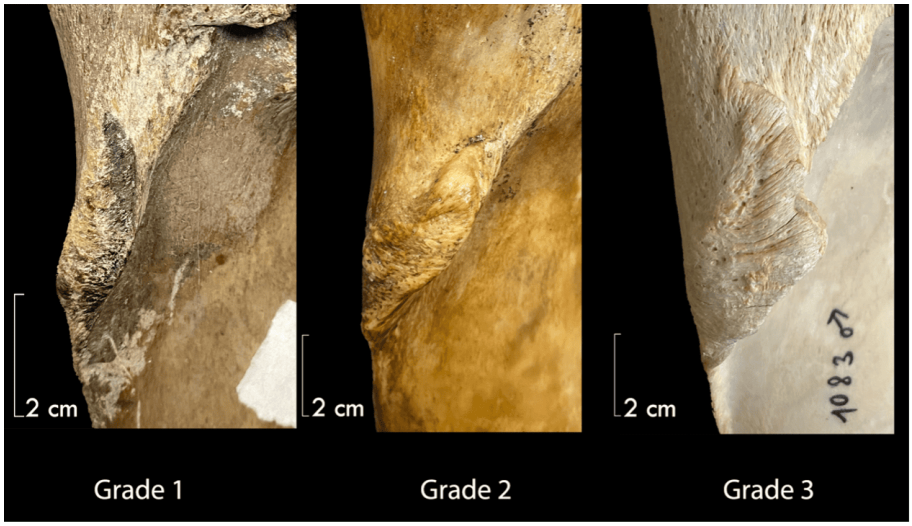



Plate C.6: Grading illustrations for the deltoideus.

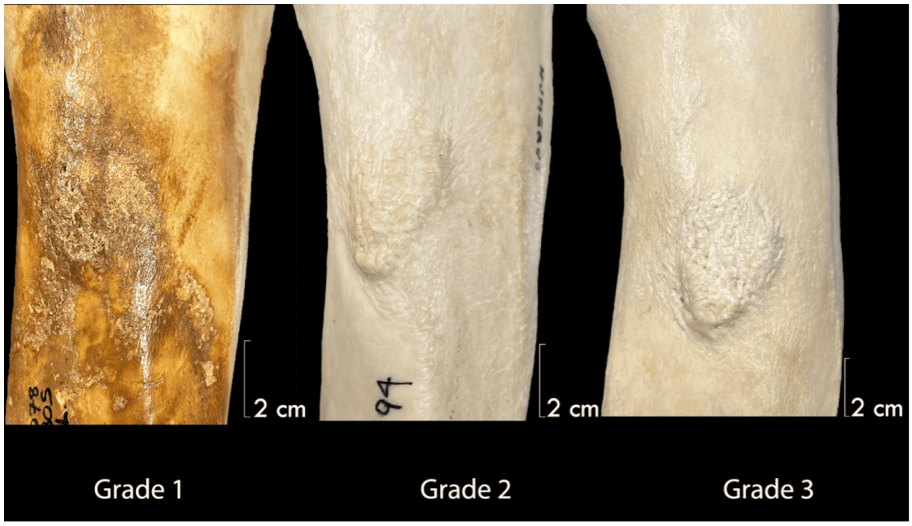



Plate C.7: Grading illustrations for the teres major.




Plate C.8: Grading illustrations for the flexor carpi radialis.




Plate C.9: Grading illustrations for the flexor carpi ulnaris.




Plate C.10: Grading illustrations for the anconeus.




Plate C.11: Grading illustrations for the flexor digitorum profundus .

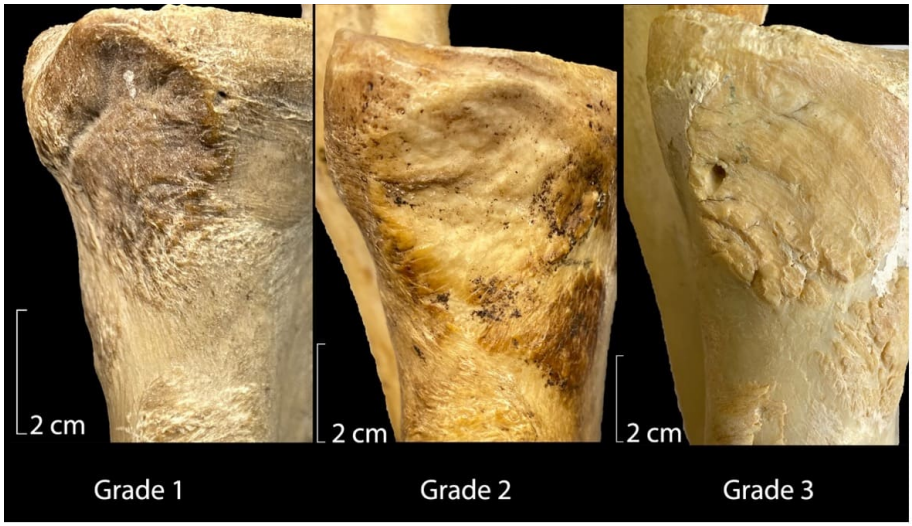



Plate C.12: Grading illustrations for the biceps brachii.

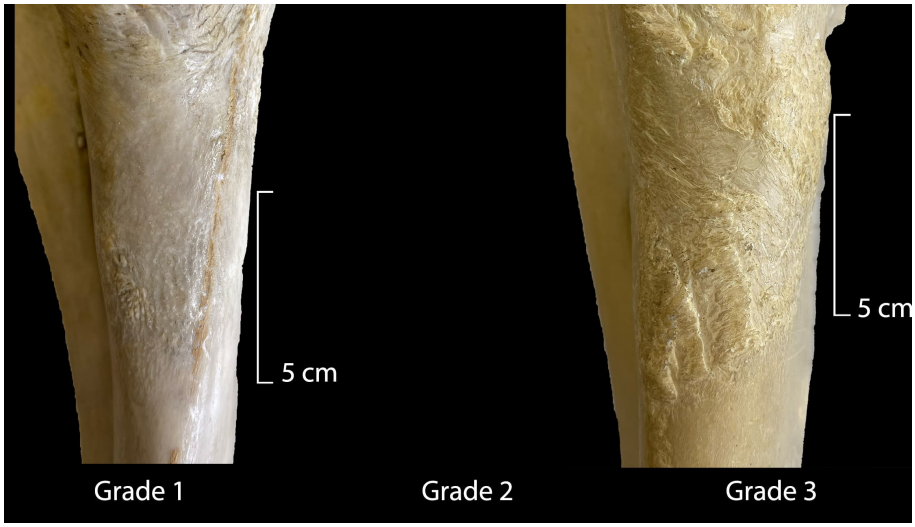



Plate C.13: Grading illustrations for the brachialis anticus.

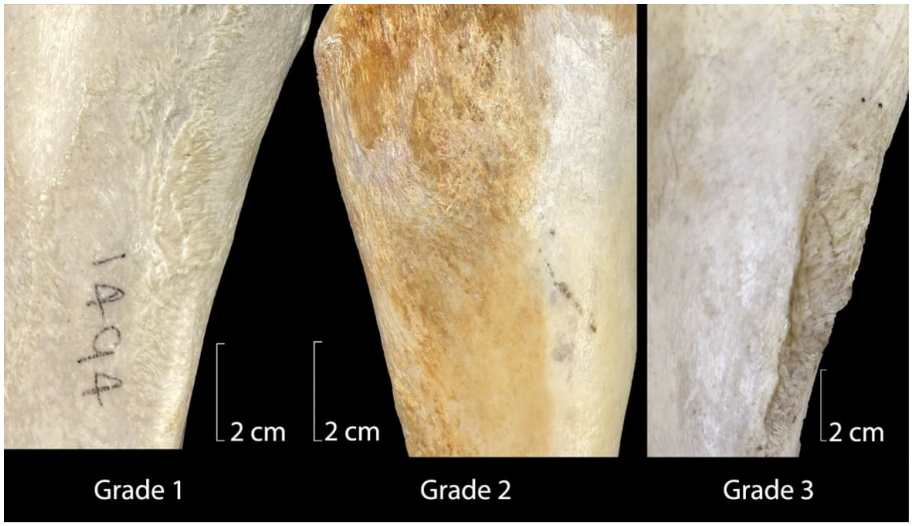



Plate C.14: Grading illustrations for the semimembranosus.




Plate C.15: Grading illustrations for the gracilis.

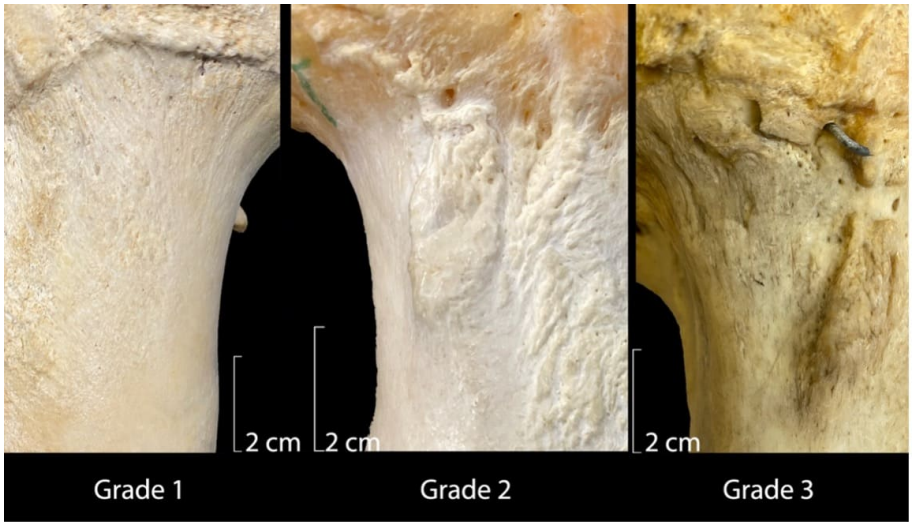



Plate C.16: Grading illustrations for the popliteus.




Plate C.17: Grading illustrations for the gluteus profundus.

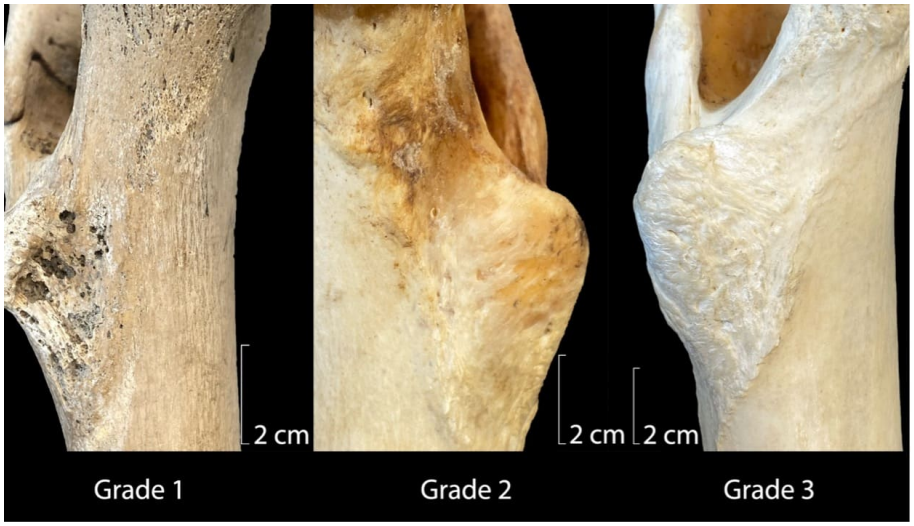



Plate C.18: Grading illustrations for the iliopsoas.

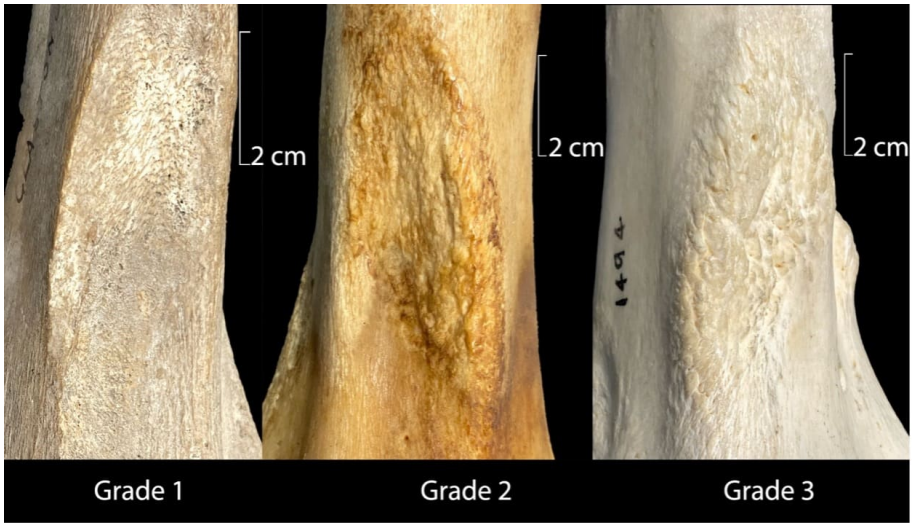



Plate C.19: Grading illustrations for the gastrocnemius caput laterale.

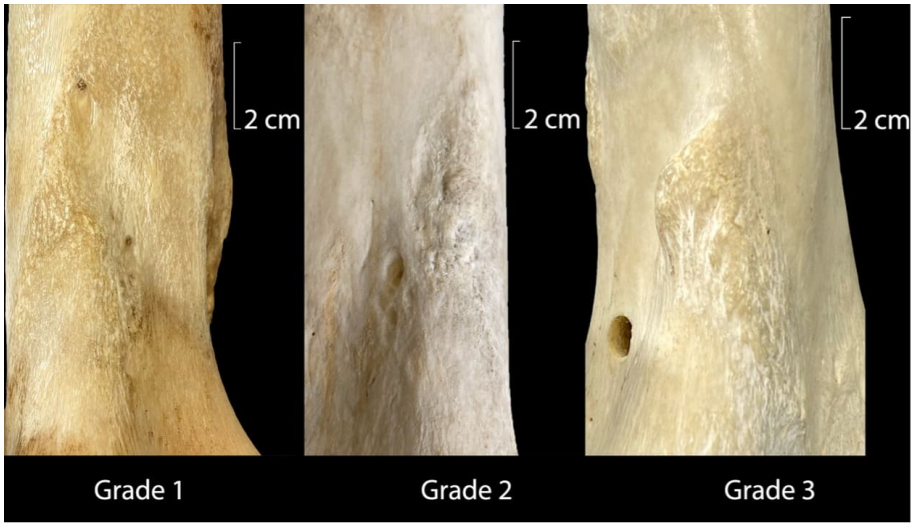



Plate C.20: Grading illustrations for the gastrocnemius caput mediale.

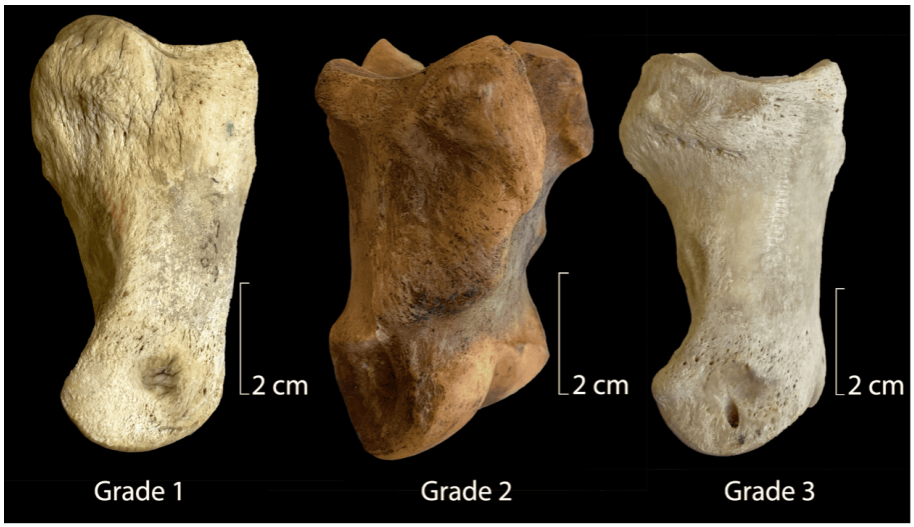



Plate C.21: Grading illustrations for the lateral collateral metacarpophalangeal/ metatarsophalangeal ligament.




Plate C.22: Grading illustrations for the medial collateral metacarpophalangeal/ metatarsophalangeal ligament.

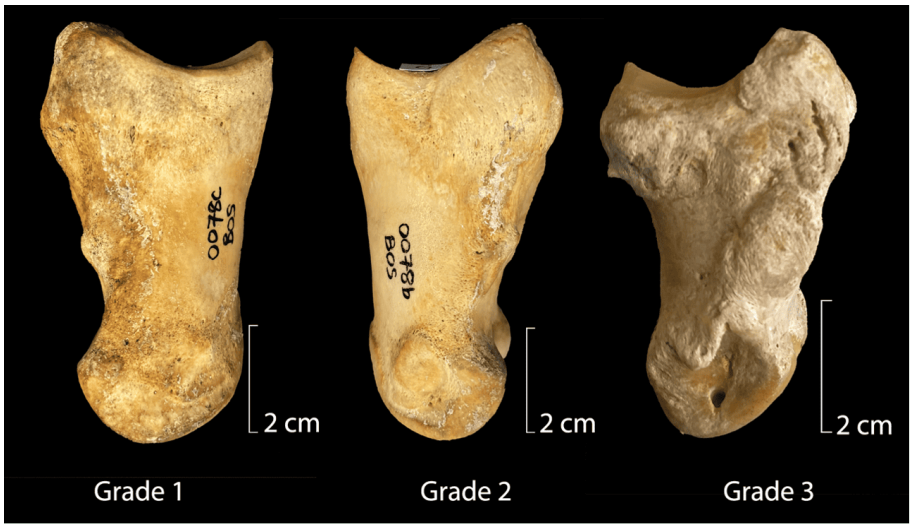



Plate C.23: Grading illustrations for the lateral collateral proximal interphalangeal ligament.




Plate C.24: Grading illustrations for the medial collateral proximal interphalangeal ligament.

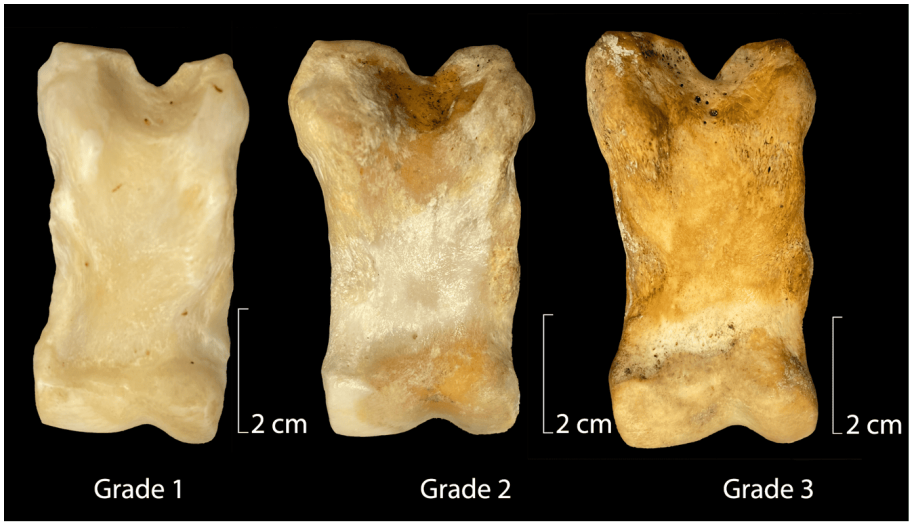



Plate C.25: Grading illustrations for the proximal digital annular ligament.

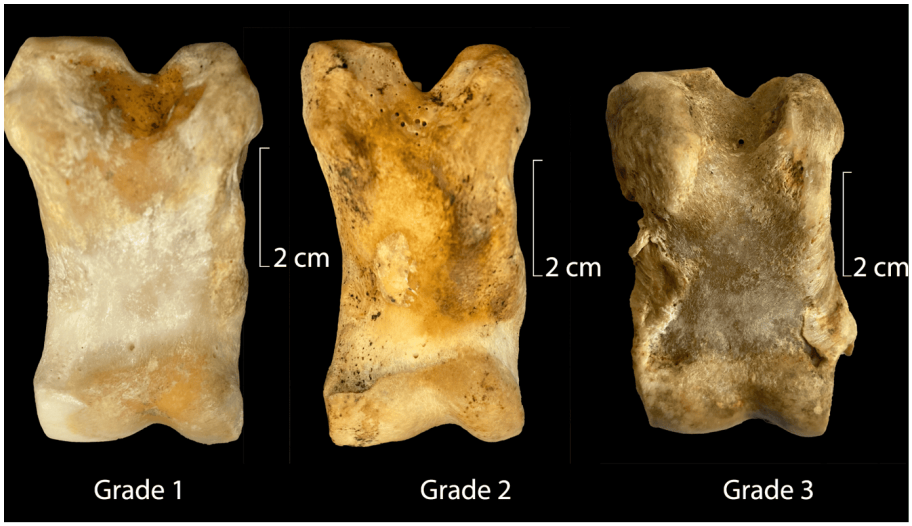



Plate C.26: Grading illustrations for the distal digital annular ligament.

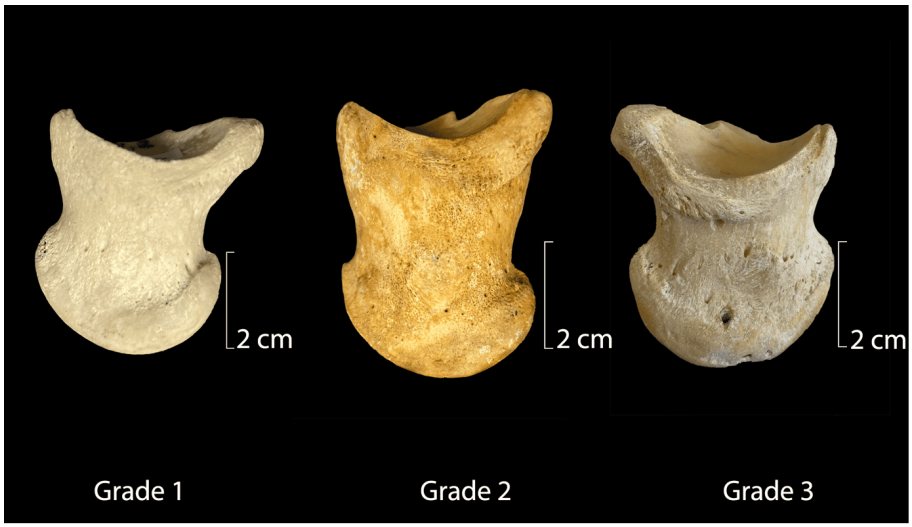



Plate C.27: Grading illustrations for the lateral interphalangeal proximal collateral ligament.

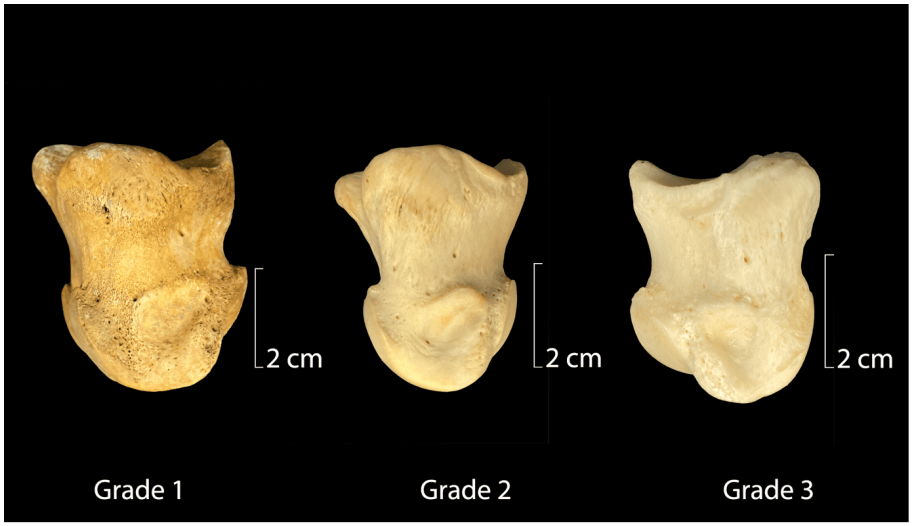



Plate C.28: Grading illustrations for the medial interphalangeal proximal collateral ligament.

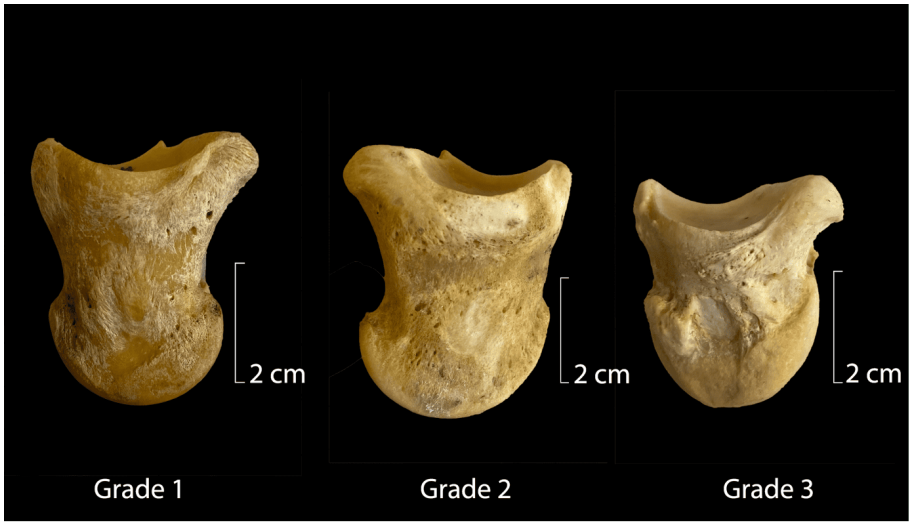



Plate C.29: Grading illustrations for the lateral interphalangeal distal collateral ligament.

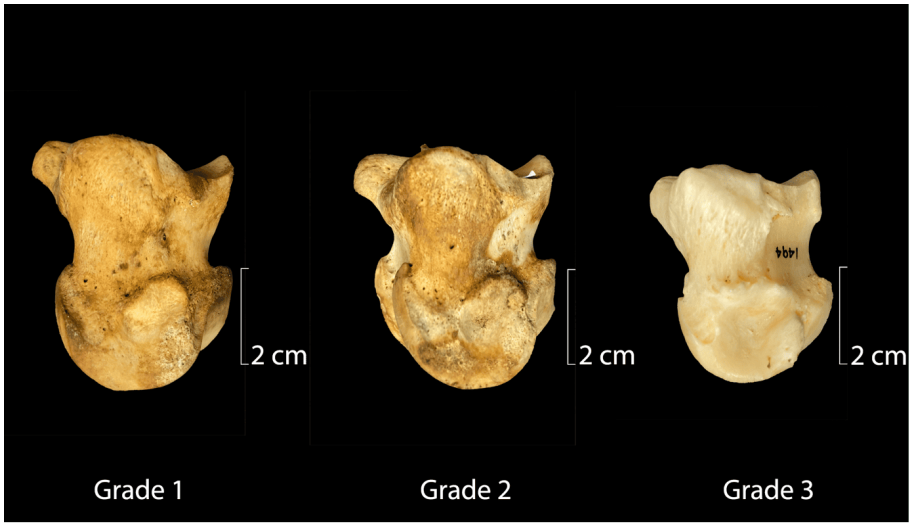



Plate C.30: Grading illustrations for the medial interphalangeal distal collateral ligament.

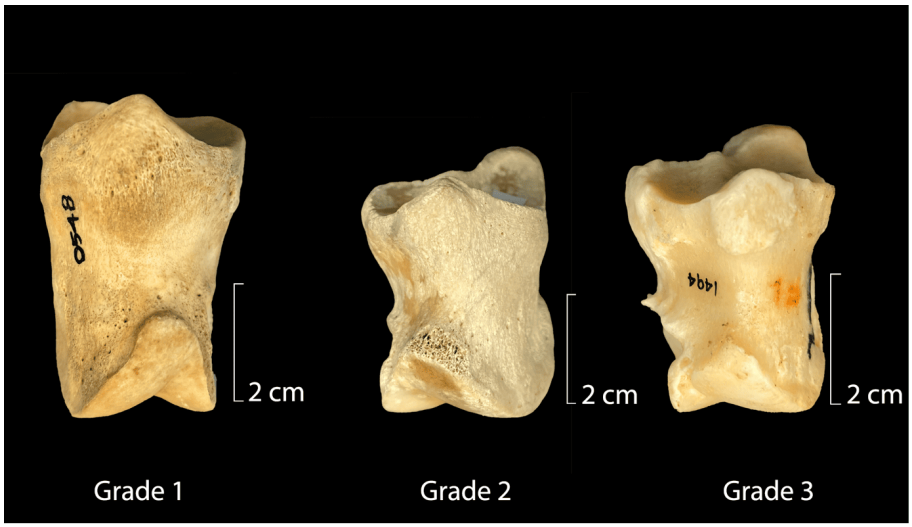



Plate C.31: Grading illustrations for the extensor digitorum communis.

# D

# BIOMETRIC RESULTS FROM THE ARCHAEOLOGICAL SITES

Refer to Table 5.5 for the abbreviations of the measurements. Metric data of archaeological sites can be downloaded from Mendeley Data (DOI: 10.17632/6zd6tswk8f).

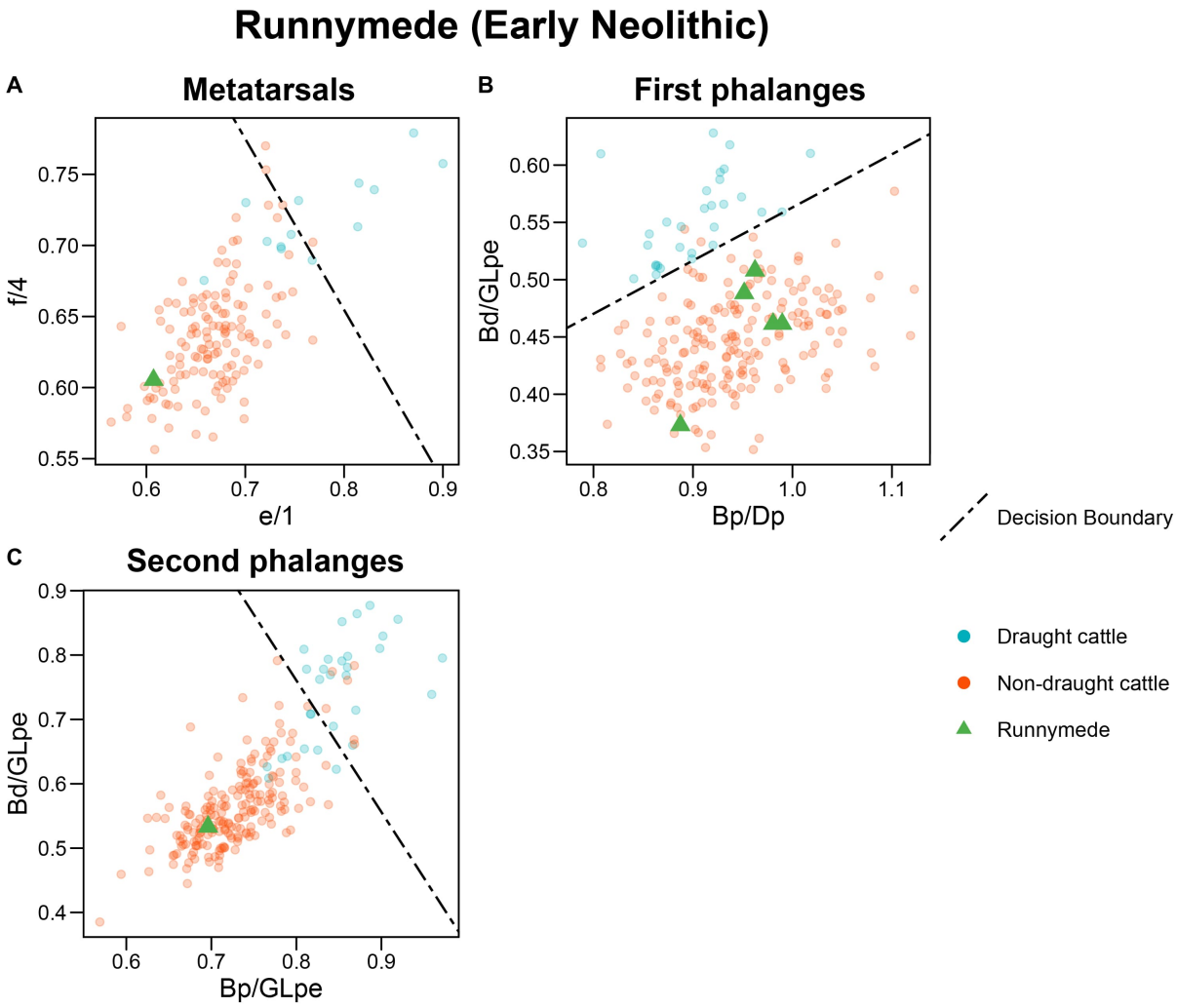



Figure D.1: Biometric results of Runnymede (Early Neolithic).

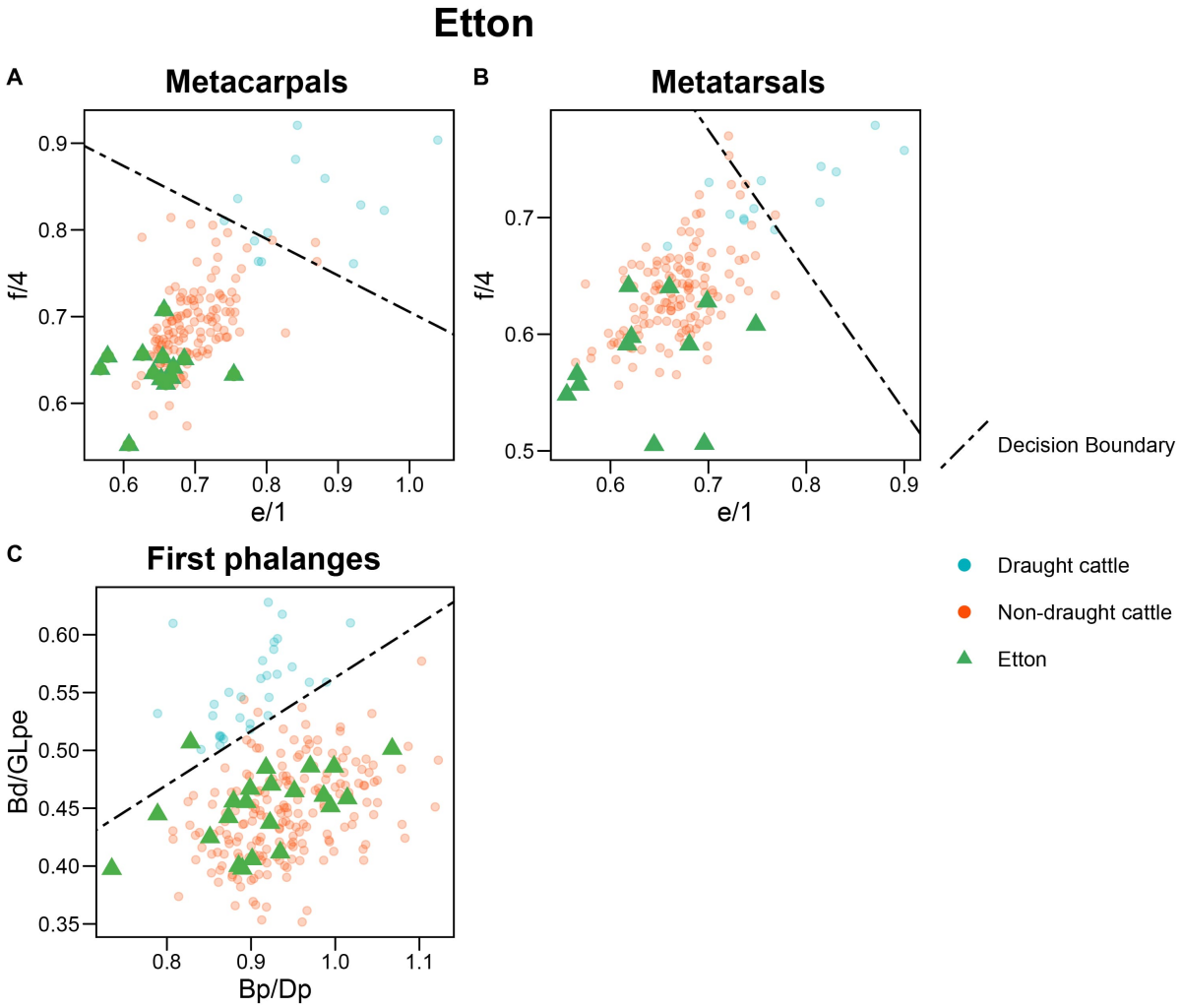



Figure D.2: Biometric results of Etton.

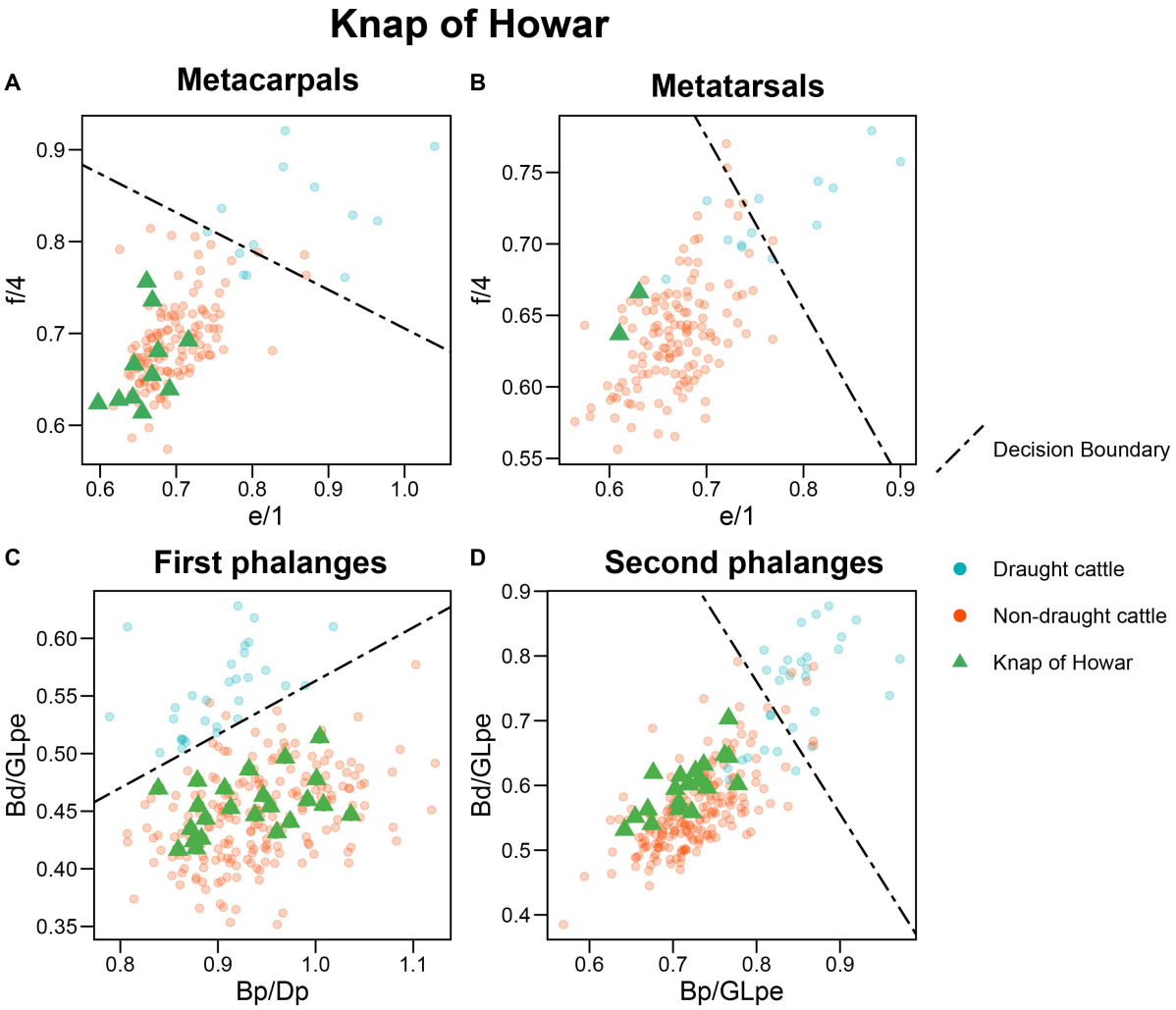



Figure D.3: Biometric results of Knap of Howar.

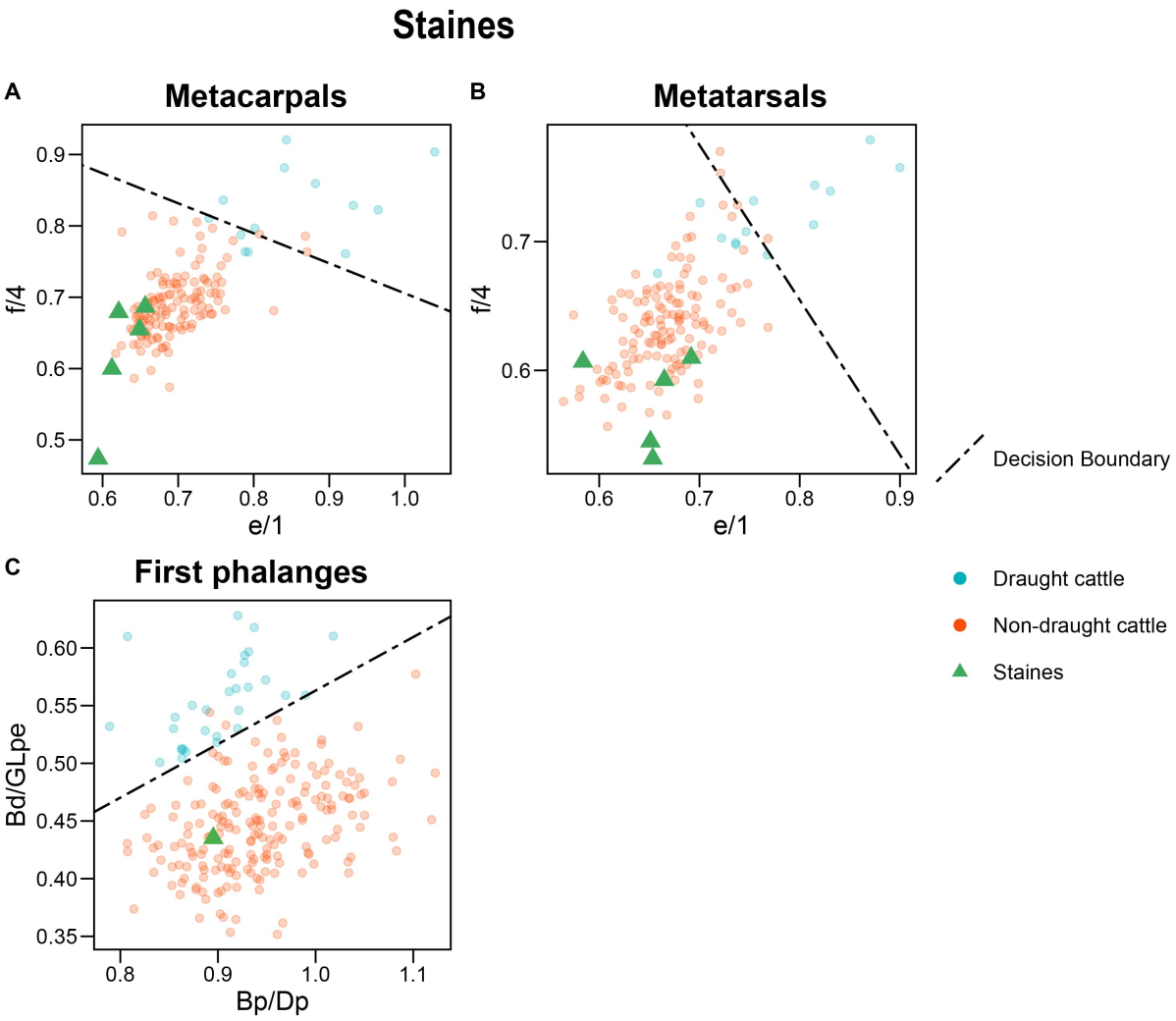



Figure D.4: Biometric results of Staines.

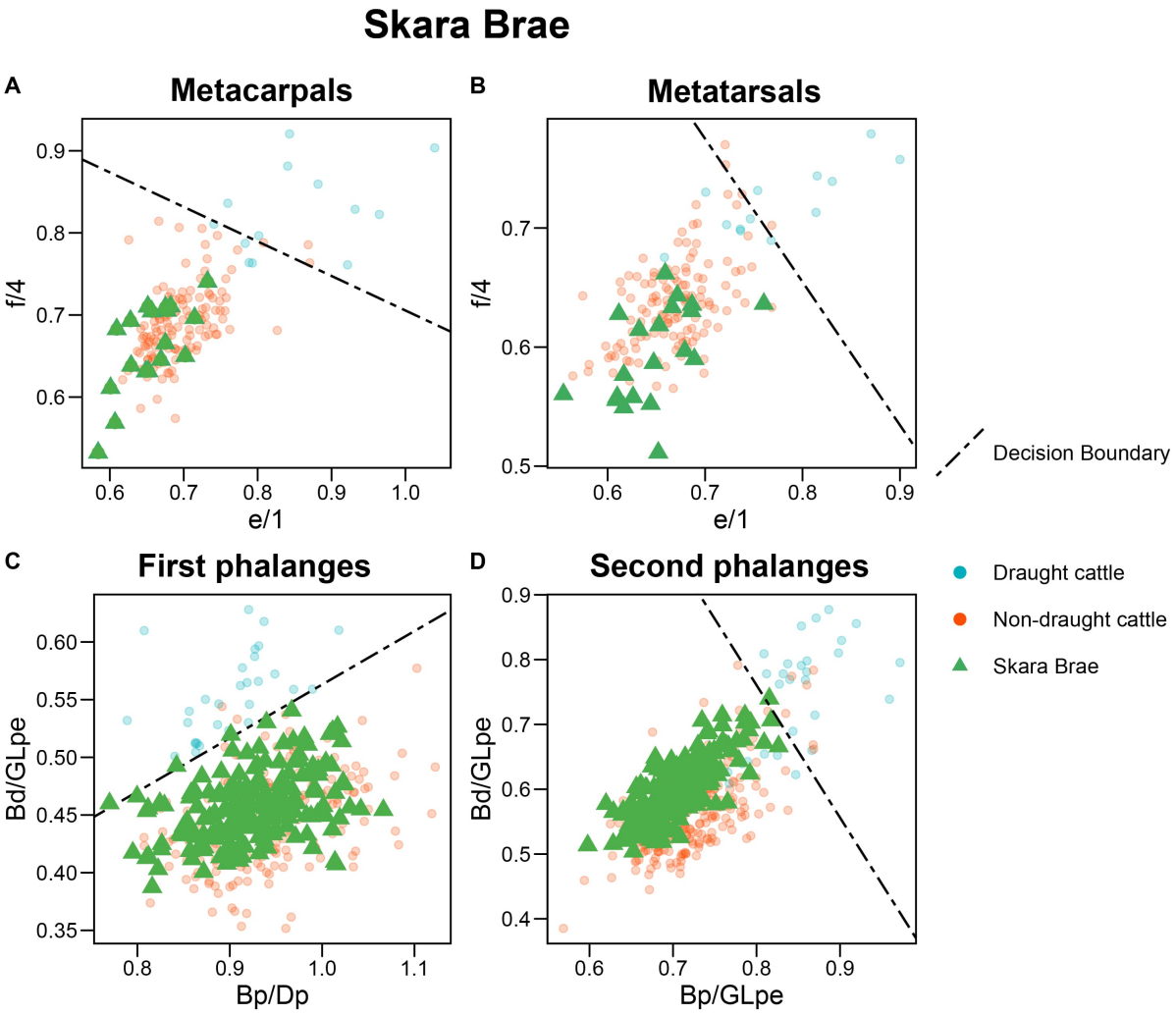



Figure D.5: Biometric results of Skara Brae.

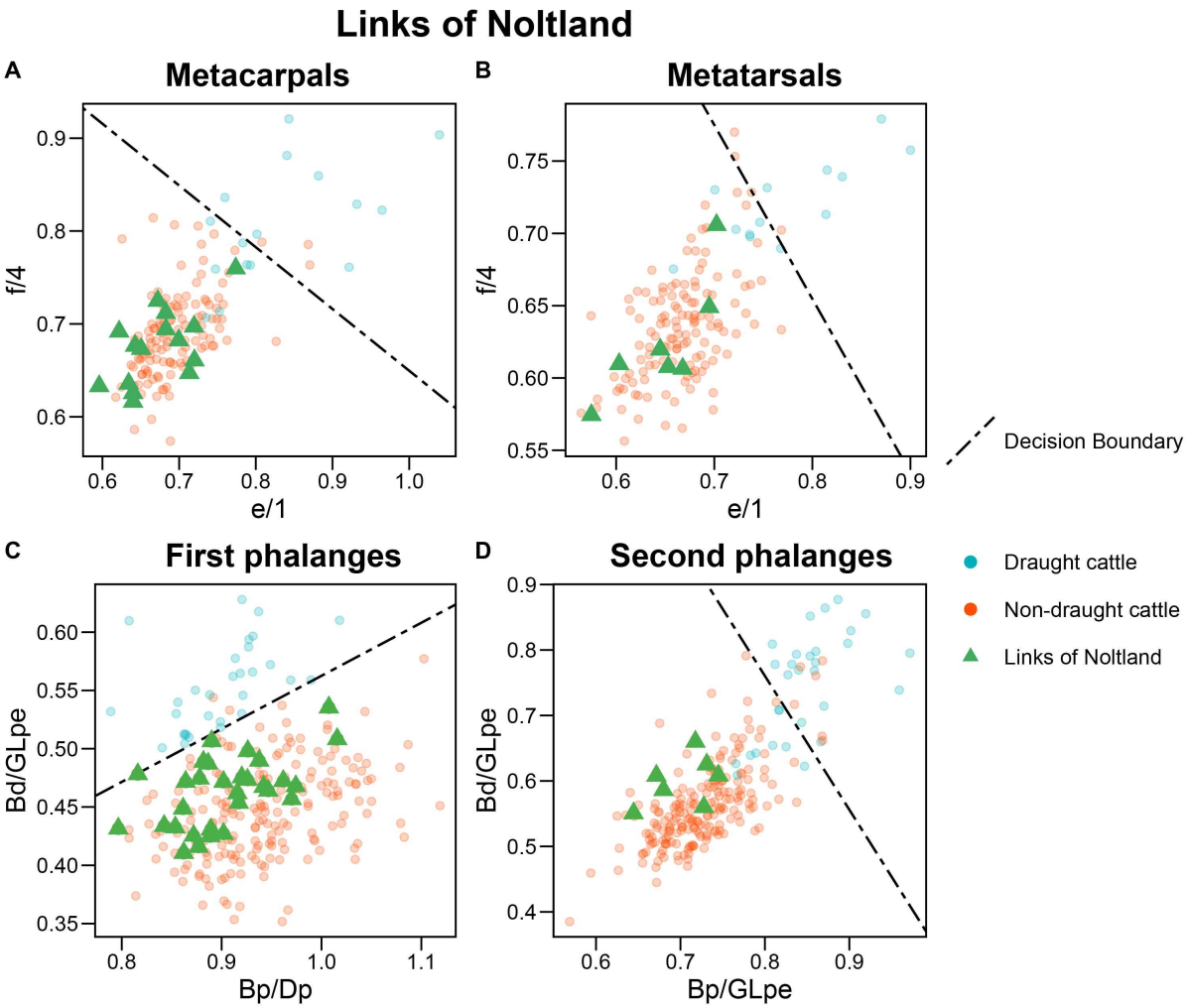



Figure D.6: Biometric results of Links of Noltland.

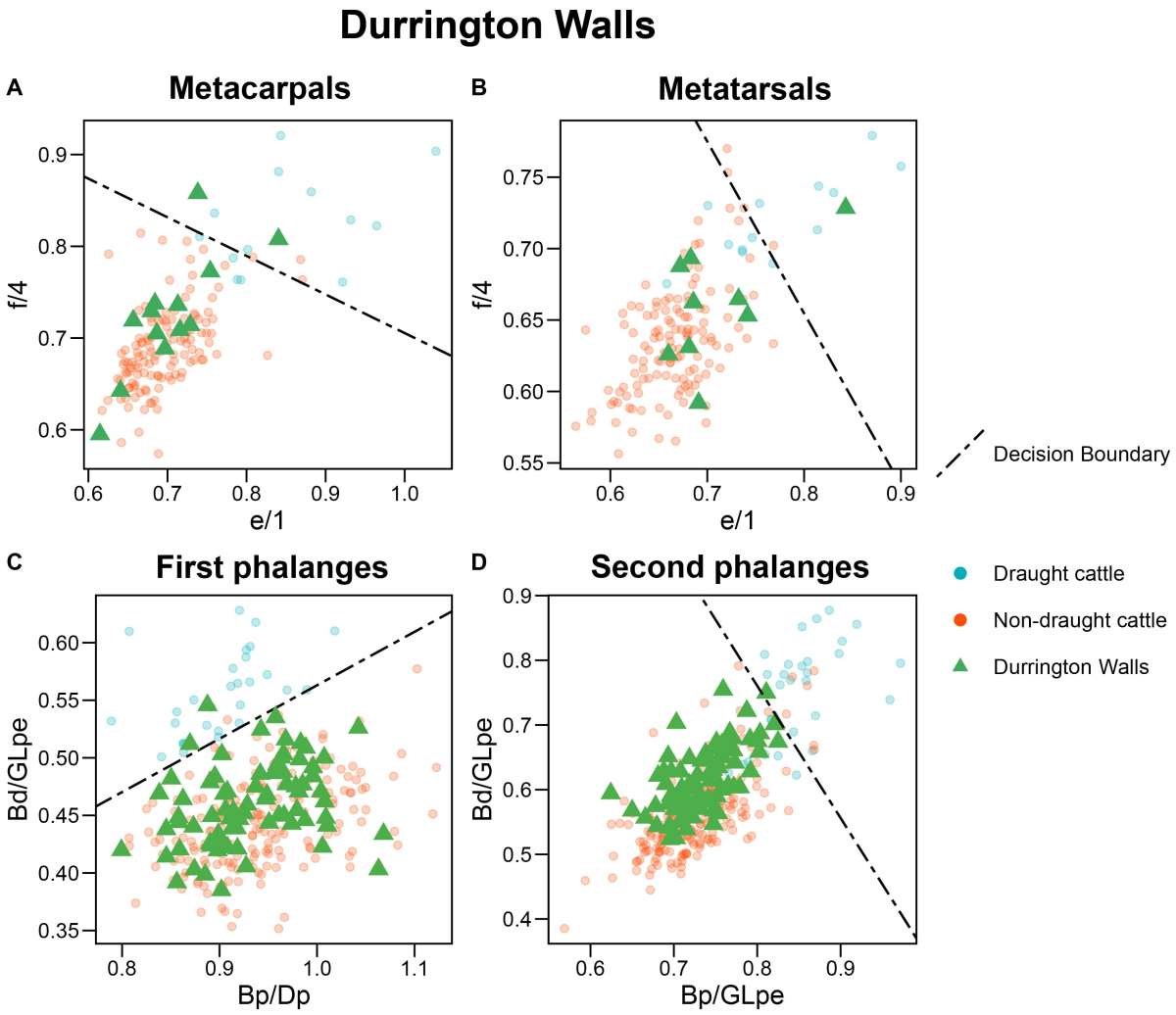



Figure D.7: Biometric results of Durrington Walls.

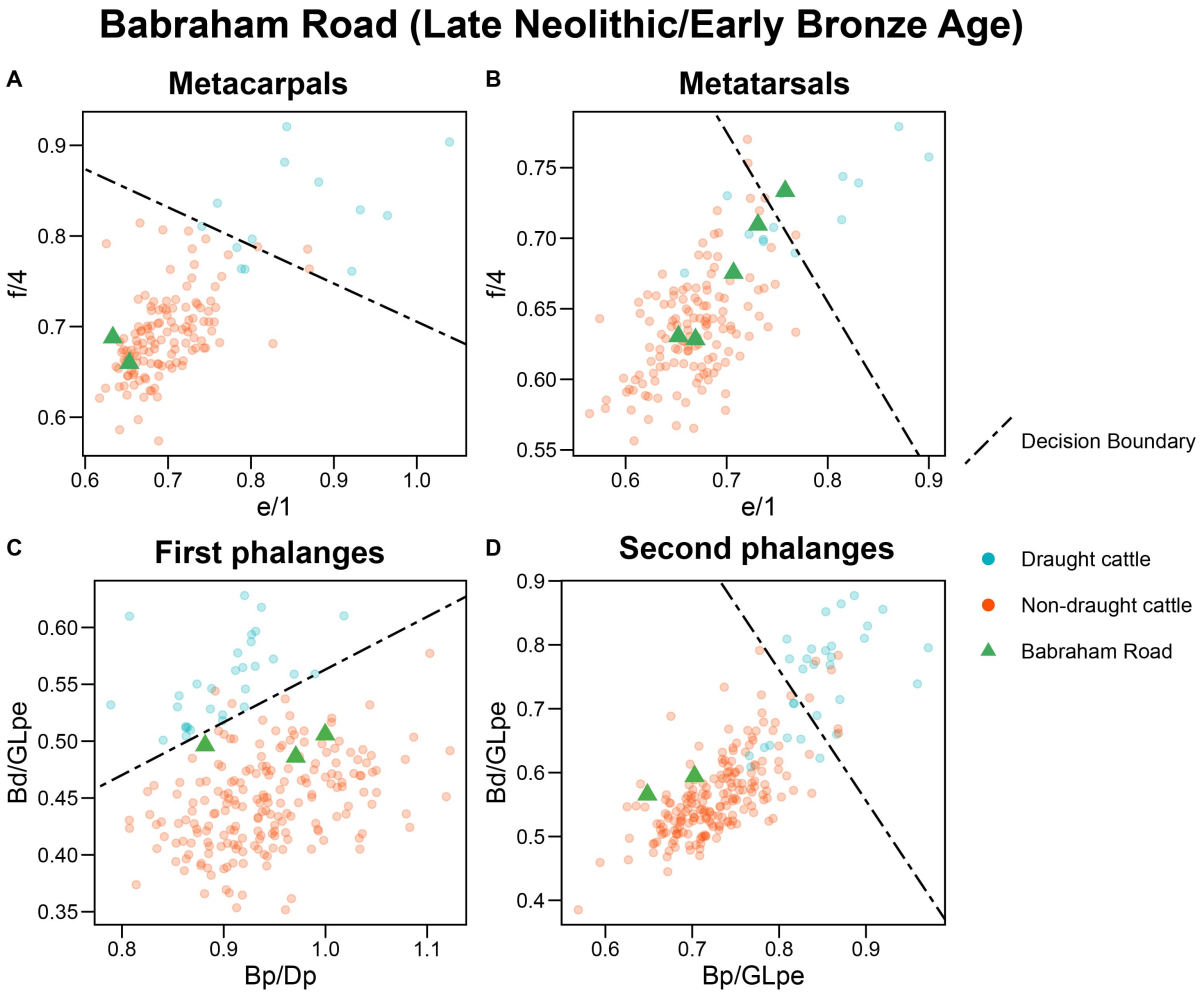



Figure D.8: Biometric results of Babraham Road (Late Neolithic/Early Bronze Age).

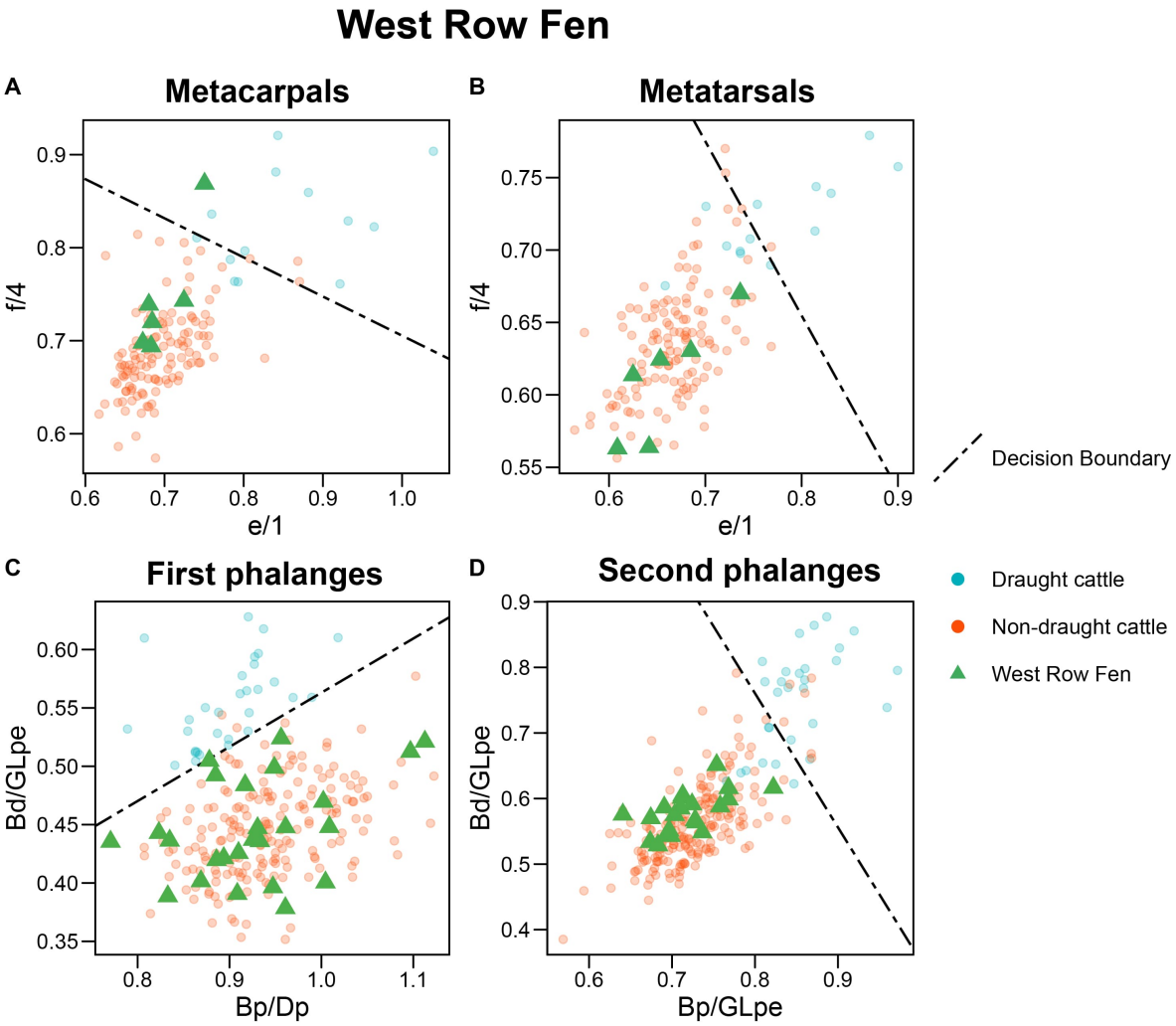



Figure D.9: Biometric results of West Row Fen.

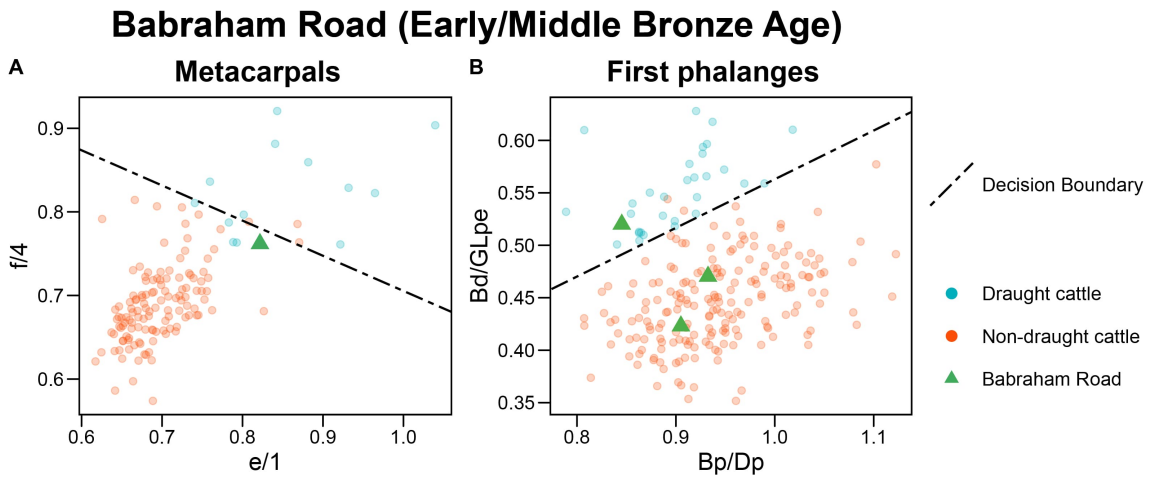



Figure D.10: Biometric results of Babraham Road (Early/Middle Bronze Age).

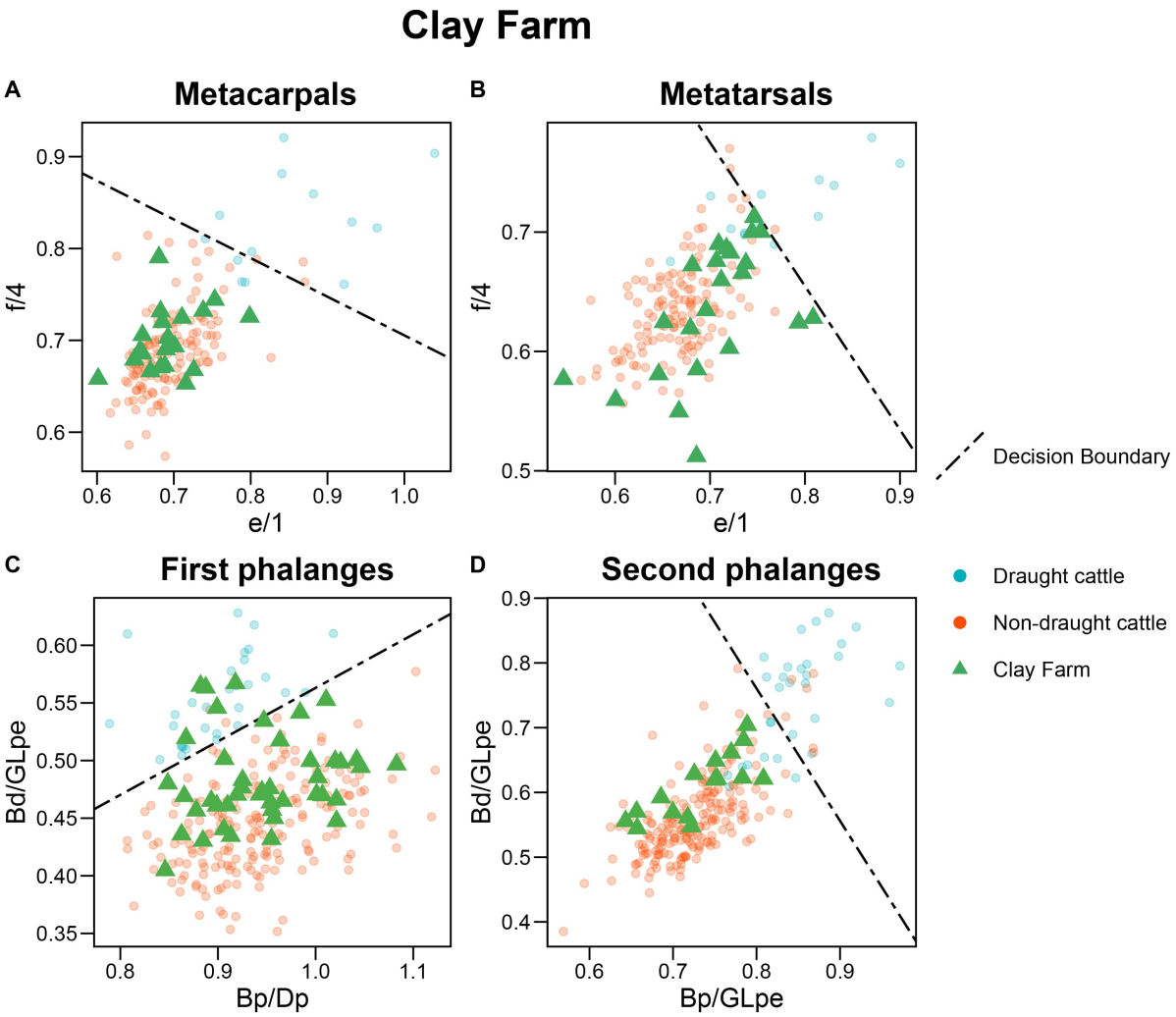



Figure D.11: Biometric results of Clay Farm.

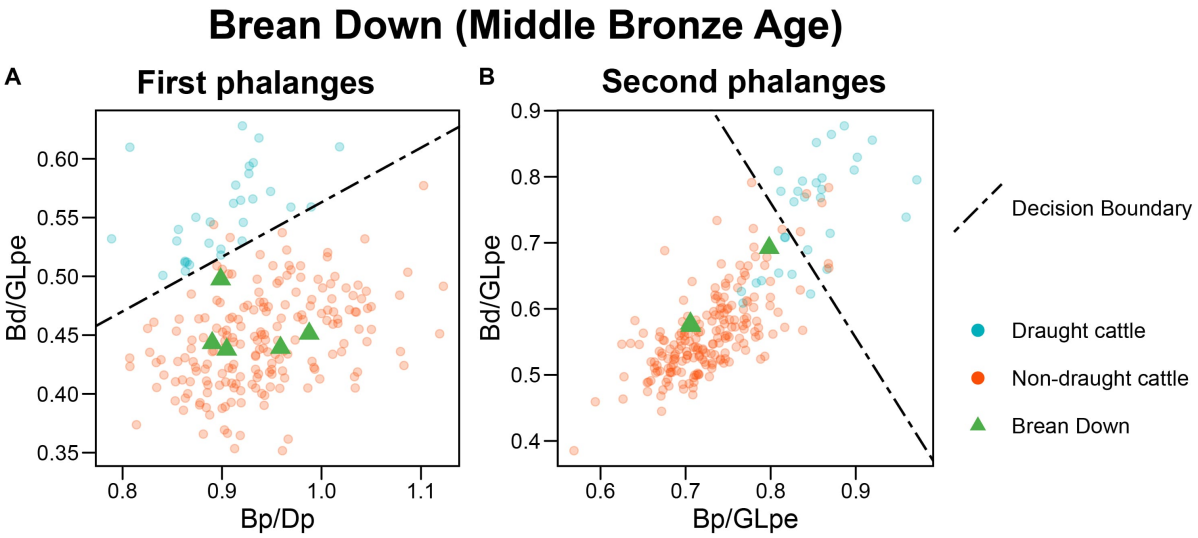



Figure D.12: Biometric results of Brean Down (Middle Bronze Age).

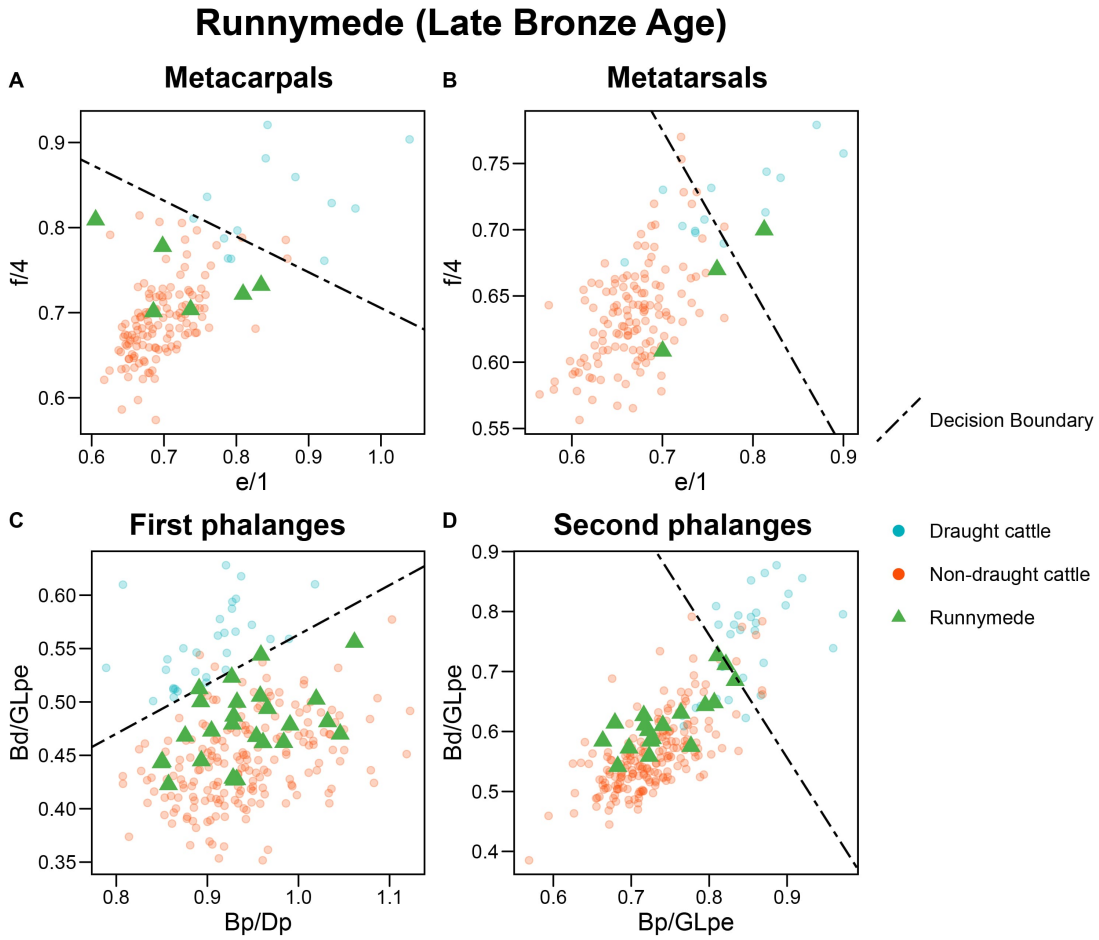



Figure D.13: Biometric results of Runnymede (Late Bronze Age).

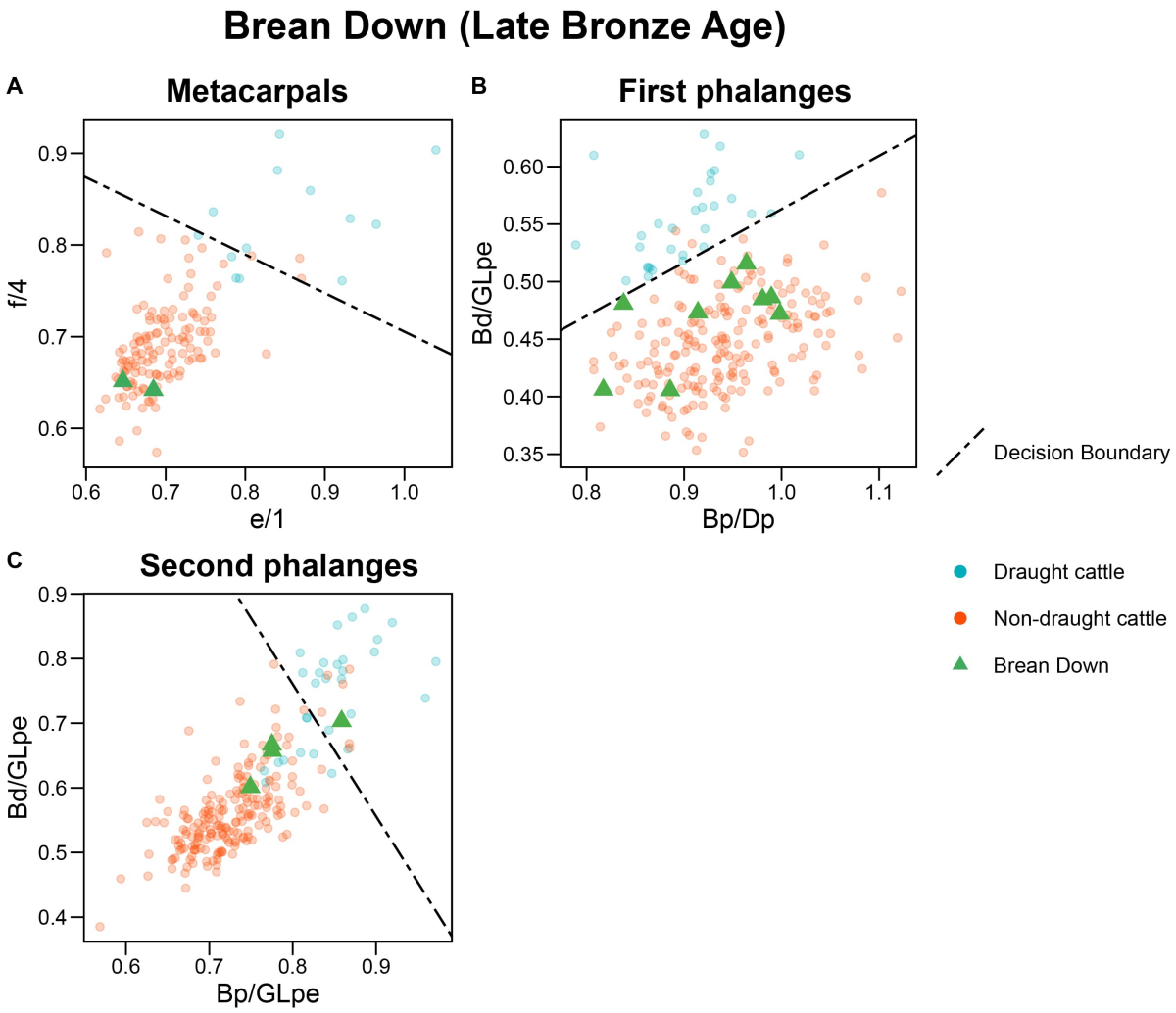



Figure D.14: Biometric results of Brean Down (Late Bronze Age).

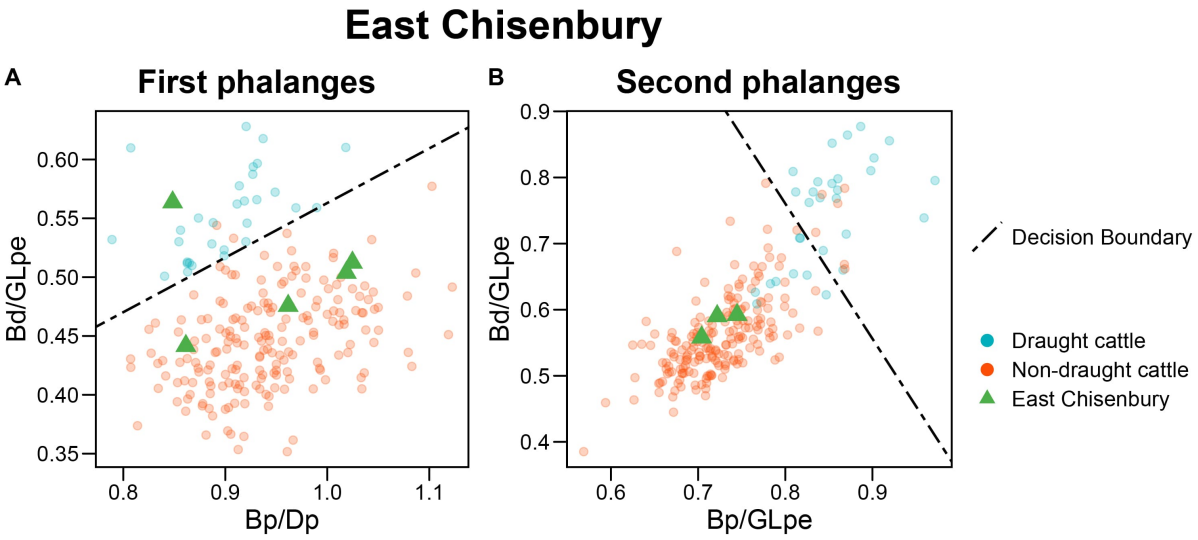



Figure D.15: Biometric results of East Chisenbury.

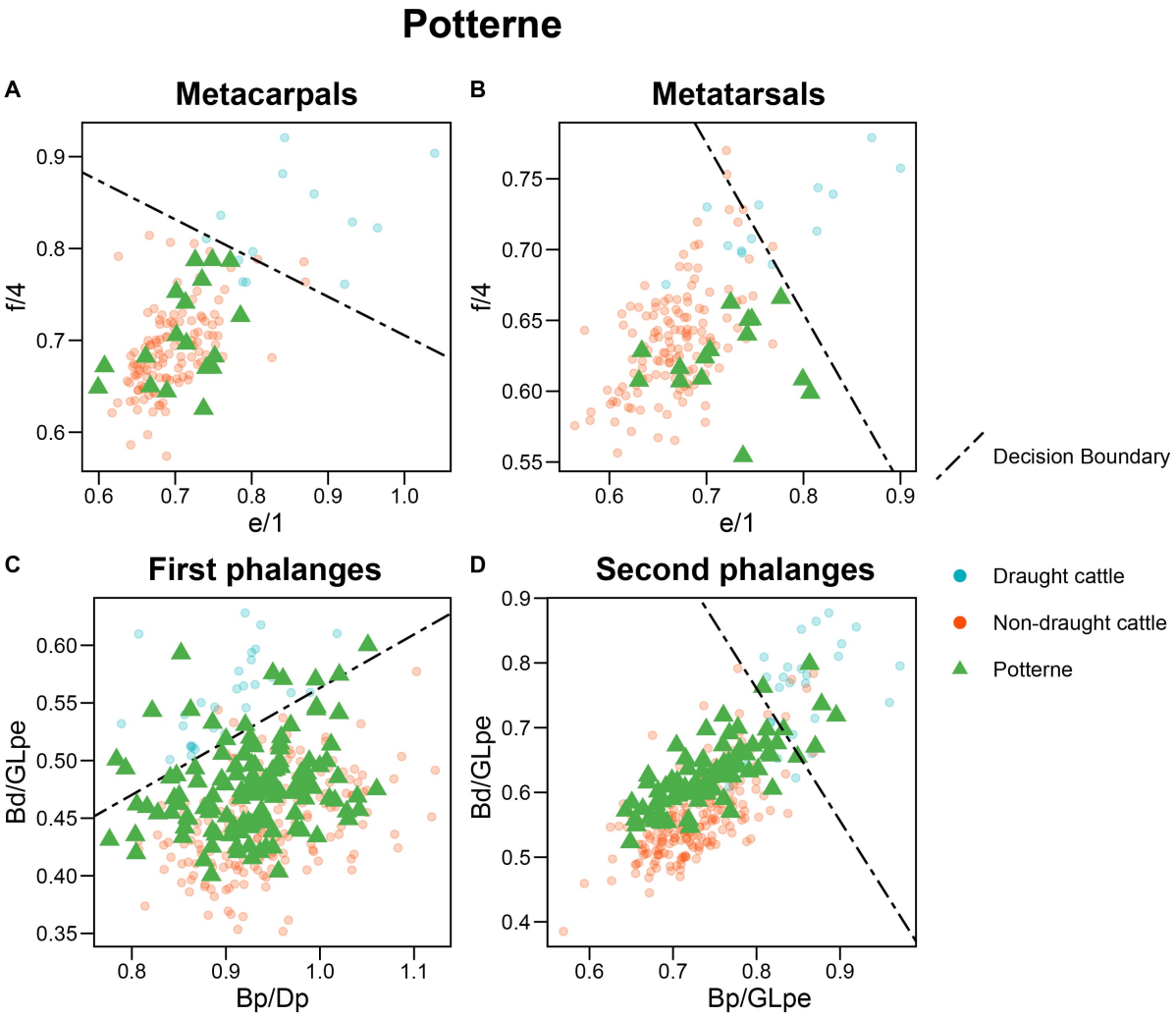



Figure D.16: Biometric results of Potterne.

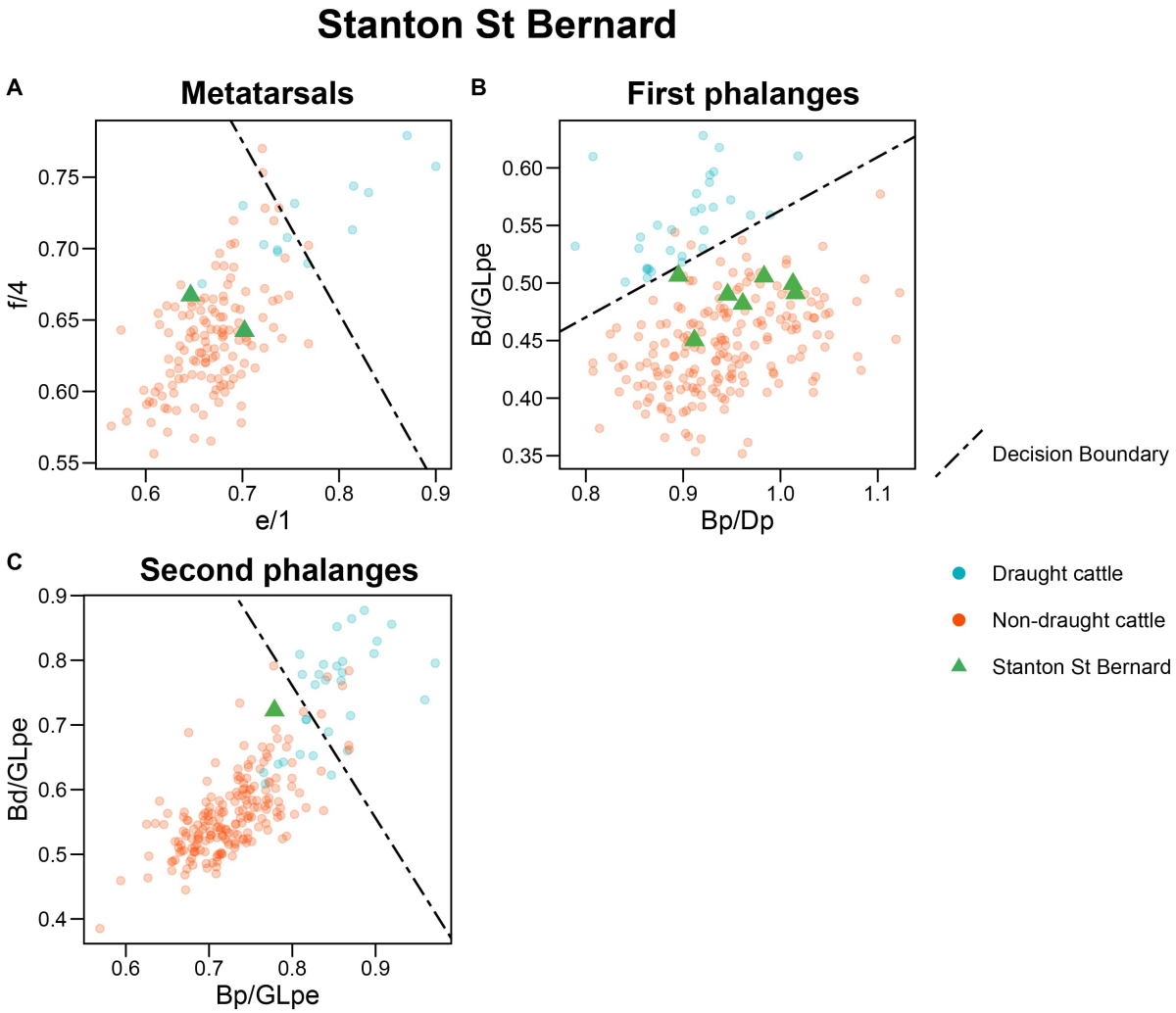



Figure D.17: Biometric results of Stanton St Bernard.

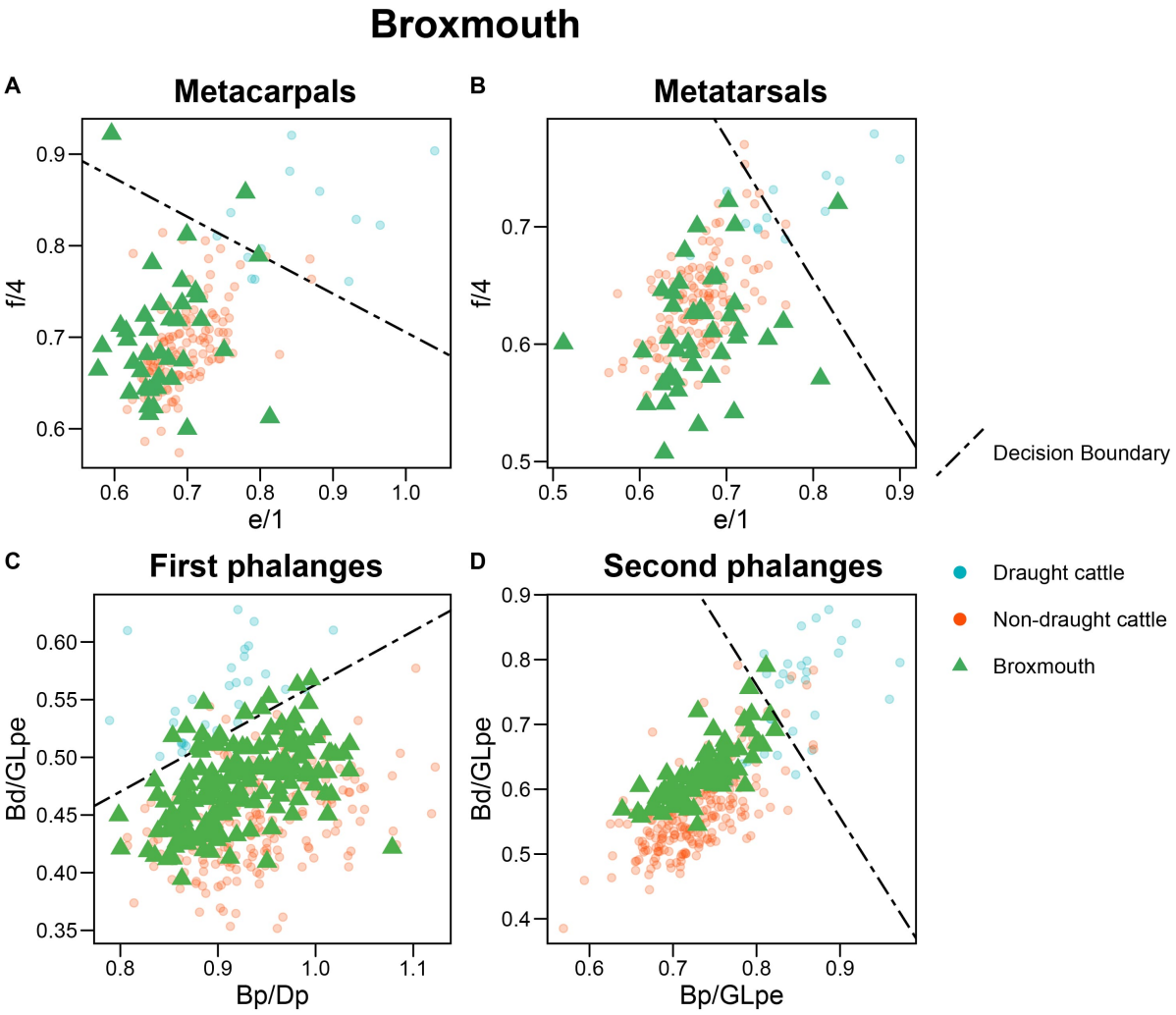



Figure D.18: Biometric results of Broxmouth.

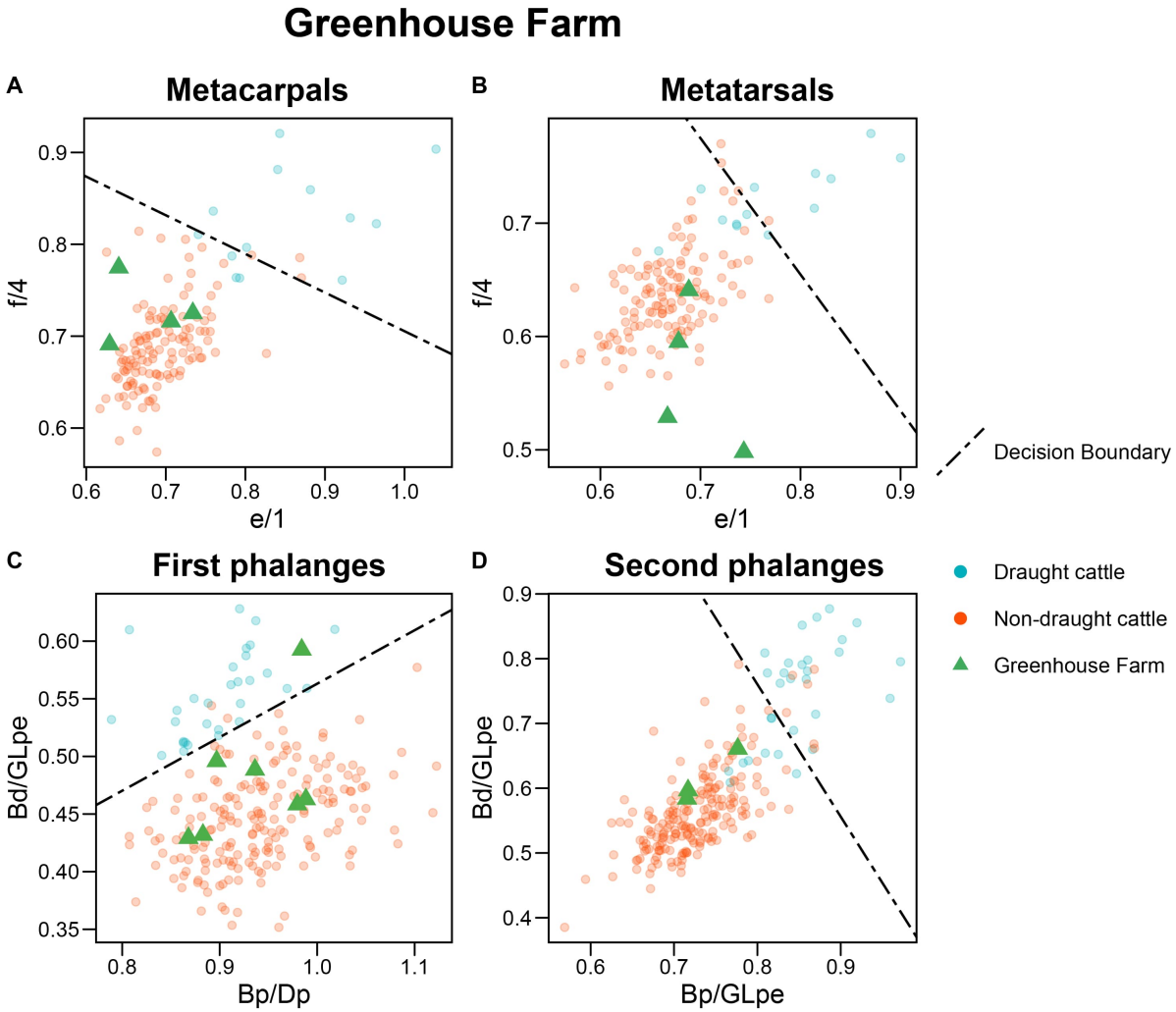



Figure D.19: Biometric results of Greenhouse Farm.

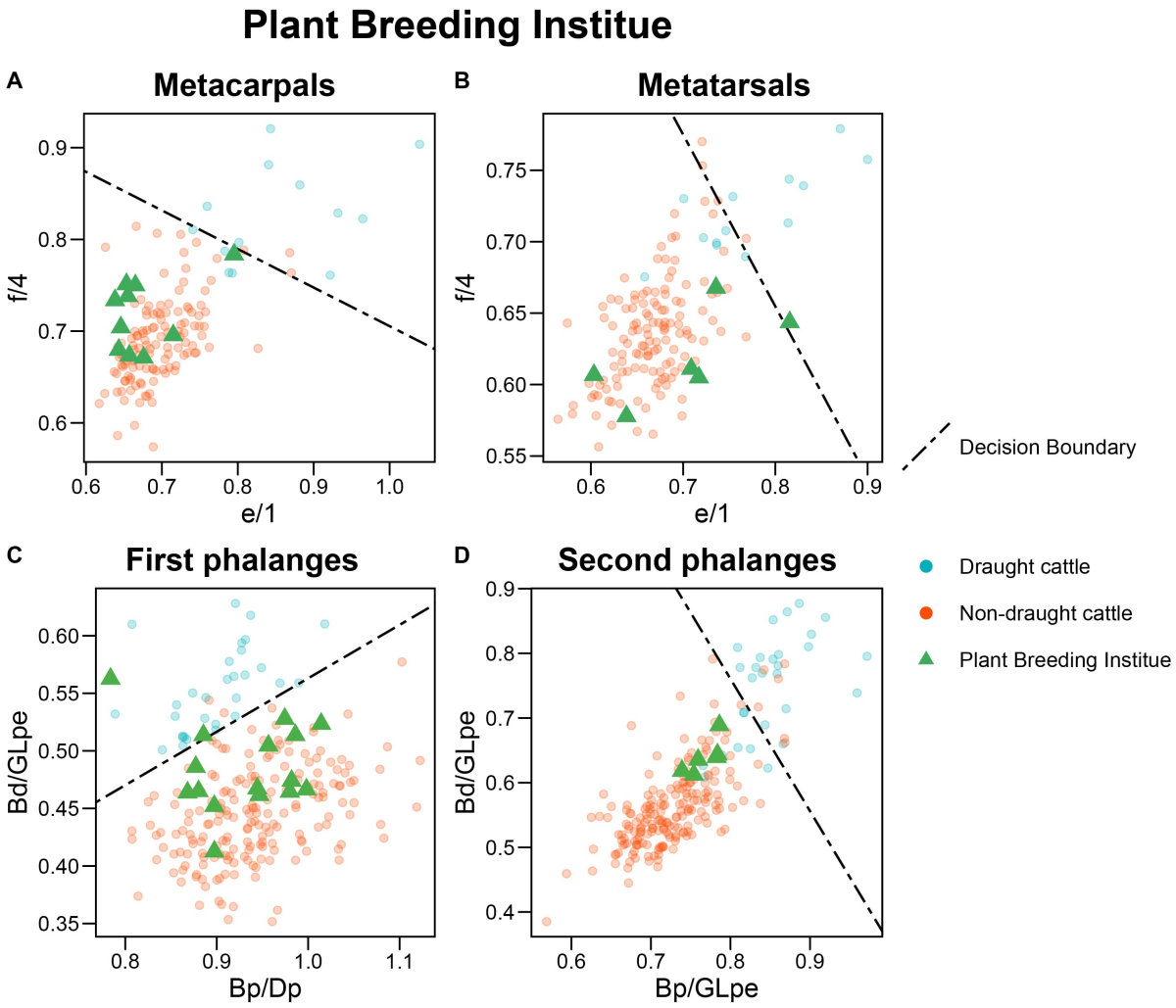



Figure D.20: Biometric results of Plant Breeding Institute.

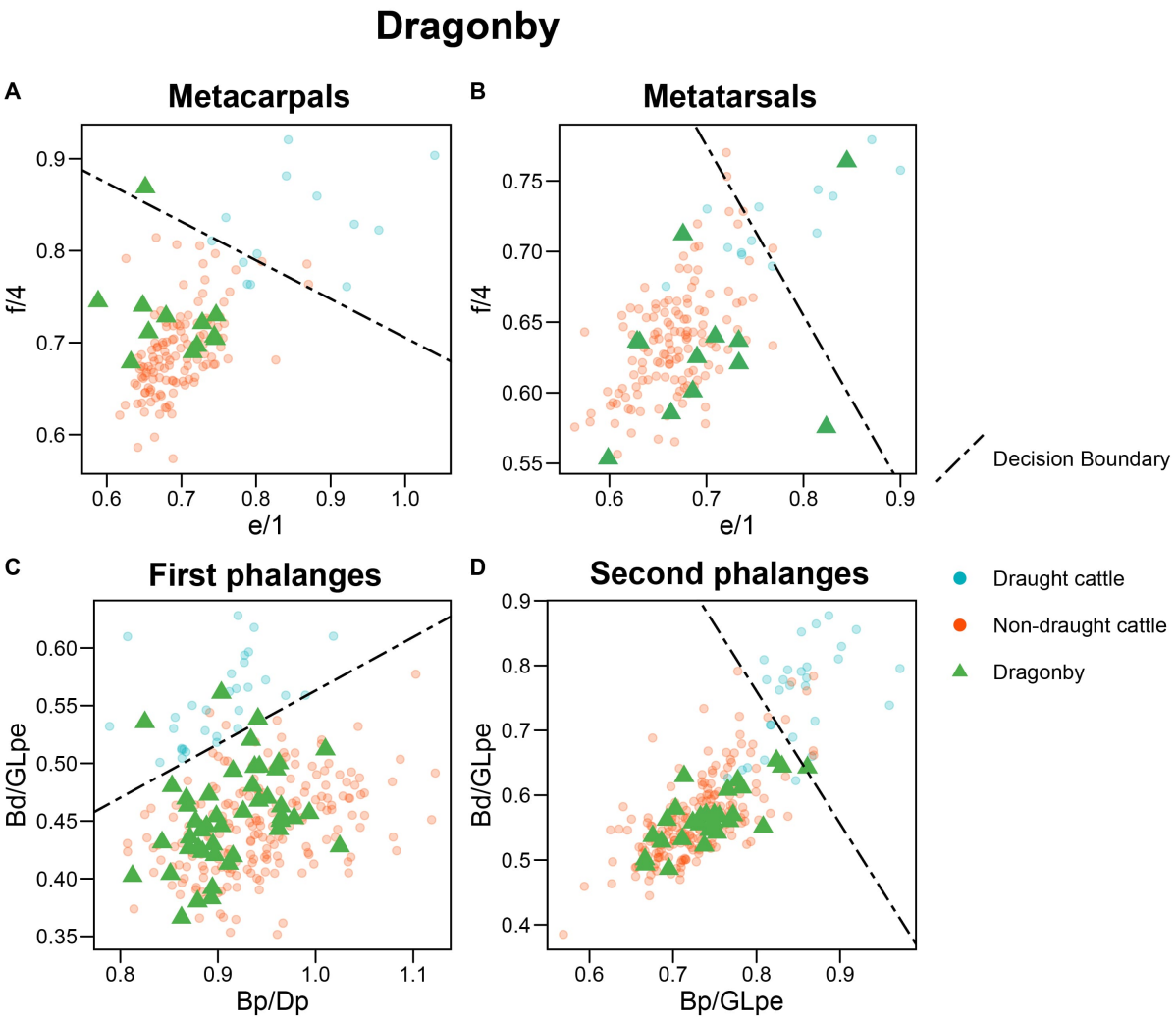



Figure D.21: Biometric results of Dragonby.

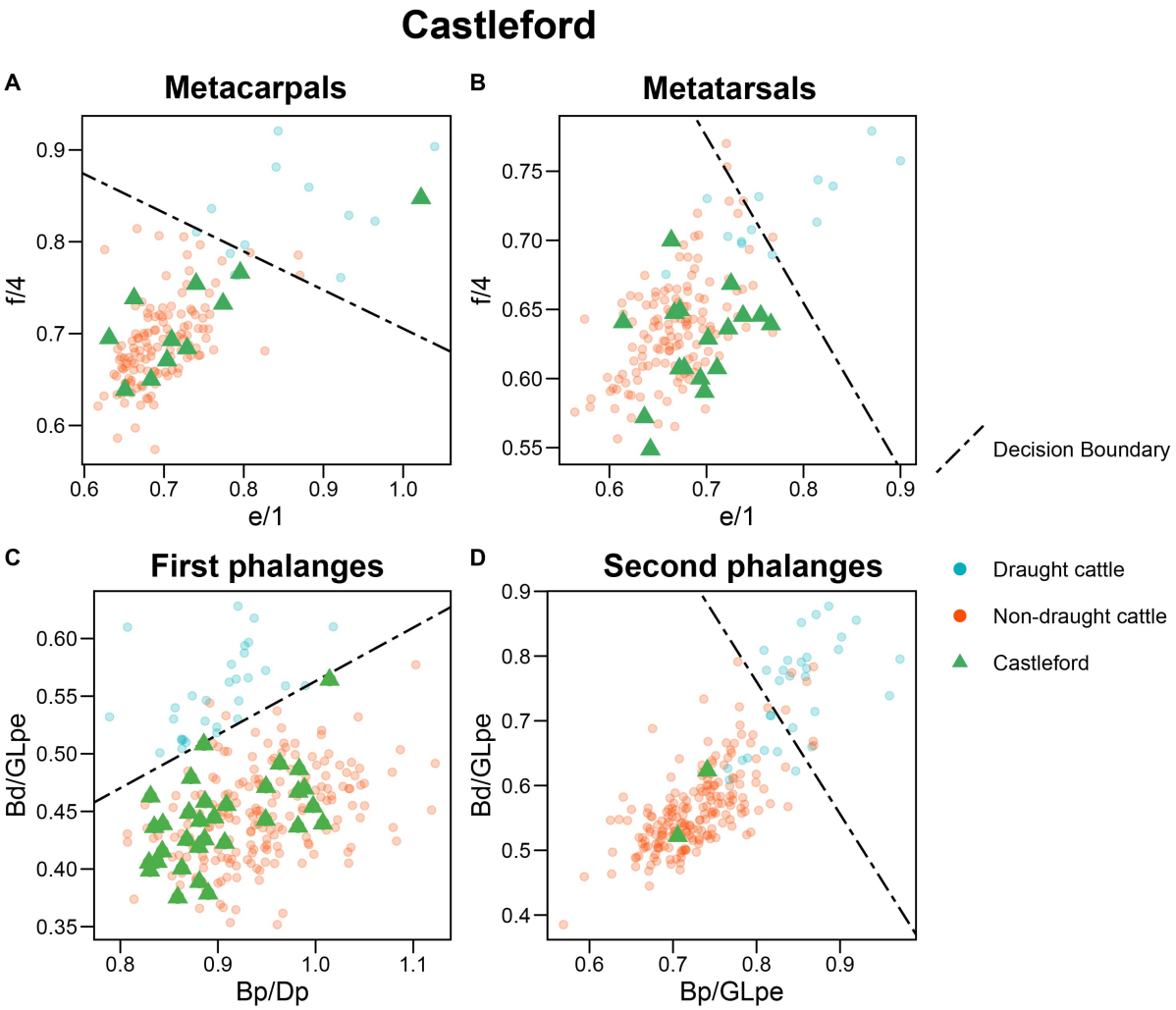



Figure D.22: Biometric results of Castleford.

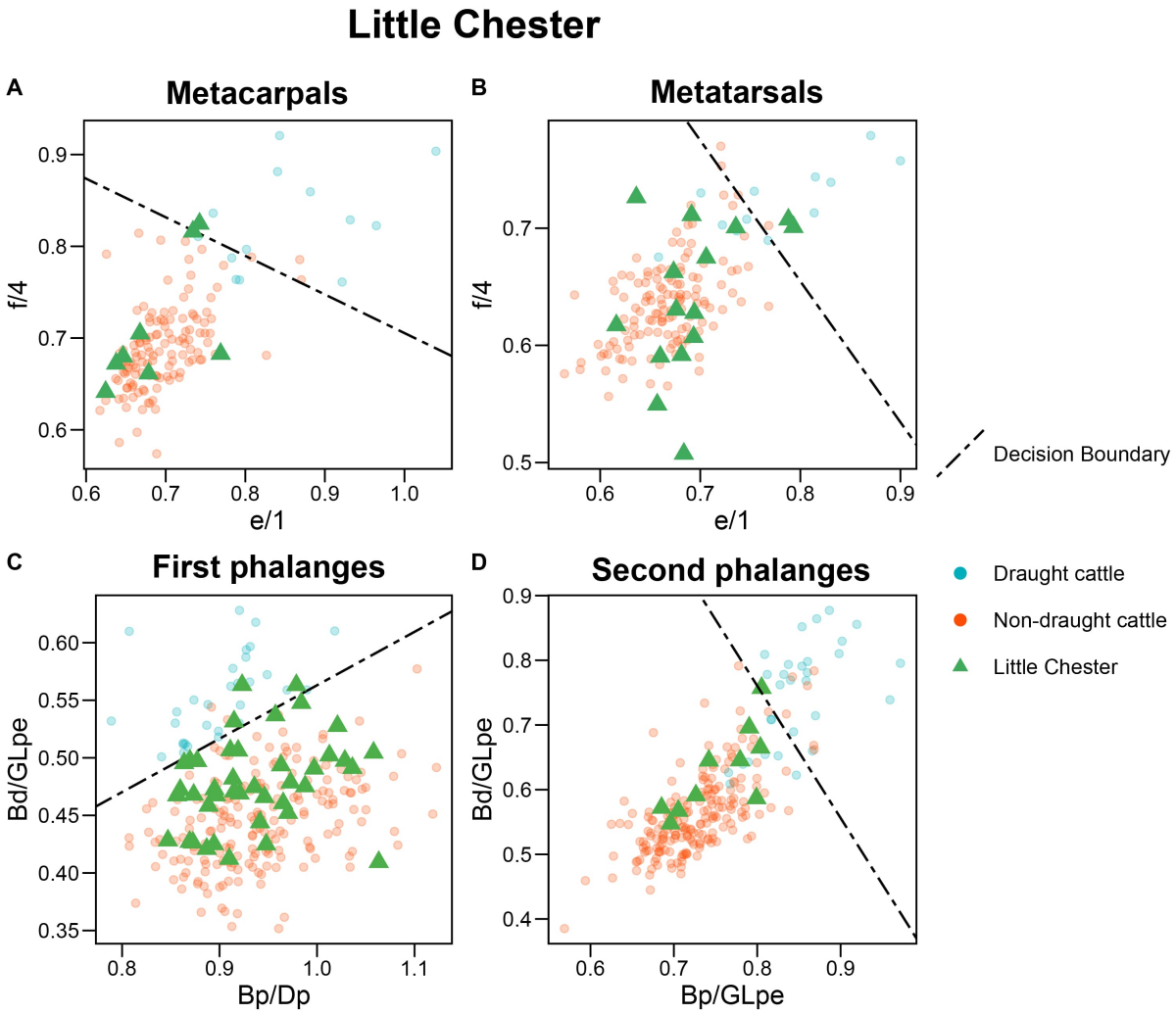



Figure D.23: Biometric results of Little Chester.

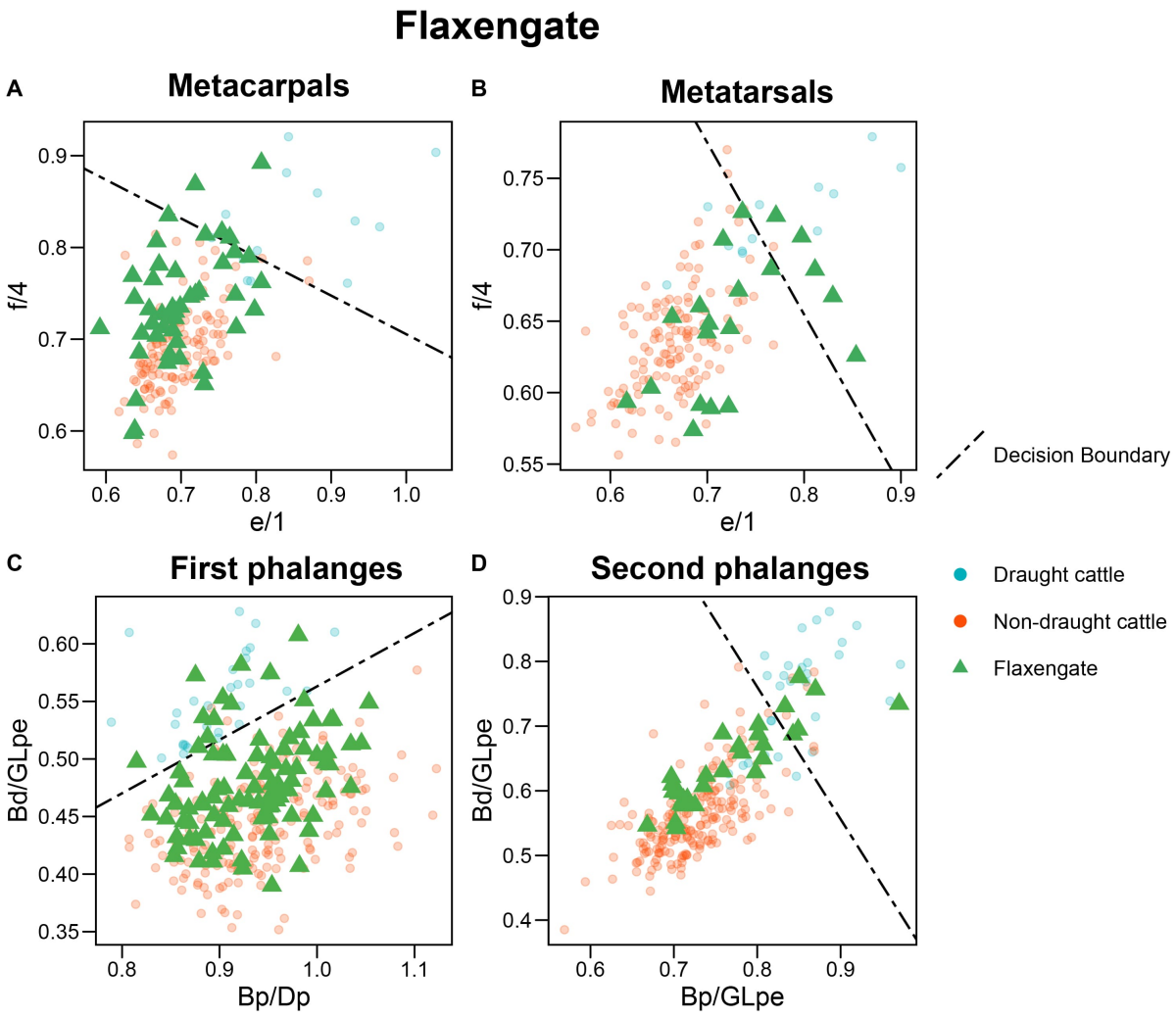



Figure D.24: Biometric results of Flaxengate.

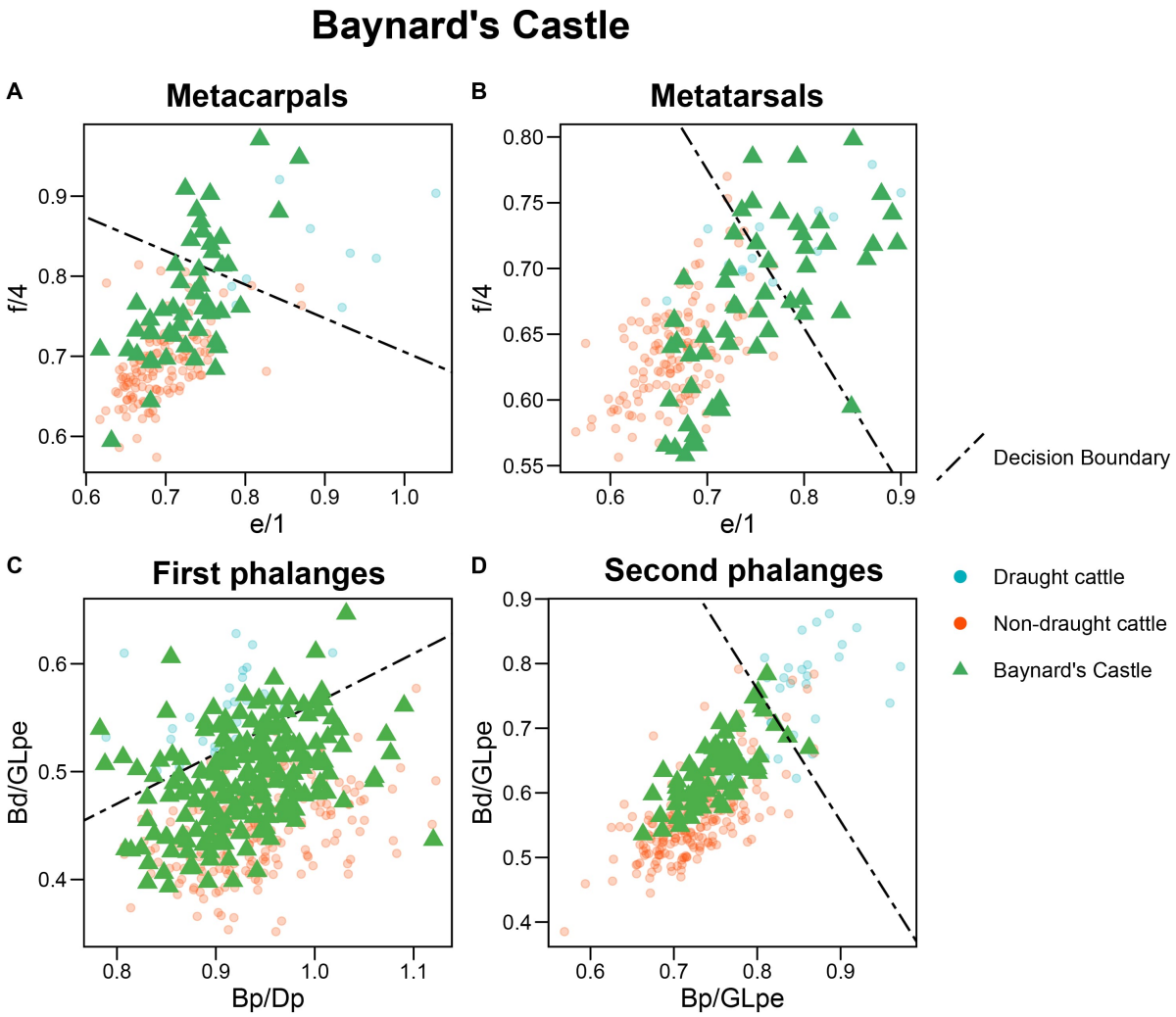



Figure D.25: Biometric results of Baynard's Castle.

# REFERENCES


Aarden, E. M., Nijweide, P. J., and Burger, E. H. (1994). "Function of Osteocytes in Bone". *Journal of Cellular Biochemistry* 55.3, pp. 287–299. DOI: 10.1002/jcb.240550304.

Abramson, P., Berg, D., and Fossick, M. (1999). *Roman Castleford. 2: The structural and environmental evidence*. Yorkshire archaeology 5. Wakefield: West Yorkshire Archaeology Service.

Albarella, U. (1995). "Depressions on Sheep Horncores". *Journal of Archaeological Science* 22.5, pp. 699–704. DOI: 10.1016/S0305-4403(95)80155-3.

— (1997). "Shape Variation of Cattle Metapodials: Age, Sex or Breed? Some Examples from Medieval and Postmedieval Sites". *Anthropozoologica* 25–26, pp. 37–47.

— (2019). *A Review of Animal Bone Evidence from Central England*. Research Report Series 61/2019. Portsmouth: Historic England.

Albarella, U., Beech, M., and Mulville, J. (1997). "The Saxon, Medieval and Post-Medieval Mammal and Bird Bones Excavated 1989-91 from Castle Mall, Norwich, Norfolk". *London: English Heritage*, p. 24.

Anati, E. (1961). *Camonica Valley: A Depiction of Village Life in the Alps from Neolithic Times to the Birth of Christ as Revealed by Thousands of Newly Found Rock Carvings*. Alfred A. Knopf, New York.

Anderson, P. C. (2003). "Observations on the Threshing Sledge and Its Products in Ancient and Present-Day Mesopotamia". In: *Le Traitement Des Récoltes: Un Regard Sur La Diversité Du Néolithique Au Prese*. Ed. by P. C. Anderson and L. Cummings. Antibes, Éditions APDCA, pp. 299–316.

Angel, J. L., Kelley, J. O., Parrington, M., and Pinter, S. (1987). "Life Stresses of the Free Black Community as Represented by the First African Baptist Church, Philadelphia, 1823–1841". *American Journal of Physical Anthropology* 74.2, pp. 213–229. DOI: 10.1002/ajpa.1330740209.

Anthony, D. W. (2007). *The Horse, the Wheel, and Language: How Bronze-Age Riders from the Eurasian Steppes Shaped the Modern World*. Princeton, N.J: Princeton University Press.

Apostolakos, J., Durant, T., Dwyer, C., Russell, R., Weinreb, J., Alaee, F., Beitzel, K., McCarthy, M., Cote, M., and Mazzocca, A. (2019). "The Enthesis: A Review of the Tendon-to-Bone Insertion". *Muscle Ligaments and Tendons Journal* 04.03, p. 333. DOI: 10.32098/mltj.03.2014.12.

Arbogast, R., Pétrequin, P., Pétrequin, A.-M., Maréchal, D., and Viellet, A. (2003). "Instances of Animal Traction in the Neolithic Village of Chalain (Jura, France). End of the 31st Century BC." *Archaeofauna* 12, pp. 175–181.

Armit, I. and McKenzie, J. (2013). *An inherited place: Broxmouth Hillfort and the south-east Scottish Iron Age*. Ed. by P. Hill and T. B. Ballin. Monographs of the Society of Antiquaries of Scotland. Edinburgh: Society of Antiquaries of Scotland.

Armitage, P. (1977). "The mammalian remains from the Tudor site of Baynard's Castle, London: A biometrical and historical analysis". PhD thesis. Royal Holloway College, London. British Museum (Natural History).

Armour-Chelu, M. and Clutton-Brock, J. (1985). "Notes on the Evidence for the Use of Cattle as Draught Animals at Etton". *An Interim Report on Excavations*

*at Etton, Maxey, Cambridgeshire, 1982–1984*. Ed. by F. Pryor, C. French, and M. Taylor, pp. 297–302.
Armour-Chelu, M. (1998). "The Animal Bone". In: Pryor, F. *Etton Excavations at a Neolithic Causewayed Enclosure near Maxey Cambridgeshire, 1982-7*. DGO - Digital original. Swindon: Historic England, pp. 273–288.
Ashbee, P. (1966). "I.—The Fussell's Lodge Long Barrow Excavations 1957". *Archaeologia* 100, pp. 1–80. DOI: 10.1017/S0261340900013709.
Ashbee, P., Smith, I. F., and Evans, J. G. (1979). "Excavation of Three Long Barrows near Avebury, Wiltshire". *Proceedings of the Prehistoric Society* 45, pp. 207–300. DOI: 10.1017/S0079497X00009762.
Baker, J. R. (1984). "The Study of Animal Diseases with Regard to Agricultural Practices and Man's Attitude to His Animals." In: *Animals and Archaeology: 4. Husbandry in Europe*. Ed. by J. Clutton-Brock and C. Grigson. British Archaeological Reports International Series 227. Oxford: B.A.R, pp. 253–257.
Baker, J. R. and Brothwell, D. (1980). *Animal Diseases in Archaeology*. Studies in Archaeological Science. London ; New York: Academic Press.
Bakker, J. A., Kruk, J., Lanting, A. E., and Milisauskas, S. (1999). "The Earliest Evidence of Wheeled Vehicles in Europe and the Near East". *Antiquity* 73.282, pp. 778–790. DOI: 10.1017/S0003598X00065522.
Bakker, J. A., Vogel, J. C., and Wiślański, T. (1969). *TRB and Other C-14 Dates from Poland*. Helinium.
Balasescu, A., Moise, D., and Radu, V. (2006). "Une utilisation des bovins pour la traction pendant le Chalcolithique en Roumanie?" In: *Premiers chariots, premiers araires: La diffusion de la traction animale en Europe pendant les IVe et IIIe millénaires avant notre ère*. Ed. by P. Pétrequin, R.-M. Arbogast, A.-M. Pétrequin, S. van Willigen, and M. Bailly. CRA monographies 29. Paris: CNRS éd, pp. 269–273.
Bamforth, M. (2024). "Chapter 13 - Wooden artefacts". In: *Must Farm pile-dwelling settlement: Volume 2. Specialist reports*. In collab. with Apollo-University Of Cambridge Repository and University Of Cambridge. McDonald Institute for Archaeological Research. DOI: 10.17863/CAM.107126.
Barbosa, J. D., Lima, D. H. S., Belo-Reis, A. S., Pinheiro, C. P., Sousa, M. G., Silva, J. B., Salvarani, F. M., and Oliveira, C. M. C. (2014). "Degenerative Joint Disease in Cattle and Buffaloes in the Amazon Region: A Retrospective Study". *Pesquisa Veterinária Brasileira* 34.9, pp. 845–850. DOI: 10.1590/S0100-736X2014000900007.
Barker, G. (1985). *Prehistoric Farming in Europe*. New Studies in Archaeology. Cambridge [Cambridgeshire] ; New York: Cambridge University Press.
Barker, G. and Webley, D. (1978). "Causewayed Camps and Early Neolithic Economies in Central Southern England". *Proceedings of the Prehistoric Society* 44, pp. 161–186. DOI: 10.1017/S0079497X00010112.
Barrett, J. C. and Needham, S. (1988). "Production, Circulation and Exchange: Problems in the Interpretation of Bronze Age Metalwork". In: *The Archaeology of Context in the Neolithic and Bronze Age: Recent Trends*. Ed. by J. C. Barrett. Recent Trends 3. Sheffield: Dep. of Archeology and Prehistory, pp. 127–140.
Barrett, J. C. (1980). "The Evolution of Later Bronze Age Settlement". In: Barrett, J. C. and Bradley, R. *Settlement and Society in the British Later Bronze Age*. BAR British Series 83. Oxford: B.A.R, pp. 77–100.
— ed. (1988). *The Archaeology of Context in the Neolithic and Bronze Age: Recent Trends*. Recent Trends 3. Sheffield: Department of Archeology and Prehistory.
— (1994). *Fragments from Antiquity: An Archaeology of Social Life in Britain, 2900-1200 BC*. Social Archaeology. Oxford: Blackwell.

Bartosiewicz, L. (2008). "Bone Structure and Function in Draft Cattle". In: *Limping Together through the Ages : Joint Afflictions and Bone Infections*. Ed. by G. Grupe, G. McGlynn, and J. Peters. Documenta Archaeobiologae 6. Verlag Marie Leidorf, Rahden, pp. 153–164.

Bartosiewicz, L., Demeure, R., Mottet, I., Neer, W. V., and Lentacker, A. (1997a). "Magnetic Resonance Imaging in the Study of Spavin in Recent and Subfossil Cattle". *Anthropozoologica* 25/26, pp. 57–60.

Bartosiewicz, L. and Gál, E. (2013). *Shuffling Nags, Lame Ducks: The Archaeology of Animal Disease*. Oxford : Oakville, CT.

Bartosiewicz, L., Van Neer, W., and Lentacker, A. (1993). "Metapodial Asymmetry in Draft Cattle". *International Journal of Osteoarchaeology* 3.2, pp. 69–75. DOI: 10.1002/oa.1390030203.

Bartosiewicz, L., Van Neer, W., and Lentacker, A. (1997b). *Draught Cattle: Their Osteological Identification and History*. vol. 281. Tervuren, Belgique: Musée royal de l'Afrique centrale.

Bartosiewicz, L. (1993). "The Anatomical Position and Metric Traits of Phalanges in Cattle (Bos Taurus L., 1758)". *Revue de Paléobiologie* 2.12, pp. 325–334.

— (2006). "Mettre le chariot devant le boeuf. Anomalies ostéologiques liées à l'utilisation des boeuf pour la traction." In: *Premiers chariots, premiers araires: La diffusion de la traction animale en Europe pendant les IVe et IIIe millénaires avant notre ère*. Ed. by P. Pétrequin, R.-M. Arbogast, A.-M. Pétrequin, S. van Willigen, and M. Bailly. CRA monographies 29. Paris: CNRS éd, pp. 259–267.

Baxter, I. L. (2007). "Skeleton of an Early-Middle Bronze Age Dog with Spondylosis Deformans from the Babraham Road Park and Ride Site, Cambridge, U.K." *Archaeofauna* 16, pp. 85–92.

— (2002). "Occipital Perforations in a Late Neolithic Probable Aurochs (Bos Primigenius Bojanus) Cranium from Letchworth, Hertfordshire, UK". *International Journal of Osteoarchaeology* 12.2, pp. 142–143. DOI: 10.1002/oa.591.

Bayliss, A., Marshall, P., Richards, C., and Whittle, A. (2017). "Islands of History: The Late Neolithic Timescape of Orkney". *Antiquity* 91.359, pp. 1171–1188. DOI: 10.15184/aqy.2017.140.

Bellido, T. (2014). "Osteocyte-Driven Bone Remodeling". *Calcified Tissue International* 94.1, pp. 25–34. DOI: 10.1007/s00223-013-9774-y.

Bendrey, R. (2008). "An Analysis of Factors Affecting the Development of an Equid Cranial Enthesopathy". *Veterinarija Ir Zootechnika* 41.63, pp. 25–31.

Benjamin, M., Kumai, T., Milz, S., Boszczyk, B., Boszczyk, A., and Ralphs, J. (2002). "The Skeletal Attachment of Tendons—Tendon 'Entheses'". *Comparative Biochemistry and Physiology Part A: Molecular & Integrative Physiology* 133.4, pp. 931–945. DOI: 10.1016/S1095-6433(02)00138-1.

Benjamin, M. and McGonagle, D. (2001). "The Anatomical Basis for Disease Localisation in Seronegative Spondyloarthropathy at Entheses and Related Sites". *Journal of Anatomy* 199.5, pp. 503–526. DOI: 10.1046/j.1469-7580.2001.19950503.x.

Benjamin, M., Toumi, H., Ralphs, J. R., Bydder, G., Best, T. M., and Milz, S. (2006). "Where Tendons and Ligaments Meet Bone: Attachment Sites ('entheses') in Relation to Exercise and/or Mechanical Load". *Journal of Anatomy* 208.4, pp. 471–490. DOI: 10.1111/j.1469-7580.2006.00540.x.

Benjamin, M. and McGonagle, D. (2007). "Histopathologic Changes at "Synovio–Entheseal Complexes" Suggesting a Novel Mechanism for Synovitis in Osteoarthritis and Spondylarthritis". *Arthritis & Rheumatism* 56.11, pp. 3601–3609. DOI: 10.1002/art.23078.

Berteaux, D. and Guintard, C. (1995). "Osteometric Study of the Metapodials of Amsterdam Island Feral Cattle". *Acta Theriologica* 40, pp. 97–110. DOI: 10.4098/AT.arch.95-10.

Bicknell, C. (1913). *Guide to the Prehistoric Rock Engravings in the Italian Maritime Alps*. Bordighera : Bessone.

Bindé, M., Cochard, D., and Knüsel, C. J. (2019). "Exploring Life Patterns Using Entheseal Changes in Equids: Application of a New Method on Unworked Specimens". *International Journal of Osteoarchaeology* 29.6, pp. 947–960. DOI: 10.1002/oa.2809.

Bishop, C. W. (1936). "Origin and Early Diffusion of the Traction-plough". *Antiquity* 10.39, pp. 261–281. DOI: 10.1017/S0003598X00011832.

Bishop, R. R. (2015). "Did Late Neolithic farming fail or flourish? A Scottish perspective on the evidence for Late Neolithic arable cultivation in the British Isles". *World Archaeology* 47.5, pp. 834–855. DOI: 10.1080/00438243.2015.1072477.

Björnsdóttir, S., Axelsson, M., Eksell, P., Sigurdsson, H., and Carlsten, J. (2010). "Radiographic and Clinical Survey of Degenerative Joint Disease in the Distal Tarsal Joints in Icelandic Horses". *Equine Veterinary Journal* 32.3, pp. 268–272. DOI: 10.2746/042516400776563590.

Bogaard, A. (2004). *Neolithic Farming in Central Europe*. Routledge. DOI: 10.4324/9780203358009.

— (2005a). "'Garden agriculture' and the nature of early farming in Europe and the Near East". *World Archaeology* 37.2, pp. 177–196. DOI: 10.1080/00438240500094572.

— (2005b). "'Garden Agriculture' and the Nature of Early Farming in Europe and the Near East". *World Archaeology* 37.2, pp. 177–196. DOI: 10.1080/00438240500094572.

— (2011). "Farming practice and society in the central European Neolithic and Bronze Age: an archaeobotanical response to the secondary products revolution model". In: Hadjikoumis, A., Robinson, E., and Viner, S. *The dynamics of neolithisation in Europe: studies in honour of Andrew Sherratt*. 1st ed. OCLC: 903286234. Oxford: Oxbow Books, pp. 266–283.

Bogucki, P. (1988). *Forest Farmers and Stockherders: Early Agriculture and Its Consequences in North-Central Europe*. New Studies in Archaeology. Cambridge [England] ; New York: Cambridge University Press.

— (1993). "Animal Traction and Household Economies in Neolithic Europe". *Antiquity* 67.256, pp. 492–503. DOI: 10.1017/S0003598X00045713.

— (2000). *The Origins of Human Society*. The Blackwell History of the World. Malden, MA: Blackwell Publishers.

Bökönyi, S. (1974). *History of Domestic Mammals in Central and Eastern Europe*. Budapest: Akadémiai Kiadó.

Bolamperti, S., Villa, I., and Rubinacci, A. (2022). "Bone remodeling: an operational process ensuring survival and bone mechanical competence". *Bone Research* 10.1, p. 48. DOI: 10.1038/s41413-022-00219-8.

Bóna, I. (1960). "Clay Models of Bronze Age Wagons and Wheels in the Middle Danube Basin." *Acta Archaeologica Academiae Scientiarum Hungaricae* 12, pp. 83–111.

Bonewald, L. F. (2011). "The Amazing Osteocyte". *Journal of Bone and Mineral Research* 26.2, pp. 229–238. DOI: 10.1002/jbmr.320.

Booth, T. J. and Brück, J. (2020). "Death is not the end: radiocarbon and histotaphonomic evidence for the curation and excarnation of human remains in Bronze Age Britain". *Antiquity* 94.377, pp. 1186–1203. DOI: 10.15184/aqy.2020.152.

Bradley, R. (1972). "Prehistorians and Pastoralists in Neolithic and Bronze Age England". *World Archaeology* 4.2, pp. 192–204. DOI: 10.1080/00438243.1972.9979532.

Bradley, R., Haselgrove, C., Linden, M. V., and Webley, L. (2016). *The Later Prehistory of North-West Europe: The Evidence of Development-Led Fieldwork*. Oxford: Oxford University Press.

Bradley, R. and Yates, D. (2007). ""After 'Celtic' Fields: The Social Organisation of Iron Age Agriculture". In: Haselgrove, C. and Pope, R. *The Earlier Iron Age in Britain and the Near Continent*. Oxford: Oxbow books, pp. 94–102.

Brassington, M. (1996). "The Roman fort at Little Chester, Derby: the East Wall and rampart, 1967-8". *The Derbyshire Archaeological Journal* 116, pp. 77–92.

Bray, F. (1978). "Swords into Plowshares: A Study of Agricultural Technology and Society in Early China". *Technology and Culture* 19.1, p. 1. DOI: 10.2307/3103306. JSTOR: 3103306.

Brophy, K. and Wright, D. (2021). "Possible Neolithic Ard Marks and Field Boundaries at Wellhill and Cranberry, Perth and Kinross, and an Evaluation of Current Physical Evidence for Neolithic Farming in Scotland". *Proceedings of the Society of Antiquaries of Scotland* 150, pp. 23–47. DOI: 10.9750/PSAS.150.1295.

Brothwell, D., Dobney, K., and Ervynck, A. (1996). "On the Causes of Perforations in Archaeological Domestic Cattle Skulls". *International Journal of Osteoarchaeology* 6.5, pp. 471–487. DOI: 10.1002/(SICI)1099-1212(199612)6:5<471::AID-OA300>3.0.CO;2-8.

Brown, A. (2007). "Dating the onset of cereal cultivation in Britain and Ireland: the evidence from charred cereal grains". *Antiquity* 81.314, pp. 1042–1052. DOI: 10.1017/S0003598X00096101.

Brück, J. (2000). "Settlement, Landscape and Social Identity: The Early-Middle Bronze Age Transition in Wessex, Sussex and the Thames Valley". *Oxford Journal of Archaeology* 19.3, pp. 273–300. DOI: 10.1111/1468-0092.00110.

— (2019). *Personifying Prehistory: Relational Ontologies in Bronze Age Britain and Ireland*. 1st edition. Oxford: Oxford University Press.

Bulatović, J., Marković, N., Stevanović, O., Marinković, D., Stojanović, I., and Krstić, N. (2016). "Spavin in Red Deer: A Case Study from the Early Neolithic Blagotin, Serbia". *International Journal of Paleopathology* 14, pp. 31–35. DOI: 10.1016/j.ijpp.2016.04.006.

Card, N. (2005). "Assessment of the Prehistoric Periods". In: Downes, J., Foster, S. M., and Wickham-Jones, C. R. *The Heart of Neolithic Orkney World Heritage Site: Research Agenda*. Edinburgh: Historic Scotland, pp. 46–65.

Cardoso, F. A. and Henderson, C. Y. (2009). "Enthesopathy Formation in the Humerus: Data from Known Age-at-Death and Known Occupation Skeletal Collections". *American Journal of Physical Anthropology*, NA–NA. DOI: 10.1002/ajpa.21171.

Carey, C., Hunnisett, K., Macphail, R., Bray, L., Toms, P., Wood, J., and Crabb, A. (2024). "What Happened before the Middle Bronze Age Land Divisions and Roundhouses? Prehistoric Soil Erosion and Landscape Change on Dartmoor, UK". *Journal of Archaeological Science: Reports* 56, p. 104506. DOI: 10.1016/j.jasrep.2024.104506.

Carlson Dietmeier, J. K. (2018). "The Oxen of Oxon Hill Manor: Pathological Analyses and Cattle Husbandry in Eighteenth-Century Maryland". *International Journal of Osteoarchaeology* 28.4, pp. 419–427. DOI: 10.1002/oa.2667.

Carter, S. (1998). "Ecofact Analyses From On-Site Contexts". In: *The Lairg Project, 1988-1996: The Evolution of an Archaeological Landscape in Northern Scotland*. Leith, Scotland: Scottish Trust for Archaeological Research.

Casanova, E., Knowles, T. D. J., Bayliss, A., Roffet-Salque, M., Heyd, V., Pyzel, J., Claßen, E., Domboróczki, L., Ilett, M., Lefranc, P., Jeunesse, C., Marciniak, A., Van Wijk, I., and Evershed, R. P. (2022). "Dating the emergence of dairying by the first farmers of Central Europe using $^{14}$C analysis of fatty acids preserved in pottery vessels". *Proceedings of the National Academy of Sciences* 119.43, e2109325118. DOI: 10.1073/pnas.2109325118.

Cashmore, L. A. and Zakrzewski, S. R. (2013). "Assessment of Musculoskeletal Stress Marker Development in the Hand: Muscle Markers in the Hand". *International Journal of Osteoarchaeology* 23.3, pp. 334–347. DOI: 10.1002/oa.1254.

Champion, T. (1999). "The Later Bronze Age". In: *The archaeology of Britain: an introduction from the Upper Palaeolithic to the Industrial Revolution*. Ed. by J. Hunter and I. Ralston. Reprinted. London: Routledge, pp. 95–112.

Chapman, J. (1982). "The 'secondary Products Revolution' and the Limitations of the Neolithic'". *Institute of Archaeology Bulletin* 19, pp. 107–122.

Childe, V. G. (1930). *The Bronze Age*. Cambridge: Cambridge university press.

— (1936). *Man Makes Himself*. Bradford-on-Avon, Wiltshire: Moonraker Press.

Clark, G. (1962). *Prehistoric England*. London: Batsford.

— (1966). "The Invasion Hypothesis in British Archaeology". *Antiquity* 40.159, pp. 172–189. DOI: 10.1017/S0003598X00032488.

Clarke, D. and Sharples, N. (1985). "Settlements and Subsistence in the Third Millennium BC". In: *The Prehistory of Orkney: BC 4000 - 1000 AD*. Ed. by C. Renfrew. Reprinted without former colour plates. Edinburgh: Edinburgh University Press, pp. 54–82.

Clarke, D., Sheridan, A., Shepherd, A., Sharples, N., Armour-Chelu, M., Hamlet, L., Bronk-Ramsey, C., Dunbar, E., Reimer, P., Marshall, P., and Whittle, A. (2017). "The End of the World, or Just 'Goodbye to All That'? Contextualising the Red Deer Heap from Links of Noltland, Westray, within Late 3rd-Millennium Cal BC Orkney". *Proceedings of the Society of Antiquaries of Scotland* 146, pp. 57–89. DOI: 10.9750/PSAS.146.1226.

Copley, M., Berstan, R., Mukherjee, A., Dudd, S., Straker, V., Payne, S., and Evershed, R. (2005). "Dairying in Antiquity. III. Evidence from Absorbed Lipid Residues Dating to the British Neolithic". *Journal of Archaeological Science* 32.4, pp. 523–546. DOI: 10.1016/j.jas.2004.08.006.

Cowie, T. G. and Shepherd, I. A. G. (2003). "The Bronze Age". In: Edwards, K. J. and Ralston, I. B. M. *Scotland After the Ice Age: Environment, Archaeology and History 8000 BC - AD 1000*. Edinburgh: Edinburgh University Press, pp. 151–168. DOI: 10.1515/9781474467995.

Cowin, S. C. (2001). "The False Premise in Wolff's Law". In: *Bone Mechanics Handbook*. Ed. by S. C. Cowin. 2nd ed. Boca Raton, Fla.: CRC Press, pp. 30-1–32-5.

Crabbé, A., Mikeska, C. A., Pişkin, E., De Kock, W., and Çakirlar, C. (2025). "Ploughing through pathologies: Traction-related bone deformations in cattle as indicators of changes in political economies in Bronze and Iron Age Anatolia". *Journal of Archaeological Science: Reports* 64, p. 105100. DOI: 10.1016/j.jasrep.2025.105100.

Craig, O. E., Chapman, J., Heron, C., Willis, L. H., Bartosiewicz, L., Taylor, G., Whittle, A., and Collins, M. (2005). "Did the first farmers of central and eastern Europe produce dairy foods?" *Antiquity* 79.306, pp. 882–894. DOI: 10.1017/S0003598X00115017.

Craig, O. E., Shillito, L.-M., Albarella, U., Viner-Daniels, S., Chan, B., Cleal, R., Ixer, R., Jay, M., Marshall, P., Simmons, E., Wright, E., and Pearson, M. P. (2015). "Feeding Stonehenge: Cuisine and Consumption at the Late Neolithic Site of Durrington Walls". *Antiquity* 89.347, pp. 1096–1109. DOI: 10.15184/aqy.2015.110.

Curwen, E. C. (1927). "Prehistoric Agriculture in Britain". *Antiquity* 1.3, pp. 261–289. DOI: 10.1017/S0003598X0000065X.

Davidson, I. and Curtis, G. R. (1973). "An Iron Age Site on the Land of the Plant Breeding Institute, Trumpington." *Proceedings of the Cambridge Antiquarian Society* 64. Publisher: Archaeology Data Service, pp. 1–14. DOI: 10.5284/1073030.

Davis, C. B., Shuler, K. A., Danforth, M. E., and Herndon, K. E. (2013). "Patterns of Interobserver Error in the Scoring of Entheseal Changes: Patterns of Interobserver Error in the Scoring of Entheseal Changes". *International Journal of Osteoarchaeology* 23.2, pp. 147–151. DOI: 10.1002/oa.2277.

Davis, S. (1992). "A Rapid Method for Recording Information about Mammal Bones from Archaeological Sites." Ancient Monuments Laboratory Report 19/92.

Davis, S., Albarella, U., Detry, C., Ginja, A., Götherström, A., Pires, A., Sendim, E., and Svensson, E. M. (2018). "An Osteometrical Method for Sexing Cattle Bones". *Annalen des Naturhistorischen Museums in Wien* Serie A.120, pp. 367–387.

De Carle, D. E. (2014). "Changing Plant Subsistence in Prehistoric Southwest Britain: Archaeobotanical and Anthracological Evidence from the South Cadbury Environs Project". PhD thesis. The University of Sheffield.

De Cupere, B., Lentacker, A., Van Neer, W., Waelkens, M., and Verslype, L. (2000). "Osteological Evidence for the Draught Exploitation of Cattle: First Applications of a New Methodology". *International Journal of Osteoarchaeology* 10.4, pp. 254–267. DOI: 10.1002/1099-1212(200007/08)10:4<254::AID-OA528>3.0.CO;2-#.

De Cupere, B. and Waelkens, M. (2002). "Draught Cattle and Its Osteological Indications: The Example of Sagalossos". In: *Archaeozoology of the Near East V*. Ed. by H. Buitenhuis, A. M. Choyke, M. Mashkour, and A. H. Al-Shiyab. Archaeozoology of the Near East 5. Groningen: ARC-bv, pp. 305–315.

De Vareilles, A., Woodbridge, J., Pelling, R., Fyfe, R., Smith, D., Campbell, G., Smith, W., Carruthers, W., Adams, S., Le Hégarat, K., and Allot, L. (2023). "The development of arable cultivation in the south-east of England and its relationship with vegetation cover: A honeymoon period for biodiversity?" *The Holocene* 33.11, pp. 1389–1406. DOI: 10.1177/09596836231185836.

Deschler-Erb, S., Leuzinger, U., and Marti-Grädel, É. (2006). "La traction animale au 34e siècle à Arbon-Bleiche (Thurgovie, Suisse)". In: *Premiers chariots, premiers araires: La diffusion de la traction animale en Europe pendant les IVe et IIIe millénaires avant notre ère*. Ed. by P. Pétrequin, R.-M. Arbogast, A.-M. Pétrequin, S. van Willigen, and M. Bailly. CRA monographies 29. Paris: CNRS éd, pp. 157–164.

Dobney, K., Jaques, D., and Irving, B. (1996). *Of Butchers & Breeds: Report on Vertebrate Remains from Various Sites in the City of Lincoln*. Lincoln Archaeological Studies no. 5. Lincoln [England]: City of Lincoln Archaeology Unit.

Done, G. (1991). "The Animal Bone". In: Needham, S. *Excavation and Salvage at Runnymede Bridge, 1978: The Late Bronze Age Waterfront Site*. London: British Museum English heritage, pp. 327–342.

Dottrens, E. (1946). "Los Phalanges Osseuses de Bos Taurus Domesticus". In: *La Faune Néolithique de La Couche Profonde de Saint-Aubin53. Revue Suisse de Zoologie, Pp. 739–774, 33.* Ed. by P. Revilliod and E. Dottrens, pp. 739–774.

Downes, J. and Lamb, R. (2000). *Prehistoric Houses at Sumburgh in Shetland: Excavations at Sumburgh Airport 1967-74*. Oxford: Oxbow Books.

Drapeau, M. S. (2008). "Enthesis Bilateral Asymmetry in Humans and African Apes". *HOMO* 59.2, pp. 93–109. DOI: 10.1016/j.jchb.2007.12.004.

Drenth, E. and Lanting, A. E. (1997). "On the importance of the ard and the wheeled vehicle for the transition from the TRB West Group to the Single Grave culture in the Netherlands". In: *Early corded ware culture: the A-horizon - fiction or fact? ; international symposium in Jutland, 2nd - 7th May 1994*. Ed. by P. Siemen. Arkæologiske rapporter / Esbjerg Museum 2. Esbjerg: Esbjerg Museum, pp. 73–80.

Dumitrescu, V. and Banateanu, T. (1965). "A Propos d'un Soc de Charrue Primitive En Bois de Cerf, Decouvert Dans La Station de Cascioarele". *Dacia* IX, pp. 59–68.

Dutour, O. (1986). "Enthesopathies (Lesions of Muscular Insertions) as Indicators of the Activities of Neolithic Saharan Populations". *American Journal of Physical Anthropology* 71.2, pp. 221–224. DOI: 10.1002/ajpa.1330710209.

Ekroth, G. (2014). "Castration, Cult and Agriculture Perspectives on Greek Animal Sacrifice". *Opuscula: Annual of the Swedish Institutes at Athens and Rome* 7, pp. 153–174.

Eksell, P., Axelsson, M., Broström, H., Ronéus, B., Häggström, J., and Carlsten, J. (1998). "Prevalence and Risk Factors of Bone Spavin in Icelandic Horses in Sweden: A Radiographic Field Study". *Acta Veterinaria Scandinavica* 39.3, pp. 339–348. DOI: 10.1186/BF03547782.

Ellison, A. (1981). "Towards a Socioeconomic Model for the Middle. Bronze Age in Southern England". In: *Pattern of the Past: Studies in Honour of David Clarke*. Ed. by I. Hodder and D. L. Clarke. Cambridge: Cambridge University Press, pp. 413–438.

Eshed, V., Gopher, A., Galili, E., and Hershkovitz, I. (2004). "Musculoskeletal Stress Markers in Natufian Hunter-Gatherers and Neolithic Farmers in the Levant: The Upper Limb". *American Journal of Physical Anthropology* 123.4, pp. 303–315. DOI: 10.1002/ajpa.10312.

Evershed, R. P., Payne, S., Sherratt, A. G., Copley, M. S., Coolidge, J., Urem-Kotsu, D., Kotsakis, K., Özdoğan, M., Özdoğan, A. E., Nieuwenhuyse, O., Akkermans, P. M. M. G., Bailey, D., Andeescu, R.-R., Campbell, S., Farid, S., Hodder, I., Yalman, N., Özbaşaran, M., Bıçakcı, E., Garfinkel, Y., Levy, T., and Burton, M. M. (2008). "Earliest date for milk use in the Near East and southeastern Europe linked to cattle herding". *Nature* 455.7212, pp. 528–531. DOI: 10.1038/nature07180.

Fabiš, M. (2005). "Pathological Alteration of Cattle Skeletons - Evidence for Draught Exploitation of Animals?" In: *Diet and Health in Past Animal Populations: Current Research and Future Directions*. Ed. by J. Davies, M. Fabiš, I. Mainland, M. Richards, and R. Thomas. Oxford: Oxbow Books, pp. 58–62.

Fabiš, M. and Thomas, R. (2011). "Not Just Cattle: Cranial Perforations Revisited: Cranial Perforations Revisited". *International Journal of Osteoarchaeology* 21.3, pp. 347–350. DOI: 10.1002/oa.1133.

Fenton, A. (1973). "Early Yoke Types in Britain". In: *A Magyar Mezőgazdasági Múzeum Közleményei 1971-1972*. Ed. by I. Wellmann. Budapest: Magyar Mezőgazdasági Múzeum, pp. 69–75.

Foltiny, S. (1959). "The Oldest Representations of Wheeled Vehicles in Central and Southeastern Europe". *American Journal of Archaeology* 63.1, pp. 53–58. DOI: 10.2307/502108.
Foster, A., Buckley, H., and Tayles, N. (2014). "Using Enthesis Robusticity to Infer Activity in the Past: A Review". *Journal of Archaeological Method and Theory* 21.3, pp. 511–533. DOI: 10.1007/s10816-012-9156-1.
Fowler, P. J. (1983). *The Farming of Prehistoric Britain*. Cambridge; New York: Cambridge University Press.
Fowler, P. J. and Evans, J. G. (1967). "Plough-Marks, Lynchets and Early Fields". *Antiquity* 41.164, pp. 289–301. DOI: 10.1017/S0003598X00033524.
Fraser, S. (2011). "The Animal Bone". In: Moore, H. and Wilson, G. *Shifting Sands: Links of Noltland, Westray : Interim Report on Neolthic and Bronze Age Excavations, 2007-09*. Historic Scotland, pp. 40–52.
— (2015). "Mammals in Late Neolithic Orkney". PhD thesis. The University of Edinburgh.
Frost, H. M. (1987). "Bone "Mass" and the "Mechanostat": A Proposal". *The Anatomical Record* 219.1, pp. 1–9. DOI: 10.1002/ar.1092190104.
Frost, H. M. (1982). "Review Article Mechanical Determinants of Bone Modeling". *Metabolic Bone Disease and Related Research* 4.4, pp. 217–229. DOI: 10.1016/0221-8747(82)90031-5.
— (1997). "Why Do Long-Distance Runners Not Have More Bone? A Vital Biomechanical Explanation and an Estrogen Effect". *Journal of Bone and Mineral Metabolism* 15.1, pp. 9–16. DOI: 10.1007/BF02439449.
Gaastra, J. S., Greenfield, H. J., and Linden, M. V. (2018). "Gaining Traction on Cattle Exploitation: Zooarchaeological Evidence from the Neolithic Western Balkans". *Antiquity* 92.366, pp. 1462–1477. DOI: 10.15184/aqy.2018.178.
Galindo-Pellicena, M., Martín-Francés, L., Gracia, A., de Gaspar, I., Arsuaga, J., and Carretero, J. (2017). "Evidences of the Use of Cattle as Draught Animals in Chalcolithic of El Portalón (Sierra de Atapuerca, Burgos)". *Quaternary International* 438, pp. 1–10. DOI: 10.1016/j.quaint.2015.11.052.
Glob, P. (1951). *Ard Og Plov i Nordens Oldtid*. Aarhus University Press.
Godde, K., Wilson Taylor, R., and Gutierrez, C. (2018). "Entheseal changes and demographic/health indicators in the upper extremity of modern Americans: Associations with age and physical activity". *International Journal of Osteoarchaeology* 28.3, pp. 285–293. DOI: 10.1002/oa.2653.
Goody, J. (1977). *Production and Reproduction*. 1st ed. Cambridge Studies in Social and Cultural Anthropology v.No.17. West Nyack: Cambridge University Press.
Grant, A. (1982). "The Use of Tooth Wear as a Guide to the Age of Domestic Ungulates". In: *Ageing and Sexing Animal Bones from Archaeological Sites*. Ed. by B. Wilson, C. Grigson, and S. Payne. BAR British Series 109. Oxford: BAR, pp. 91–108.
Greenfield, H. J. (1988). "The Origins of Milk and Wool Production in the Old World: A Zooarchaeological Perspective from the Central Balkans [and Comments]". *Current Anthropology* 29.4, pp. 573–593. DOI: 10.1086/203676.
— (2005). "A Reconsideration of the Secondary Products Revolution in South-Eastern Europe: On the Origins and Use of Domestic Animals for Milk, Wool, and Traction in the Central Balkans". In: *The Zooarchaeology of Fats, Oils, Milk and Dairying*. Ed. by J. Mulville and A. K. Outram. Oxford: Oxbow, pp. 14–31.
— (2010). "The Secondary Products Revolution: The Past, the Present and the Future". *World Archaeology* 42.1, pp. 29–54. DOI: 10.1080/00438240903429722.

Greenfield, H. J. (2014). "Introduction". In: *Animal Secondary Products: Domestic Animal Exploitation in Prehistoric Europe, the Near East and the Far East*. Ed. by H. J. Greenfield. Oxford ; Philadelphia: Oxbow Books, pp. 1–17.

Griffiths, S. (2021). "Beside the Ocean of Time: A Chronology of Neolithic Burial Monuments and Houses in Orkney". In: *The Development of Neolithic House Societies in Orkney*. Ed. by C. Richards, R. Jones, and S. Jeffrey. s.l.: Oxbow Books.

Halliday, S. P., Hill, P., and Stevenson, J. (1981). "Early Agriculture in Sctoland". In: *Farming Practice in British Prehistory*. Ed. by R. J. Mercer. Edinburgh: University Press, pp. 55–65.

Halstead, P. (1987). "Man and Other Animals in Later Greek Prehistory". *The Annual of the British School at Athens* 82, pp. 71–83. DOI: 10.1017/S0068245400020323.

— (1995). "Plough and power: the economic and social significance of cultivation with the ox-drawn ard in the Mediterranean". *Bulletin on Sumerian Agriculture* 8, pp. 11–22.

— (2014). *Two Oxen Ahead: Pre-Mechanized Farming in the Mediterranean*. Hoboken, New Jersey: Wiley-Blackwell.

Halstead, P. and Isaakidou, V. (2011). "Revolutionary Secondary Products: The Development and Significance of Milking, Animal-Traction and Wool- Gathering in Later Prehistoric Europe and the Near East". In: *Interweaving Worlds: Systemic Interactions in Eurasia, 7th to 1st Millennia BC*. Ed. by T. C. Wilkinson, S. Sherratt, and J. Bennet. Oakville, CT: Oxbow Books.

Havelková, P., Villotte, S., Velemínský, P., Poláček, L., and Dobisíková, M. (2011). "Enthesopathies and Activity Patterns in the Early Medieval Great Moravian Population: Evidence of Division of Labour: Enthesopathies in the Great Moravian Population". *International Journal of Osteoarchaeology* 21.4, pp. 487–504. DOI: 10.1002/oa.1164.

Hawkey, D. E. and Merbs, C. F. (1995). "Activity-Induced Musculoskeletal Stress Markers (MSM) and Subsistence Strategy Changes among Ancient Hudson Bay Eskimos". *International Journal of Osteoarchaeology* 5.4, pp. 324–338. DOI: 10.1002/oa.1390050403.

Healy, F., Bayliss, A., Whittle, A., Allen, M. J., Mercer, R., Rawlings, M., Sharples, N., and Thomas, N. (2011a). "South Wessex". In: Whittle, A. W. R., Healy, F., Bayliss, A., and Allen, M. J. *Gathering Time: Dating the Early Neolithic Enclosures of Southern Britain and Ireland*. Oxford ; Oakville, CT: Oxbow Books, pp. 111–206.

Healy, F., Whittle, A. W. R., Bayliss, A., Hey, G., Robertson-Mackay, R., Allen, T., and Ford, S. (2011b). "The Thames valley". In: Whittle, A. W. R., Healy, F., Bayliss, A., and Allen, M. J. *Gathering time: dating the early Neolithic enclosures of southern Britain and Ireland*. OCLC: ocn709890503. Oxford ; Oakville, CT: Oxbow Books.

Hedges, R. E. M., Housley, R. A., Ramsey, C. B., and Klinken, G. J. V. (1995). "Radiocarbon Dates from the Oxford AMS System: Archaeometry Datelist 20". *Archaeometry* 37.2, pp. 417–430. DOI: 10.1111/j.1475-4754.1995.tb00754.x.

Helmer, D., Blaise, E., Gourichon, L., and Sana-Segui, M. (2018). "Using Cattle for Traction and Transport during the Neolithic Period Contribution of the Study of the First and Second Phalanxes". *Bulletin de La Société Préhistorique Française* 115.1, pp. 71–98.

Henderson, C. Y., Mariotti, V., Pany-Kucera, D., Villotte, S., and Wilczak, C. (2013). "Recording Specific Entheseal Changes of Fibrocartilaginous Entheses: Initial Tests Using the Coimbra Method: Recording Entheseal Changes". *International Journal of Osteoarchaeology* 23.2, pp. 152–162. DOI: 10.1002/oa.2287.

Henderson, C. Y., Mariotti, V., Pany-Kucera, D., Villotte, S., and Wilczak, C. (2016). "The New 'Coimbra Method': A Biologically Appropriate Method for Recording Specific Features of Fibrocartilaginous Entheseal Changes: The New 'Coimbra Method'". *International Journal of Osteoarchaeology* 26.5, pp. 925–932. DOI: 10.1002/oa.2477.

Henriksen, K., Neutzsky-Wulff, A. V., Bonewald, L. F., and Karsdal, M. A. (2009). "Local Communication on and within Bone Controls Bone Remodeling". *Bone* 44.6, pp. 1026–1033. DOI: 10.1016/j.bone.2009.03.671.

Higham, C. (1969). "The Metrical Attributes of Two Samples of Bovine Limb Bones". *Journal of Zoology* 157.1, pp. 63–74. DOI: 10.1111/j.1469-7998.1969.tb01689.x.

Higham, C., Kijngam, A., Manly, B., and Moore, S. (1981). "The Bovid Third Phalanx and Prehistoric Ploughing". *Journal of Archaeological Science* 8.4, pp. 353–365. DOI: 10.1016/0305-4403(81)90035-2.

Holmberg, T. and Reiland, S. (1984). "The Influence of Age, Breed, Rearing Intensity and Exercise on The Incidence of Spavin in Swedish Dairy Cattle: A Clinical and Morphological Investigation". *Acta Veterinaria Scandinavica* 25.1, pp. 113–127. DOI: 10.1186/BF03547285.

Holmes, M., Hamerow, H., and Thomas, R. (2021a). "Close Companions? A Zooarchaeological Study of the Human–Cattle Relationship in Medieval England". *Animals* 11.4, p. 1174. DOI: 10.3390/ani11041174.

Holmes, M. and Thomas, R. (2022). ""…in Winter, Plough": Zooarchaeological Evidence for the Changing Role of Draught Cattle and Horses in Medieval England AD 400-1400". In: Kropp, C. and Zoll, L. *Draft Animals in the Past, Present and Future*. Heidelberg: Propylaeum, pp. 63–70.

Holmes, M., Thomas, R., and Hamerow, H. (2021b). "Identifying Draught Cattle in the Past: Lessons from Large-Scale Analysis of Archaeological Datasets". *International Journal of Paleopathology* 33, pp. 258–269. DOI: 10.1016/j.ijpp.2021.05.004.

— (2021c). "Lesions in Sheep Elbows: Insights from a Large-Scale Study". *International Journal of Paleopathology* 34, pp. 50–62. DOI: 10.1016/j.ijpp.2021.05.007.

Hopfen, H. J. (1981). *Farm implements for arid and tropical regions*. OCLC: 476318370. Rome: Food and Agriculture Organization of the United Nations.

Hudson, G., Wilson, I., Payne, B. I., Elson, J., Samuels, D. C., Santibanez-Korev, M., Hall, S. J., and Chinnery, P. F. (2012). "Unique Mitochondrial DNA in Highly Inbred Feral Cattle". *Mitochondrion* 12.4, pp. 438–440. DOI: 10.1016/j.mito.2012.05.003.

Huet, T. (2017). "New Perspectives on the Chronology and Meaning of Mont Bégo Rock Art (Alpes-Maritimes, France)". *Cambridge Archaeological Journal* 27.2, pp. 199–221. DOI: 10.1017/S0959774316000524.

Hull, E., Niinimäki, S., and Salmi, A.-K. (2020). "Differences in Entheseal Changes in the Phalanges between Ecotypes of Fennoscandian Reindeer". *International Journal of Osteoarchaeology* 30.5, pp. 666–678. DOI: 10.1002/oa.2897.

Isaakidou, V. (2006). "Ploughing with Cows: Knossos and the 'Secondary Products Revolution'". In: *Animals in the Neolithic of Britain and Europe*. Ed. by D. Serjeantson and D. Field. Neolithic Studies Group Seminar Papers 7. Oxford: Oxbow Books, pp. 95–112.

— (2008). ""The Fauna and Economy of Neolithic Knossos' Revisited". In: *Escaping the Labyrinth: The Cretan Neolithic in Context*. Ed. by V. Isaakidou and P. Tomkins. Sheffield Studies in Aegean Archaeology 8. Oxford : Oakville, CT: Oxbow Books ; David Brown Book Co., [distributor], pp. 90–114.

Isaakidou, V. (2011). "Farming Regimes in Neolithic Europe: Gardening with Cows and Other Models". In: *The Dynamics of Neolithisation in Europe: Studies in Honour of Andrew Sherratt*. Ed. by A. Hadjikoumis, E. Robinson, and S. Viner. 1st ed (Online-ausg.) Oxford: Oxbow Books, pp. 266–283.

Ivanova, M. (2017). "The 'Green Revolution' in Prehistory: Late Neolithic Agricultural Innovations as a Technological System". In: *Appropriating Innovations: Entangled Knowledge in Eurasia, 5000-1500 BCE*. Ed. by P. W. Stockhammer and J. Maran. Oxbow Books, pp. 40–49. DOI: 10.2307/j.ctt1vgw6v1. JSTOR: 10.2307/j.ctt1vgw6v1.

Jee, W. S. (2001). "Integrated Bone Tissue Physiology: Anatomy and Physiology". In: *Bone Mechanics Handbook*. Ed. by S. C. Cowin. 2nd ed. Boca Raton, Fla.: CRC Press, pp. 1–68.

Jewell, P. (1963). "Cattle from British Archaeological Sites". In: *Man and Cattle*. Ed. by A. E. Mourant and F. Zcuner. London: Royal Anthropological Institute of Great Britain & Ireland, pp. 80–91.

Johannsen, N. N. (2005). "Palaeopathology and Neolithic Cattle Traction: Methodological Issues and Archaeological Perspectives". In: *Diet and Health in Past Animal Populations: Current Research and Future Directions*. Ed. by J. Davies, M. Fabiš, I. Mainland, M. Richards, and R. Thomas. Oxford: Oxbow Books, pp. 39–51.

— (2006). "Draught Cattle and the South Scandinavian Economies of the 4th Millennium BC". *Environmental Archaeology* 11.1, pp. 35–48. DOI: 10.1179/174963106x97043.

— (2011). "Past and Present Strategies for Draught Exploitation of Cattle". In: *Ethnozooarchaeology: The Present and Past of Human-Animal Relationships*. Ed. by U. Albarella and A. Trentacoste. Oxford : Oakville, CT: Oxbow Books ; David Brown Book Co, pp. 13–19.

— (2017). "Appropriating Draught Cattle Technology in Southern Scandinavia: Roles, Context and Consequences". In: *Appropriating Innovations: Entangled Knowledge in Eurasia, 5000-1500 BCE*. Ed. by J. Maran and P. Stockhammer. Havertown: Oxbow Books, pp. 122–135.

Johnstone, C. and Albarella, U. (2015). "The Late Iron Age and Romano-British Mammal and Bird Bone Assemblage from Elms Farm, Heybridge, Essex". In: *Heybridge: A Late Iron Age and Roman Settlement, Excavations at Elms Farm 1993-5*. Ed. by M. Atkinson and S. Preston. Vol. 40. Internet Archaeology.

Jones, G. G. and Sadler, P. (2012). "Age at Death in Cattle: Methods, Older Cattle and Known-Age Reference Material". *Environmental Archaeology* 17.1, pp. 11–28. DOI: 10.1179/1461410312Z.0000000002.

Jones, G. and Bogaard, A. (2017). "Integration of cereal cultivation and animal husbandry in the British Neolithic: the evidence of charred plant remains from timber buildings at Lismore Fields". In: *Economic zooarchaeology: studies in hunting, herding and early agriculture*. Ed. by P. Rowley-Conwy, D. Serjeantson, and P. Halstead. Oxford ; Philadelphia: Oxbow Books, pp. 221–226.

Jones, G. and Rowley-Conwy, P. (2007). "On the importance of cereal cultivation in the British Neolithic". In: Colledge, S. and Conolly, J. *The Origins and Spread of Domestic Plants in Southwest Asia and Europe*. OCLC: 781310264. Walnut Creek: Left Coast Press, Inc.

Jurmain, R. and Villotte, S. (2010). "Terminology. Entheses in Medical Literature and Physical Anthropology: A Brief Review".

Jurmain, R., Cardoso, F. A., Henderson, C., and Villotte, S. (2012). "Bioarchaeology's Holy Grail: The Reconstruction of Activity". In: *A Companion to Pa-*

*leopathology*. Ed. by A. L. Grauer. Oxford, UK: Wiley-Blackwell, pp. 531–552. DOI: 10.1002/9781444345940.ch29.

Kamjan, S., Erdil, P., Hummel, E., Çilingiroğlu, Ç., and Çakırlar, C. (2022). "Traction in Neolithic Çatalhöyük? Palaeopathological Analysis of Cattle and Aurochs Remains from the East and West Mounds". *Journal of Anthropological Archaeology* 66, p. 101412. DOI: 10.1016/j.jaa.2022.101412.

Karakostis, F. A., Hotz, G., Tourloukis, V., and Harvati, K. (2018). "Evidence for Precision Grasping in Neandertal Daily Activities". *Science Advances* 4.9, eaat2369. DOI: 10.1126/sciadv.aat2369.

Karakostis, F. A., Jeffery, N., and Harvati, K. (2019). "Experimental proof that multivariate patterns among muscle attachments (entheses) can reflect repetitive muscle use". *Scientific Reports* 9.1, p. 16577. DOI: 10.1038/s41598-019-53021-8.

Kenkre, J. and Bassett, J. (2018). "The bone remodelling cycle". *Annals of Clinical Biochemistry: International Journal of Laboratory Medicine* 55.3, pp. 308–327. DOI: 10.1177/0004563218759371.

Kennedy, K. A. (1998). "Markers of Occupational Stress: Conspectus and Prognosis of Research". *International Journal of Osteoarchaeology* 8.5, pp. 305–310. DOI: 10.1002/(SICI)1099-1212(1998090)8:5<305::AID-OA444>3.0.CO;2-A.

Kierdorf, U., Meng, S., and Kahlke, R.-D. (2016). "Resorptive Depressions on a Horn Core of Late Pleistocene (MIS 3) Bison Priscus (Bovidae, Mammalia) from Northeastern Germany". *International Journal of Paleopathology* 15, pp. 76–82. DOI: 10.1016/j.ijpp.2016.08.006.

Kramer, A., Bittmann, F., and Nösler, D. (2014). "New Insights into Vegetation Dynamics and Settlement History in Hümmling, North-Western Germany, with Particular Reference to the Neolithic". *Vegetation History and Archaeobotany* 23.5, pp. 461–478. DOI: 10.1007/s00334-013-0409-z.

Landis, J. R. and Koch, G. G. (1977). "The Measurement of Observer Agreement for Categorical Data". *Biometrics* 33.1, p. 159. DOI: 10.2307/2529310. JSTOR: 2529310.

Lawson, A. J., Allen, M. J., and Bayliss, A. (2000a). "Radiocarbon Dating". In: Lawson, A. J. *Potterne 1982-5: Animal Husbandry in Later Prehistoric Wiltshire*. Wessex Archaeology Report 17. Salisbury: Trust for Wessex Archaeology, pp. 39–41.

Lawson, A. J., Powell, A., and Thomas, R. (2000b). "Discussion". In: Lawson, A. J. *Potterne 1982-5: Animal Husbandry in Later Prehistoric Wiltshire*. Wessex Archaeology Report 17. Salisbury: Trust for Wessex Archaeology, pp. 251–272.

Leese, M. (1991). "Radiocarbon Dating". In: Needham, S. *Excavation and Salvage at Runnymede Bridge, 1978: The Late Bronze Age Waterfront Site*. London: British Museum English heritage, pp. 347–353.

Leppek, M. (2017). "Innovation, Interaction and Society in Europe in the 4th Millennium BCE: The 'Traction Complex' as Innovation and 'Technology Cluster'". In: *Appropriating Innovations: Entangled Knowledge in Eurasia, 5000-1500 BCE*. Ed. by J. Maran and P. Stockhammer. Oxford Haverton, PA: Oxbow Books, pp. 98–108.

Lerche, G. and Steensberg, A. (1980). *Agricultural Tools and Field Shapes: Twenty Five Years of Activity by the International Secretariat*. International Secretariat for Research on the History of Agricultural Implements no. 3. Copenhagen: National Museum of Denmark.

Lerner, U. H. (2012). "Osteoblasts, Osteoclasts, and Osteocytes: Unveiling Their Intimate-Associated Responses to Applied Orthodontic Forces". *Seminars in Orthodontics* 18.4, pp. 237–248. DOI: 10.1053/j.sodo.2012.06.002.

Lieverse, A. R., Bazaliiskii, V. I., Goriunova, O. I., and Weber, A. W. (2009). "Upper Limb Musculoskeletal Stress Markers among Middle Holocene Foragers of Siberia's Cis-Baikal Region". *American Journal of Physical Anthropology* 138.4, pp. 458–472. DOI: 10.1002/ajpa.20964.

Lignereux, Y., Vaquer, J., and Collonge, J. (2006). "Traction animale et lésions osseuses. Quelques cas dans le Néolithique final languedocien (France)". In: *Premiers chariots, premiers araires: La diffusion de la traction animale en Europe pendant les IVe et IIIe millénaires avant notre ère*. Ed. by P. Pétrequin, R.-M. Arbogast, A.-M. Pétrequin, S. van Willigen, and M. Bailly. CRA monographies 29. Paris: CNRS éd, pp. 31–37.

Lin, M. (2022). *Origins of Cattle Traction and the Making of Early Civilisations in North China*. Interdisciplinary Contributions to Archaeology. Cham: Springer International Publishing. DOI: 10.1007/978-3-031-15535-2.

Lin, M., Luan, F., Fang, H., Xu, H., Zhao, H., and Barker, G. (2018). "Pathological Evidence Reveals Cattle Traction in North China by the Early Second Millennium BC". *The Holocene* 28.8, pp. 1205–1215. DOI: 10.1177/0959683618771483.

Lin, M., Miracle, P., and Barker, G. (2016). "Towards the Identification of the Exploitation of Cattle Labour from Distal Metapodials". *Journal of Archaeological Science* 66, pp. 44–56. DOI: 10.1016/j.jas.2015.12.006.

Littauer, M. A. and Crouwel, J. (1979). *Wheeled Vehicles and Ridden Animals in the Ancient near East*. Boston: BRILL.

Liu, P. (2021). "Entheseal Changes in Modern Bovidae: Exploring The Potential Application to Reconstruct Activity Patterns". Unpublished Master Dissertation. The University of Sheffield.

Llado, E., Gaitero, L., Pumarola, M., and Saña, M. (2008). "Perforations in Archaeological Neolithic Cattle Skulls: A New Methodological Approximation for Their Study and Explanation". *Veterinarija Ir Zootechnika* 43.65, pp. 58–61.

Locker, A. (2000). "Animal Bone". In: Lawson, A. *Potterne 1982-5: Animal Husbandry in Later Prehistoric Wiltshire*. Wessex Archaeology Report 17. Salisbury: Trust for Wessex Archaeology, pp. 101–118.

Lodwick, L. (2023). "Cultivating Villa Economies: Archaeobotanical and Isotopic Evidence for Iron Age to Roman Agricultural Practices on the Chalk Downlands of Southern Britain". *European Journal of Archaeology* 26.4, pp. 445–466. DOI: 10.1017/eaa.2022.47.

Longley, D. (1980). *Runnymede Bridge 1976: Excavations on the Site of a Late Bronze Age Settlement*. Research Volume of the Surrey Archaeological Society 6. Guildford: Surrey Archaeological Soc.

Louwe Kooijmans, L. (2006). "Les débuts de la traction animale aux Pays-Bas et ses conséquences". In: *Premiers chariots, premiers araires: La diffusion de la traction animale en Europe pendant les IVe et IIIe millénaires avant notre ère*. Ed. by P. Pétrequin, R.-M. Arbogast, A.-M. Pétrequin, S. van Willigen, and M. Bailly. CRA monographies 29. Paris: CNRS éd, pp. 191–206.

Madgwick, R., Esposito, C., and Lamb, A. L. (2023). "Farming and Feasting during the Bronze Age–Iron Age Transition in Britain (ca. 900–500 Bce): Multi-Isotope Evidence for Societal Change". *Frontiers in Environmental Archaeology* 2, p. 1221581. DOI: 10.3389/fearc.2023.1221581.

Manaseryan, N. H., Dobney, K., and Ervynck, A. (1999). "On the Causes of Perforations in Archaeological Domestic Cattle Skulls: New Evidence". *International Journal of Osteoarchaeology* 9.1, pp. 74–75. DOI: 10.1002/(SICI)1099-1212(199901/02)9:1<74::AID-OA463>3.0.CO;2-1.

Manby, T. (1980). "Bronze Age Settlement in Eastern Yorkshire". In: Barrett, J. C. and Bradley, R. *Settlement and Society in the British Later Bronze Age*. BAR British Series 83. Oxford: B.A.R, pp. 307–371.
Marciniak, A. (2011). "The Secondary Products Revolution: Empirical Evidence and Its Current Zooarchaeological Critique". *Journal of World Prehistory* 24.2-3, pp. 117–130. DOI: 10.1007/s10963-011-9045-7.
Mariotti, V., Facchini, F., and Belcastro, M. G. (2004). "Enthesopathies–Proposal of a Standardized Scoring Method and Applications". *Collegium Antropologicum* 28.1, pp. 145–159.
Mariotti, V., Facchini, F., and Giovanna Belcastro, M. (2007). "The Study of Entheses: Proposal of a Standardised Scoring Method for Twenty-Three Entheses of the Postcranial Skeleton". *Collegium Antropologicum* 31.1, pp. 291–313.
Martin, E. and Murphy, P. (1988). "West Row Fen, Suffolk: A Bronze Age Fen-Edge Settlement Site". *Antiquity* 62.235, pp. 353–358. DOI: 10.1017/S0003598X00074196.
Martin, R. B. (2003). "Fatigue Damage, Remodeling, and the Minimization of Skeletal Weight". *Journal of Theoretical Biology* 220.2, pp. 271–276. DOI: 10.1006/jtbi.2003.3148.
Martin, R. B., Burr, D. B., Sharkey, N. A., and Fyhrie, D. P. (2015). *Skeletal Tissue Mechanics*. New York, NY: Springer New York. DOI: 10.1007/978-1-4939-3002-9.
Marzatico, F. (2006). "L'araire et le joug de Lavagnone et de Fiavé (Italie)". In: *Premiers chariots, premiers araires: La diffusion de la traction animale en Europe pendant les IVe et IIIe millénaires avant notre ère*. Ed. by P. Pétrequin, R.-M. Arbogast, A.-M. Pétrequin, S. van Willigen, and M. Bailly. CRA monographies 29. Paris: CNRS éd.
Mateescu, C. N. (1975). "Remarks on Cattle Breeding and Agriculture in the Middle and Late Neolithic on the Lower Danube". *Dacia* 19, pp. 13–18.
May, J. (1996). *Dragonby: Report on Excavations at an Iron Age and Romano-British Settlement in North Lincolnshire*. Oxbow Monograph 61. Oxford: Oxbow Books.
Mays, S. (2001). "Effects of Age and Occupation on Cortical Bone in a Group of 18th-19th Century British Men". *American Journal of Physical Anthropology* 116.1, pp. 34–44. DOI: 10.1002/ajpa.1099.
— (2021). *The Archaeology of Human Bones*. 3rd ed. Third edition. | New York : Routledge, 2021.: Routledge. DOI: 10.4324/9781315171821.
Mazza, B. (2019). "Entheseal Changes among Late Holocene Hunter-Gatherers from the Southern Extreme of La Plata Basin (Argentina)". *Archaeological and Anthropological Sciences* 11.5, pp. 1865–1885. DOI: 10.1007/s12520-018-0638-2.
Mercer, R. J. (1981). "Introduction". In: *Farming Practice in British Prehistory*. Ed. by R. J. Mercer. Edinburgh: University Press.
Midgley, M. S. (1992). *TRB Culture: The First Farmers of the North European Plain*. Edinburgh: Edinburgh University Press.
Milella, M., Giovanna Belcastro, M., Zollikofer, C. P., and Mariotti, V. (2012). "The Effect of Age, Sex, and Physical Activity on Entheseal Morphology in a Contemporary Italian Skeletal Collection". *American Journal of Physical Anthropology* 148.3, pp. 379–388. DOI: 10.1002/ajpa.22060.
Milisauskas, S. and Kruk, J. (1991). "Utilization of Cattle for Traction during the Later Neolithic in Southeastern Poland". *Antiquity* 65.248, pp. 562–566. DOI: 10.1017/S0003598X00080170.
Miller, M. E. (2003). "The Bone Disease of Preterm Birth: A Biomechanical Perspective". *Pediatric Research* 53.1, pp. 10–15. DOI: 10.1203/00006450-200301000-00005.

Mischka, D. (2011). "The Neolithic Burial Sequence at Flintbek LA 3, North Germany, and Its Cart Tracks: A Precise Chronology". *Antiquity* 85.329, pp. 742–758. DOI: 10.1017/S0003598X00068289.

Miszkiewicz, J. J. and Mahoney, P. (2016). "Ancient Human Bone Microstructure in Medieval England: Comparisons between Two Socio-Economic Groups: Ancient Human Bone Microstructure and Social Status". *The Anatomical Record* 299.1, pp. 42–59. DOI: 10.1002/ar.23285.

Moore, H. and Wilson, G. (2011). *Shifting Sands: Links of Noltland, Westray : Interim Report on Neolthic and Bronze Age Excavations, 2007-09*. Historic Scotland.

Mould, C. (1996). *An Archaeological Evaluation at Greenhouse Farm, Newmarket Road, Cambridge 1996*. Artwork Size: 1 pdf file Medium: PDF. Birmingham Archaeology, 1 pdf file. DOI: 10.5284/1032311.

Müller, H.-H. (1992). "Archaeozoological Research on Vertebrates in Central Europe with Special Reference to the Medieval Period". *International Journal of Osteoarchaeology* 2.4, pp. 311–324. DOI: 10.1002/oa.1390020407.

Munson Chapman, N. E. (1997). "Evidence for Spanish Influence on Activity Induced Musculoskeletal Stress Markers at Pecos Pueblo". *International Journal of Osteoarchaeology* 7.5, pp. 497–506. DOI: 10.1002/(SICI)1099-1212(199709/10)7:5<497::AID-OA394>3.0.CO;2-H.

Murphy, P. (1987). "Environmental Evidence". In: *The Bronze Age and Saxon Settlement of Springfield Lyons, Essex: An Interim Report*. Occasional Paper 5. Chelmsford: Essex County Council Archaeology Section, p. 12.

— (2013). "IX. Carbonised Plant Remains from Neolithic, Late Bronze Age and Roman Contexts". In: Brown, N. and Medlycott, M. *The Neolithic and Bronze Age Enclosures at Springfield Lyons, Essex: Excavations 1981-91*. East Anglian Archaeology report no. 149. Chelmsford: Essex County Council, pp. 126–140.

Nacambo, S., Hässig, M., Lischer, C., and Nuss, K. (2007). "Difference in the Length of the Medial and Lateral Metacarpal and Metatarsal Condyles in Calves and Cows – A Post-Mortem Study". *Anatomia, Histologia, Embryologia: Journal of Veterinary Medicine Series C* 36.6, pp. 408–412. DOI: 10.1111/j.1439-0264.2007.00785.x.

Needham, S. (1991). *Excavation and Salvage at Runnymede Bridge, 1978: The Late Bronze Age Waterfront Site*. London: British Museum English heritage.

— (1996). *Runnymede Bridge Research Excavations Vol. II: Refuse and Disposal: Refuse and Disposal at Area 16 East Runnymede*. 1. publ. London: British Museum Press.

— (2000). *The Passage of the Thames: Holocene Environment and Settlement at Runnymede*. Runnymede Bridge Research Excavations v. 1. London: British Museum.

— (2007). "800 BC, the great divide". In: Haselgrove, C. and Pope, R. *The earlier iron age in Britain and the near continent*. Oxford: Oxbow books, pp. 39–63.

— (2009). "Encompassing the Sea: 'maritories' and Bronze Age Maritime Interactions". In: *Bronze Age Connections: Cultural Contact in Prehistoric Europe*. Ed. by P. Clark. Oxford ; Oakville, CT: Oxbow Books, pp. 12–34.

Niesioowska-Śreniowska, E. (1999). "The Early TRB 'Ploughmarks' from Sarnowo in Central Poland: A New Interpretation". *Oxford Journal of Archaeology* 18.1, pp. 17–22. DOI: 10.1111/1468-0092.00069.

Niinimäki, S. and Baiges Sotos, L. (2013). "The Relationship Between Intensity of Physical Activity and Entheseal Changes on the Lower Limb: Physical Activity and Entheses in the Lower Limb". *International Journal of Osteoarchaeology* 23.2, pp. 221–228. DOI: 10.1002/oa.2295.

Niinimäki, S. and Salmi, A.-K. (2016). "Entheseal Changes in Free-Ranging Versus Zoo Reindeer—Observing Activity Status of Reindeer". *International Journal of Osteoarchaeology* 26.2, pp. 314–323. DOI: 10.1002/oa.2423.

Niinimäki, S. (2011). "What Do Muscle Marker Ruggedness Scores Actually Tell Us?: What Muscle Ruggedness Tells Us?" *International Journal of Osteoarchaeology* 21.3, pp. 292–299. DOI: 10.1002/oa.1134.

Niinimäki, S. and Salmi, A.-K. (2021). "Covariation between Entheseal Changes and Cross-Sectional Properties of Reindeer Long Bones – Considering Bone Functional Adaptation as Partial Contributing Factor". *Journal of Archaeological Science: Reports* 36, p. 102840. DOI: 10.1016/j.jasrep.2021.102840.

Niskanen, M. and Bindé, M. (2021). "Scaling with Size in Horses May Have Implications for Reconstructing Activity from Entheseal Changes". In: *Archaeologies of Animal Movement. Animals on the Move*. Ed. by A.-K. Salmi and S. Niinimäki. Cham: Springer International Publishing, pp. 11–19. DOI: 10.1007/978-3-030-68744-1_2.

Nobles, G. (2014). "Features". In: *A Mosaic of Habitation at Zeewijk (the Netherlands): Late Neolithic Behavioural Variability in a Dynamic Landscape*. Ed. by E. Theunissen, O. Brinkkemper, R. Lauwerier, B. Smit, and I. van der Jagt. Nederlandse Archeologische Rapporten 47. Amersfoort: Cultural Heritage Agency of the Netherlands, pp. 39–54.

Noddle, B. A. (1979). "A Brief History of Domestic Animals in the Orkney Islands, Scotland, from the 4th Millenium B.C. to the 18th Century". In: *Proceedings of the 3rd International Archaeozoology Conference, 23rd April 1978,* ed. by M. Kubasiewicz. Szczecin, Poland: Szczecin: Szczecin Agricultural Academy, pp. 286–303.

Nowakowski, J. A. (2017). "Living in the Sands - Bronze Age Gwithian, Cornwall, Revisited". In: *Land and People: Papers in Memory of John G. Evans*. Ed. by J. G. Evans, M. J. Allen, N. Sharples, and T. P. O'Connor. Paperback edition. Prehistoric Society Research Paper no. 2. Oxford Oakville: Oxbow Books, pp. 115–125.

O'Connell, M. and Molloy, K. (2002). "Farming and Woodland Dynamics in Ireland during the Neolithic". *Biology and Environment : Proceedings of the Royal Irish Academy* 101.1-2, pp. 99–128.

O'Connor, T. P. (1982). *Animal Bones from Flaxengate, Lincoln c. 870 - 1500*. The Archeology of Lincoln Vol. 18, Environmental Studies 18,1 1. London: Council for British Archaeology.

— (1988). *Bones from the General Accident Site, Tanner Row*. The Archaeology of York 2. London: the Council for British Archaeology for the York archaeological trust.

— (2008). "On the Differential Diagnosis of Arthropathy in Bovids". In: *Limping Together through the Ages : Joint Afflictions and Bone Infections*. Ed. by G. Grupe, G. McGlynn, and J. Peters. Documenta Archaeobiologae 6. Verlag Marie Leidorf, Rahden, pp. 165–186.

Olsen, S. (1994). "Exploitation of Mammals at the Early Bronze Age Site of West Row Fen (Mildenhall 165), Suffolk, England". *Annals of Carnegie Museum* 63.2, pp. 115–153.

Onar, V., Kahvecioğlu, K. O., Kostov, D., Armutak, A., Pazvant, G., Chrószcz, A., and İnce, N. G. (2015). "Osteological Evidences Of Byzantine Draught Cattle From Theodosius Harbour At Yenikapi, Istanbul". DOI: 10.5281/ZENODO.16602.

al-Oumaoui, I., Jiménez-Brobeil, S., and du Souich, P. (2004). "Markers of Activity Patterns in Some Populations of the Iberian Peninsula". *International Journal of Osteoarchaeology* 14.5, pp. 343–359. DOI: 10.1002/oa.719.

Palmer, J. L. A., Quintelier, K., Inskip, S., and Waters-Rist, A. L. (2019). "A Comparison of Two Methods for Recording Entheseal Change on a Post-Medieval Urban Skeletal Collection from Aalst (Belgium): Entheseal Change on a Skeletal Collection from Aalst (Belgium)". *Archaeometry* 61.1, pp. 211–225. DOI: 10.1111/arcm.12409.

Páral, V., Tichý, F., and Fabiš, M. (2004). "Functional Structure of Metapodial Bones of Cattle". *Acta Veterinaria Brno* 73.4, pp. 413–420. DOI: 10.2754/avb200473040413.

Pare, C. F. E. (1992). *Wagons and Wagon-Graves of the Early Iron Age in Central Europe*. Monograph / Oxford University Committee for Archaeology no. 35. Oxford: Oxford University Committee for Archaeology : Distributed by Oxbow Books.

Parker Pearson, M., Pollard, J., Richard, C., Thomas, J., Welham, K., Albarella, U., Chan, B., Marshall, P., and Viner, S. (2011). "Feeding Stonehenge: Feasting in Late Neolithic Britain". In: Aranda Jiménez, G., Montón-Subías, S., and Sánchez Romero, M. *Guess Who's Coming to Dinner: Feasting Rituals in the Prehistoric Societies of Europe and the near East*. Oakville, CT: Oxbow Books, pp. 73–90.

Parker Pearson, M. (2005). *Bronze Age Britain*. Rev. ed. English Heritage. London: Batsford.

Parmenter, P. C. R. (2014). "A Reassessment of the Role of Animals at the Etton Causewayed Enclosure". PhD thesis. The University of Exeter.

Patterson, N. et al. (2022). "Large-Scale Migration into Britain during the Middle to Late Bronze Age". *Nature* 601.7894, pp. 588–594. DOI: 10.1038/s41586-021-04287-4.

Payne, F. G. (1957). "The British Plough: Some Stages in Its Development". *Agricultural history review* 5.2, pp. 72–84.

— (1947). "The Plough in Ancient Britain". *Archaeological Journal* 104.1, pp. 82–111. DOI: 10.1080/00665983.1947.10853867.

Pearson, O. M. and Lieberman, D. E. (2004). "The Aging of Wolff's "Law": Ontogeny and Responses to Mechanical Loading in Cortical Bone". *American Journal of Physical Anthropology* 125.S39, pp. 63–99. DOI: 10.1002/ajpa.20155.

Phillips, T. and Mortimer, R. (2012). *Clay Farm, Trumpington, Cambridgeshire-Post-Excavation Assessment*. Post-Excavation Assessment OA East Report No: 1294. Oxford Archaeology East.

Piggott, S. (1949). "An Iron Age Yoke from Northern Ireland". *Proceedings of the Prehistoric Society* 15, pp. 192–193. DOI: 10.1017/S0079497X00019307.

— (1959). "A Tripartite Disc Wheel from Blair Drummond, Perthshire". *Proceedings of the Society of Antiquaries of Scotland* 90, pp. 238–241.

— (1969). "The Earliest Wheeled Vehicles and the Caucasian Evidence". *Proceedings of the Prehistoric Society* 34, pp. 266–318. DOI: 10.1017/S0079497X00013918.

— (1981). "Early Prehistory". In: *The Agrarian History of England and Wales Volume 1 I. Prehistory*. Ed. by S. Piggott. First paperback edition. New York: Cambridge University Press, pp. 3–59.

— (1983). *The Earliest Wheeled Transport: From the Atlantic Coast to the Caspian Sea*. London: Thames and Hudson.

— (1992). *Wagon, Chariot, and Carriage: Symbol and Status in the History of Transport*. London: Thames and Hudson.

Pigière, F. and Smyth, J. (2023). "First Evidence for Cattle Traction in Middle Neolithic Ireland: A Pivotal Element for Resource Exploitation". *PLOS ONE* 18.1, e0279556. DOI: 10.1371/journal.pone.0279556.

Pitfield, R., Deter, C., and Mahoney, P. (2019). "Bone histomorphometric measures of physical activity in children from medieval England". *American Journal of Physical Anthropology* 169.4, pp. 730–746. DOI: 10.1002/ajpa.23853.

Pollex, A. (1999). "Comments on the Interpretation of the So-Called Cattle Burials of Neolithic Central Europe". *Antiquity* 73.281, pp. 542–550. DOI: 10.1017/S0003598X00065091.

Prøsch-Danielsen, L. (1993). "Prehistoric Agriculture Revealed by Pollen Analysis, Plough-Marks and Sediment Studies at Sola, South-Western Norway". *Vegetation History and Archaeobotany* 2.4. DOI: 10.1007/BF00198164.

Pryor, F. (1996). "Sheep, stockyards and field systems: Bronze Age livestock populations in the Fenlands of eastern England". *Antiquity* 70.268, pp. 313–324. DOI: 10.1017/S0003598X00083290.

— (1998). *Etton Excavations at a Neolithic Causewayed Enclosure near Maxey Cambridgeshire, 1982-7*. DGO - Digital original. Swindon: Historic England.

Pryor, F., French, C., Taylor, M., Barrett, J. C., and Halliday, T. M. (1986). "Flag Fen, Fengate, Peterborough I: Discovery, Reconnaissance and Initial Excavation (1982–85)." *Proceedings of the Prehistoric Society* 52, pp. 1–24. DOI: 10.1017/S0079497X00006551.

Pullen, D. J. (1992). "Ox and Plow in the Early Bronze Age Aegean". *American Journal of Archaeology* 96.1, pp. 45–54. DOI: 10.2307/505757.

Rabey, K. N., Green, D. J., Taylor, A. B., Begun, D. R., Richmond, B. G., and McFarlin, S. C. (2015). "Locomotor Activity Influences Muscle Architecture and Bone Growth but Not Muscle Attachment Site Morphology". *Journal of Human Evolution* 78, pp. 91–102. DOI: 10.1016/j.jhevol.2014.10.010.

Rassadnikov, A. (2021). "Bone Pathologies of Modern Non-Draft Cattle (Bos Taurus) in the Context of Grazing Systems and Environmental Influences in the South Urals, Russia". *International Journal of Paleopathology* 32, pp. 87–102. DOI: 10.1016/j.ijpp.2020.11.003.

Rees, S. E. (1981). "Agricultural Tools: Function and Use". In: *Farming Practice in British Prehistory*. Ed. by R. J. Mercer. Edinburgh: University Press, pp. 66–84.

— (1983). "A Wooden Ard-Share from Dundarg, Aberdeenshire, with a Note on Other Wooden Plough Pieces". *Proceedings of the Society of Antiquaries of Scotland* 113, pp. 457–463.

— (1979). *Agricultural Implements in Prehistoric and Roman Britain*. BAR British Series 69. Oxford, England: B.A.R.

Refai, O. (2019). "Entheseal Changes in Ancient Egyptians from the Pyramid Builders of Giza-Old Kingdom". *International Journal of Osteoarchaeology* 29.4, pp. 513–524. DOI: 10.1002/oa.2748.

Reinhold, S., Gresky, J., Berezina, N., Kantorovich, A., Knipper, C., Maslov, V., Petrenko, V., Alt, K., and Belinsky, A. (2017). "Contextualising Innovation: Cattle Owners and Wagon Drivers in the North Caucasus and Beyond". In: *Appropriating Innovations: Entangled Knowledge in Eurasia, 5000-1500 BCE*. Ed. by J. Maran and P. Stockhammer. Oxford Haverton, PA: Oxbow Books, pp. 78–97.

Reynolds, P. J. (1967). "Experiment in Iron Age Agriculture". *Transactions of the Bristol & Gloucestershire Archaeological Society* 86.

— (1981). "Deadstock and Livestock". In: *Farming Practice in British Prehistory*. Ed. by R. J. Mercer. Edinburgh: University Press, pp. 97–122.

— (1982). "The Donnerupland Ard". DOI: 10.6067/XCV8418204.

Rhode, M. (2013). "Entheseal Change". In: *Photographic Regional Atlas of Bone Disease: A Guide to Pathologic and Normal Variation in the Human Skeleton*. 3rd ed. Springfield . Ill: Charles C. Thomas, Publisher, pp. 203–211.

Rideout, J. S. (1995). "Cam Dubh, Moulin, Perthshire: Survey and Excavation of an Archaeological Landscape 1987-90".

Ritchie, A., Bramwell, D., Collins, G. H., Dickson, C., Evans, J. G., Henshall, A. S., Inskeep, R., Kenward, H., Noddle, B. A., Vaughan, M., Wheeler, A., Whittington, G., and Williams, D. F. (1984). "Excavation of a Neolithic Farmstead at Knap of Howar, Papa Westray, Orkney". *Proceedings of the Society of Antiquaries of Scotland* 113, pp. 40–121. DOI: 10.9750/PSAS.113.40.121.

Robb, J. E. (1998). "The Interpretation of Skeletal Muscle Sites: A Statistical Approach". *International Journal of Osteoarchaeology* 8.5, pp. 363–377. DOI: 10.1002/(SICI)1099-1212(1998090)8:5<363::AID-OA438>3.0.CO;2-K.

Robertson-Mackay, R., Butcher, S., Cameron, F., Chandra, H., Conway, B., Dawes, J., Dimes, F., Grigson, C., Healey, E., Helbaek, H., Higgs, E., Hodges, H., Pengelly, H., and Whittle, A. (1987). "The Neolithic Causewayed Enclosure at Staines, Surrey: Excavations 1961–63". *Proceedings of the Prehistoric Society* 53.1, pp. 23–128. DOI: 10.1017/S0079497X00006174.

Robinson, D. M. (1931). "Bouzyges and the First Plough on a Krater by the Painter of the Naples Hephaistos". *American Journal of Archaeology* 35.2, pp. 152–160. DOI: 10.2307/498246.

Robinson, M. (2000). "Further Considerations of Neolithic Charred Cereals, Fruit and Nuts". In: Fairbairn, A. S. *Plants in Neolithic Britain and Beyond*. Neolithic Studies Group Seminar Papers 5. Oxford: Oxbow, pp. 85–90.

Robling, A. G. and Stout, S. D. (2008). "Histomorphometry of Human Cortical Bone: Applications to Age Estimation". In: *Biological Anthropology of the Human Skeleton*. Ed. by M. A. Katzenberg and S. R. Saunders. Hoboken, NJ, USA: John Wiley & Sons, Inc., pp. 149–182. DOI: 10.1002/9780470245842.ch5.

Rosenstock, E. (2022). "Speeding up. Prehistoric Animal Traction and the Revolute Joint". In: *Draft Animals in the Past, Present and Future*. Ed. by C. Kropp and L. Zoll. Heidelberg: Propylaeum, pp. 47–62.

Rowley-Conwy, P. (1987). "The Interpretation of Ard Marks". *Antiquity* 61.232, pp. 263–266. DOI: 10.1017/S0003598X00052091.

— (2004). "No Fixed Abode? Nomadism in the Northwest European Neolithic". In: *Stones and Bones: Formal Disposal of the Dead in Atlantic Europe during the Mesolithic-Neolithic Interface 6000 - 3000 BC ; Archaeological Conference in Honour of the Late Professor Michael J. O'Kelly ; Proceedings of the Stones and Bones Conference in Sligo, Ireland, May 1 - 5, 2002*. Ed. by G. Burenhult and M. J. O'Kelly. BAR International Series 1201. Oxford: Archaeopress.

Rowley-Conwy, P., Gron, K. J., Bishop, R. R., Dunne, J., Evershed, R. P., Longford, C., Schulting, R., and Edward, T. (2020). "The Earliest Farming in Britain : Towards a New Synthesis". In: *Farmers at the Frontier: A Pan-European Perspective on Neolithisation*. Ed. by K. J. Gron, L. Sørensen, and P. Rowley-Conwy. Philadelphia: Oxbow Books, pp. 401–424.

Ruff, C. (2000). "Body Size, Body Shape, and Long Bone Strength in Modern Humans". *Journal of Human Evolution* 38.2, pp. 269–290. DOI: 10.1006/jhev.1999.0322.

Ruff, C., Holt, B., and Trinkaus, E. (2006). "Who's Afraid of the Big Bad Wolff?: "Wolff's Law" and Bone Functional Adaptation". *American Journal of Physical Anthropology* 129.4, pp. 484–498. DOI: 10.1002/ajpa.20371.

Ryder, M. L. (1970). "The Animal Remains from Petergate, York". *Yorkshire Archaeological Journal* 42, pp. 418–428.

Sabatini, S., Frei, K. M., De Grossi Mazzorin, J., Cardarelli, A., Pellacani, G., and Frei, R. (2022). "Investigating sheep mobility at Montale, Italy, through strontium isotope analyses". *Journal of Archaeological Science: Reports* 41, p. 103298. DOI: 10.1016/j.jasrep.2021.103298.

Sagona, A. G. (2018). *The Archaeology of the Caucasus: From the Earliest Settlements to the Iron Age*. Cambridge World Archaeology. New York, NY: Cambridge University Press.

Salmi, A.-K. and Niinimäki, S. (2016). "Entheseal Changes and Pathological Lesions in Draught Reindeer Skeletons – Four Case Studies from Present-Day Siberia". *International Journal of Paleopathology* 14, pp. 91–99. DOI: 10.1016/j.ijpp.2016.05.012.

Salmi, A.-K., Niinimäki, S., and Pudas, T. (2020). "Identification of Working Reindeer Using Palaeopathology and Entheseal Changes". *International Journal of Paleopathology* 30, pp. 57–67. DOI: 10.1016/j.ijpp.2020.02.001.

Salque, M., Bogucki, P. I., Pyzel, J., Sobkowiak-Tabaka, I., Grygiel, R., Szmyt, M., and Evershed, R. P. (2013). "Earliest evidence for cheese making in the sixth millennium bc in northern Europe". *Nature* 493.7433, pp. 522–525. DOI: 10.1038/nature11698.

Schlecht, S. H. (2012). "Understanding Entheses: Bridging the Gap Between Clinical and Anthropological Perspectives". *The Anatomical Record: Advances in Integrative Anatomy and Evolutionary Biology* 295.8, pp. 1239–1251. DOI: 10.1002/ar.22516.

Schlichtherle, H. (2006). "Chemins, roues et chariots : innovations de la fin du Néolithique dans le sud-ouest de l'Allemagne". In: *Premiers chariots, premiers araires: La diffusion de la traction animale en Europe pendant les IVe et IIIe millénaires avant notre ère*. Ed. by P. Pétrequin, R.-M. Arbogast, A.-M. Pétrequin, S. van Willigen, and M. Bailly. CRA monographies 29. Paris: CNRS éd, pp. 165–178.

Scott, K. M. (1983). "Prediction of Body Weight of Fossil Artiodactyla". *Zoological Journal of the Linnean Society* 77.3, pp. 199–215. DOI: 10.1111/j.1096-3642.1983.tb00098.x.

Seeman, E. (2001). "During Aging, Men Lose Less Bone Than Women Because They Gain More Periosteal Bone, Not Because They Resorb Less Endosteal Bone". *Calcified Tissue International* 69.4, pp. 205–208. DOI: 10.1007/s00223-001-1040-z.

Serjeantson, D. (1996). "The Animal Bones". In: *Runnymede Bridge Research Excavations Vol. II: Refuse and Disposal: Refuse and Disposal at Area 16 East Runnymede*. London: British Museum Press, pp. 194–223.

— (2006). "Food or Feast at Neolithic Runnymede?" In: *Animals in the Neolithic of Britain and Europe*. Neolithic Studies Group Seminar Papers 7. Oxford: Oxbow books, pp. 113–134.

— (2007). "Intensification of Animal Husbandry in the Late Bronze Age? The Contribution of Sheep and Pigs". In: Haselgrove, C. and Pope, R. *The Earlier Iron Age in Britain and the near Continent*. 80–93. Oxford: Oxbow books.

— (2011). *A Review of Animal Remains from the Neolithic and Early Bronze Age of Southern Britain*. Research Report Series 29/2011. Portsmouth: Historic England.

Sharples, N. (2010). *Social Relations in Later Prehistory: Wessex in the First Millennium BC*. Oxford: Oxford University Press.

Shaw, H. M. and Benjamin, M. (2007). "Structure-Function Relationships of Entheses in Relation to Mechanical Load and Exercise: Tendon and Ligament

Entheses". *Scandinavian Journal of Medicine & Science in Sports* 17.4, pp. 303–315. DOI: 10.1111/j.1600-0838.2007.00689.x.
Sheridan, A. (2002). "The Radiocarbon Dating Programmes of The National Museums of Scotland". *Antiquity* 76.293, pp. 794–796. DOI: 10.1017/S0003598X00091250.
Sherratt, A. (1981). "Plough and Pastoralism: Aspects of the Secondary Products Revolution". In: *Pattern of the Past: Studies in Honour of David Clarke*. Ed. by I. Hodder, G. Isaac, and N. Hammond. Digitally printed version. Cambridge: Cambridge University Press.
— (1983). "The Secondary Exploitation of Animals in the Old World". *World Archaeology* 15.1, pp. 90–104. JSTOR: 124640.
— (1997). *Economy and Society in Prehistoric Europe: Changing Perspectives*. Edinburgh: Edinburgh University Press.
— (2006). "La traction animale et la transformation de l?Europe néolithique (Animal traction and the transformation of Europe)". In: *Premiers chariots, premiers araires: La diffusion de la traction animale en Europe pendant les IVe et IIIe millénaires avant notre ère*. Ed. by P. Pétrequin, R.-M. Arbogast, A.-M. Pétrequin, S. van Willigen, and M. Bailly. CRA monographies 29. Paris: CNRS éd, pp. 329–360.
Shipman, P. (2014). "And the Last Shall Be First". In: *Animal Secondary Products: Domestic Animal Exploitation in Prehistoric Europe, the Near East and the Far East*. Ed. by H. J. Greenfield. Oxford ; Philadelphia: Oxbow Books, pp. 40–54.
Stanley, M., McDermott, C., Moore, C., and Murray, C. (2003). "Throwing off the Yoke". *Archaeology Ireland* 17.2, pp. 6–8.
Starkey, P. (1989). *Harnessing and implements for animal traction: an animal traction resource book for Africa*. A Publication of Deutsches Zentrum für Entwicklungstechnologien - GATE and Division 421 - Agricultural Production Systems in: Deutsche Gesellschaft für Technische Zusammenarbeit. Braunschweig: Vieweg.
Starkey, P. and Mudamburi, B. (2022). "Draft Animals in the World". In: *Draft Animals in the Past, Present and Future*. Ed. by C. Kropp and L. Zoll. Heidelberg: Propylaeum, pp. 9–28.
Steppan, K. (2006). "Les Boeufs néolithiques de Seekirch (Lkr. Biberach, Allemagne) et leurs modfications pathologiques". In: *Premiers chariots, premiers araires: La diffusion de la traction animale en Europe pendant les IVe et IIIe millénaires avant notre ère*. Ed. by P. Pétrequin, R.-M. Arbogast, A.-M. Pétrequin, S. van Willigen, and M. Bailly. CRA monographies 29. Paris: CNRS éd, pp. 179–185.
Stevens, C. J. and Fuller, D. Q. (2012). "Did Neolithic farming fail? The case for a Bronze Age agricultural revolution in the British Isles". *Antiquity* 86.333, pp. 707–722. DOI: 10.1017/S0003598X00047864.
Stone, J. F. S., Piggott, S., and Booth, A. St. J. (1954). "Durrington Walls, Wiltshire: Recent Excavations at a Ceremonial Site of the Early Second Millennium B.C." *The Antiquaries Journal* 34.3–4, pp. 155–177. DOI: 10.1017/S0003581500059837.
Tarrús, J., Saña, M., Chinchilla, J., and Bosch, À. (2006). "La Draga (Banyoles, Catalogne): Traction Animale à La Fin Du VIè Millénaire?" In: *Premiers Chariots, Premiers Araires: La Diffusion de La Traction Animale En Europe Pendant Les IVe et IIIe Millénaires Avant Notre Ère*. Ed. by P. Pétrequin, R.-M. Arbogast, A.-M. Pétrequin, S. van Willigen, and M. Bailly. CRA Monographies 29. Paris: CNRS éd, pp. 25–30.

Taylor, M. (2001). "The Wood". In: *The Flag Fen Basin: Archaeology and Environment of a Fenland Landscape*. English Heritage Archaeological Reports. London: English Heritage, pp. 167–212.

Tegtmeier, U. (1993). *Neolithische und bronzezeitliche Pflugspuren in Norddeutschland und den Niederlanden*. Archäologische Berichte 3. Bonn: Deutsche Gesellschaft für Ur- und Frühgeschichte.

Telldahl, Y. (2005). "Can Palaeopathology Be Used as Evidence for Draught Animals". In: *Diet and Health in Past Animal Populations: Current Research and Future Directions*. Ed. by J. Davies, M. Fabiš, I. Mainland, M. Richards, and R. Thomas. Oxford: Oxbow Books, pp. 63–67.

— (2012). "Skeletal Changes in Lower Limb Bones in Domestic Cattle from Eketorp Ringfort on the Öland Island in Sweden". *International Journal of Paleopathology* 2.4, pp. 208–216. DOI: 10.1016/j.ijpp.2012.09.002.

Telldahl, Y., Svensson, E., Götherström, A., and Storå, J. (2012). "Osteometric and Molecular Sexing of Cattle Metapodia". *Journal of Archaeological Science* 39.1, pp. 121–127. DOI: 10.1016/j.jas.2011.09.009.

Thomas, A. (1970). "Bronze Age Spade Marks at Gwithian, Cornwall". In: *The Spade in Northern and Atlantic Europe*. Ed. by I. Gailey and A. Fenton. Ulster Folk & Transport Museum, pp. 10–17.

Thomas, A. (2014). "Bioarchaeology of the Middle Neolithic: Evidence for Archery among Early European Farmers: Bioarchaeology of the Middle Neolithic". *American Journal of Physical Anthropology* 154.2, pp. 279–290. DOI: 10.1002/ajpa.22504.

Thomas, R. (1988). "A Statistical Evaluation of Criteria Used in Sexing Cattle Metapodials". *Archaeozoologia* 2 (1.2), pp. 83–92.

Thomas, R. (2008). "Diachronic Trends in Lower Limb Pathologies in Later Medieval and Post-Medieval Cattle from Britain". In: *Limping Together through the Ages : Joint Afflictions and Bone Infections*. Ed. by G. Grupe, G. McGlynn, and J. Peters. Documenta Archaeobiologae 6. Verlag Marie Leidorf, Rahden, pp. 187–201.

Thomas, R., Bellis, L., Gordon, R., Holmes, M., Johannsen, N. N., Mahoney, M., and Smith, D. (2021). "Refining the Methods for Identifying Draught Cattle in the Archaeological Record: Lessons from the Semi-Feral Herd at Chillingham Park". *International Journal of Paleopathology* 33, pp. 84–93. DOI: 10.1016/j.ijpp.2021.02.003.

Thomas, R. and Mainland, I. (2005). "Introduction: Animal Diet and Health – Current Perspectives and Future Directions". In: *Diet and Health in Past Animal Populations: Current Research and Future Directions*. Ed. by J. Davies, M. Fabiš, I. Mainland, M. Richards, and R. Thomas. Oxford : Oakville, CT: Oxbow Books ; David Brown Book Co.

Thomas, R., Sykes, N., Doherty, S., and Smith, D. (2018). "Ring Depressions in Cattle Horncores as Indicators of Traction Use – a Cautionary Note". *International Journal of Paleopathology* 22, pp. 140–142. DOI: 10.1016/j.ijpp.2018.07.002.

Thomson, R. G. (1969). "Vertebral Body Osteophytes in Bulls". *Pathologia veterinaria* 6.1_suppl, pp. 1–71. DOI: 10.1177/030098586900601s01.

Thrane, H. (1989). "Danish Plough-Marks from the Neolithic and Bronze Age". *Journal of Danish Archaeology* 8.1, pp. 111–125. DOI: 10.1080/0108464X.1989.10590023.

Traill, W. and Kirkness, W. (1937). "Hower, a Prehistoric Structure on Papa Westray, Orkney". *Proceedings of the Society of Antiquaries of Scotland* 71, pp. 309–321. DOI: 10.9750/PSAS.071.309.321.

Train, K. E. (2009). *Discrete choice methods with simulation*. 2nd ed. Cambridge: Cambridge university press.
Trammell, L. H. and Kroman, A. M. (2013). "Bone and Dental Histology". In: *Research Methods in Human Skeletal Biology*. Elsevier, pp. 361–395. DOI: 10.1016/B978-0-12-385189-5.00013-3.
Tschumi, O. (1949). *Urgeschichte Der Schweiz*. Frauenfeld.
Tubb, P. C. (2011). *The LBA/EIA Transition in the Vale of Pewsey, Wiltshire*. BAR Publishing. DOI: 10.30861/9781407308418.
Tucker, K., Berezina, N., Reinhold, S., Kalmykov, A., Belinskiy, A., and Gresky, J. (2017). "An Accident at Work? Traumatic Lesions in the Skeleton of a 4th Millennium BCE "Wagon Driver" from Sharakhalsun, Russia". *HOMO* 68.4, pp. 256–273. DOI: 10.1016/j.jchb.2017.05.004.
Turcotte, C. M., Rabey, K. N., Green, D. J., and McFarlin, S. C. (2022). "Muscle Attachment Sites and Behavioral Reconstruction: An Experimental Test of Muscle-bone Structural Response to Habitual Activity". *American Journal of Biological Anthropology* 177.1, pp. 63–82. DOI: 10.1002/ajpa.24410.
Turney, C. S., Jones, R. T., Thomas, Z. A., Palmer, J. G., and Brown, D. (2016). "Extreme Wet Conditions Coincident with Bronze Age Abandonment of Upland Areas in Britain". *Anthropocene* 13, pp. 69–79. DOI: 10.1016/j.ancene.2016.02.002.
Tyers, I., Marshall, P., Bronk Ramsey, C., Dunbar, E., Hajdas, I., Palstra, S. W. L., Reimer, P., and Wacker, L. (2024). "Chapter 33 - Chronology". In: *Must Farm pile-dwelling settlement: Volume 2. Specialist reports*. In collab. with Apollo-University Of Cambridge Repository and University Of Cambridge. McDonald Institute for Archaeological Research. DOI: 10.17863/CAM.107132.
Van Pelt, R. W. (1975). "Tarsal Degenerative Joint Disease in Cattle: Blood and Synovial Fluid Changes". *American Journal of Veterinary Research* 36.7, pp. 1009–1014.
Van Willigen, S., Ozainne, S., Guélat, M., Haller, A.-L. G., and Haller, M. (2024). "New evidence for prehistoric ploughing in Europe". *Humanities and Social Sciences Communications* 11.1, p. 372. DOI: 10.1057/s41599-024-02837-5.
Vann, S. (2008). "Animal Palaeopathology at Two Roman Sites in Southern Britain". In: *Current Research in Animal Palaeopathology: Proceedings of the Second ICAZ Animal Palaeopathology Working Group Conference*. Ed. by Z. Miklíková and R. Thomas. BAR International Series 1844. Oxford, England: Archaeopress, pp. 27–39.
Vigne, J. D. and Helmer, D. (2007). "Was Milk a "Secondary Product" in the Old World Neolithisation Process? Its Role in the Domestication of Cattle, Sheep and Goats". *Anthropozoologica* 42.2, pp. 9–40.
Villotte, S. and Knüsel, C. J. (2013). "Understanding Entheseal Changes: Definition and Life Course Changes: Understanding Entheseal Changes". *International Journal of Osteoarchaeology* 23.2, pp. 135–146. DOI: 10.1002/oa.2289.
Villotte, S., Castex, D., Couallier, V., Dutour, O., Knüsel, C. J., and Henry-Gambier, D. (2009). "Enthesopathies as Occupational Stress Markers: Evidence from the Upper Limb". *American Journal of Physical Anthropology*, NA–NA. DOI: 10.1002/ajpa.21217.
Villotte, S., Assis, S., Cardoso, F. A., Henderson, C. Y., Mariotti, V., Milella, M., Pany-Kucera, D., Speith, N., Wilczak, C. A., and Jurmain, R. (2016). "In Search of Consensus: Terminology for Entheseal Changes (EC)". *International Journal of Paleopathology* 13, pp. 49–55. DOI: 10.1016/j.ijpp.2016.01.003.
Villotte, S. and Santos, F. (2023). "The Effect of Age on Entheseal Changes: A Study of Modifications at Appendicular Attachment Sites in a Large Sample of

Identified Human Skeletons". *International Journal of Osteoarchaeology* 33.3, pp. 389–401. DOI: 10.1002/oa.3197.
von den Driesch, A. (1976). *A Guide to the Measurement of Animal Bones from Archaeological Sites*. Peabody Museum Bulletin 1. Cambridge, Mass: Peabody Museum of Archaeology and Ethnology, Harvard University.
Wainwright, G. J. and Longworth, I. H. (1971). *Durrington Walls Excavations, 1966-1968*. London: The Society of Antiquaries.
Walker, J. (1990). "Scientific Dating". In: Bell, M. *Brean down: Excavations 1983-1987*. Swindon: English Heritage, pp. 107–112.
Wallace, I. J., Winchester, J. M., Su, A., Boyer, D. M., and Konow, N. (2017). "Physical Activity Alters Limb Bone Structure but Not Entheseal Morphology". *Journal of Human Evolution* 107, pp. 14–18. DOI: 10.1016/j.jhevol.2017.02.001.
Ward, W. H. (1910). *The Seal Cylinders of Western Asia*. The Carnegie Institute of Washington.
Watson, D. (1931). "The Animal Bones from Skara Brae". In: *Skara Brae: A Pictish Village in Orkney*. London: Kegan Paul, Trench, Trubner, pp. 198–204.
Weiss, E., Corona, L., and Schultz, B. (2012). "Sex Differences in Musculoskeletal Stress Markers: Problems with Activity Pattern Reconstructions". *International Journal of Osteoarchaeology* 22.1, pp. 70–80. DOI: 10.1002/oa.1183.
Weiss, E. (2004). "Understanding Muscle Markers: Lower Limbs". *American Journal of Physical Anthropology* 125.3, pp. 232–238. DOI: 10.1002/ajpa.10397.
— (2014). "Bipedalism and Musculoskeletal Stress Markers: Variation and What It Reveals About Adaptation, Environmental Stress, and Reconstructing Activity Patterns". In: *Reconstructing Mobility*. Ed. by K. J. Carlson and D. Marchi. Boston, MA: Springer US, pp. 31–47. DOI: 10.1007/978-1-4899-7460-0_3.
— (2015). "Examining Activity Patterns and Biological Confounding Factors: Differences between Fibrocartilaginous and Fibrous Musculoskeletal Stress Markers: Entheseal Changes and Activity Reconstruction". *International Journal of Osteoarchaeology* 25.3, pp. 281–288. DOI: 10.1002/oa.2290.
Whitefield, A. (2017). "Neolithic 'Celtic' Fields? A Reinterpretation of the Chronological Evidence from Céide Fields in North-western Ireland". *European Journal of Archaeology* 20.2, pp. 257–279. DOI: 10.1017/eaa.2016.5.
Whitehead, G. K. (1953). *The Ancient White Cattle of Britain and Their Descendants*. Faber and Faber Limited. London.
Whittle, A. (2002). "The Coming of Agriculture People, Landscapes, and Change c.4000 –1500 Bc". In: Slack, P. and Ward, R. *The Peopling of Britain: The Shaping of a Human Landscape*. Linacre Lectures 1999. Oxford New York: Oxford University Press, pp. 77–109.
Whittle, A., Bayliss, A., and Healy, F. (2011). "The North Wiltshire Downs". In: *Gathering Time: Dating the Early Neolithic Enclosures of Southern Britain and Ireland*. Oxford ; Oakville, CT: Oxbow Books, pp. 60–110.
Wilczak, C. A. (1998). "Consideration of Sexual Dimorphism, Age, and Asymmetry in Quantitative Measurements of Muscle Insertion Sites". *International Journal of Osteoarchaeology* 8.5, pp. 311–325. DOI: 10.1002/(SICI)1099-1212(1998090)8:5<311::AID-OA443>3.0.CO;2-E.
Wimmer, B. (2018). "Sexual Dimorphism in Cattle Molars: A Metrical Investigation Comparing Dental and Cranial Variables Based on Modern Specimens from the Julius Kühn Collection at Halle, Germany". Unpublished Master Dissertation. The University of Sheffield.
Wolff, J. (1986). *The Law of Bone Remodelling*. Berlin, Heidelberg: Springer Berlin Heidelberg. DOI: 10.1007/978-3-642-71031-5.

Worley, F., Madgwick, R., Pelling, R., Marshall, P., Evans, J. A., Lamb, A. L., López-Dóriga, I. L., Bronk Ramsey, C., Dunbar, E., Reimer, P., Vallender, J., and Roberts, D. (2019). "Understanding Middle Neolithic Food and Farming in and around the Stonehenge World Heritage Site: An Integrated Approach". *Journal of Archaeological Science: Reports* 26, p. 101838. DOI: 10.1016/j.jasrep.2019.05.003.

Wright, T., Miller, N. F., and Redding, R. (1980). "Time and Process in an Uruk Rural Center". In: *L'Archéologie de l'Iraq: Perspectives et Limites de l'Interpretation Anthropologique Des Documents*. Ed. by M. Barrelet. Paris: Èditions du CNRS, pp. 265–284.

Yates, D. (1999). "Bronze Age Field Systems in the Thames Valley". *Oxford Journal of Archaeology* 18.2, pp. 157–170. DOI: 10.1111/1468-0092.00077.

— (2001). "Bronze Age Agricultural Intensification in the Thames Valley and Estuary". In: Brück, J. *Bronze age landscapes: tradition and transformation*. Oxford: Oxbow books, pp. 65–82.

— (2007). *Land, power and prestige: bronze age field systems in Southern England*. Oxford: Oxbow.

Yonemoto, S. (2016). "Differences in the Effects of Age on the Development of Entheseal Changes among Historical Japanese Populations". *American Journal of Physical Anthropology* 159.2, pp. 267–283. DOI: 10.1002/ajpa.22870.

Zeder, M. A. (2008). "Domestication and early agriculture in the Mediterranean Basin: Origins, diffusion, and impact". *Proceedings of the National Academy of Sciences* 105.33, pp. 11597–11604. DOI: 10.1073/pnas.0801317105.

Zumwalt, A. (2006). "The Effect of Endurance Exercise on the Morphology of Muscle Attachment Sites". *Journal of Experimental Biology* 209.3, pp. 444–454. DOI: 10.1242/jeb.02028.