The Number of Distinct Elements: Extending a landmark-based counting unit to other taxa

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Abstract

Quantification of skeletal remains in faunal assemblages is often central to the study of human behavior at archaeological sites. Recently, we introduced the Number of Distinct Elements (NDE) as a simpler, experimentally robust alternative to the Minimum Number of Elements (MNE). The MNE is a widely used counting method that has been shown to inflate the representation of rare elements and is affected by the issue of aggregation, among other problems (Morin et al. 2017, *Journal of Archaeological Method and Theory* 24, 938–973). The NDE approach avoids both of these issues because it focuses on a specific suite of constant landmarks, which means that counts are independent of sample size. The present paper discusses how the NDE differs from MNE and zone-based recording methods and expands its use to equids, suiformes, camelids, tapirids, proboscideans, rhinocerotids and carnivores. A list of NDE landmarks is also presented for typically smaller animals, such as glires (rodents and lagomorphs), birds and turtles/tortoises.

Keywords: Faunal analysis; Zooarchaeology; Archaeozoology; NISP; MNE; NDE

Introduction

Quantifying the abundance of animal remains generally plays a pivotal role in archaeozoological research (e.g., Davis 1987; Lyman 2008; Reitz and Wing 2008; Gifford-Gonzalez 2018). Producing accurate and reproducible counts allows for meaningful comparisons between assemblages varying in sample size and taxonomic and/or anatomical abundances, among other factors. Analyses of skeletal representation that require counts based on independent elements commonly use Binford's (1978, 1984) Minimum Number of Elements (MNE) for assessing abundance. However, MNE is afflicted by a number of problems. First, values are not additive and must be re-calculated each time the size and/or the boundaries of a sample are modified (the "problem of aggregation," Grayson 1984). Another well-known problem associated with MNE is a severe lack of standardization in how to count specimens (e.g., Marean et al. 2001; Lyman 2008; Reitz and Wing 2008; Gifford-Gonzalez 2018). Furthermore, recent research shows that MNE inflates the representation of rare elements (Morin et al. 2017). As we show below, these problems are important as they have undesirable effects on the robustness and accuracy of MNE as a measure of abundance. By "accuracy," we mean that the tallies are expected to be statistically representative, at least at the ordinal level, of the relative abundances of elements recovered at a site.

We have previously introduced a landmark-based approach—the Number of Distinct Elements (NDE)—as a possible solution to these problems (Morin et al. 2017). In the previous paper, we identified the rationale for the NDE and presented landmarks for bovids and cervids. The present contribution has two main goals: i) to give an overview of the NDE concept and how it differs from MNE and from other recording

systems based on diagnostic zones (e.g., Watson 1979; Dobney and Rielly 1988; Davis 1992), and ii) to extend the NDE approach to several new taxa, including equids, suiformes, camelids, tapirids, proboscideans, rhinocerotids, carnivores, glires (rodents and lagomorphs), birds and turtles/tortoises. With these new additions, it should now be possible to apply the NDE approach to whole assemblages in a wide range of archaeological contexts. However, before introducing these new landmarks, it is useful to place the NDE into a broader historical context.

Watson's "diagnostic zones" approach and the "greater than 50%" rule

While studying the fauna from Khirokitia, a Neolithic site in Cyprus, Watson (1979) noted problems when estimating the relative abundances of taxa in the assemblage. Among other issues, he emphasized that variation in fragmentation and patterns of juvenile representation could bias counts against or in favor of certain species. Such variations are a source of concern because greater fragmentation, or a greater proportion of juveniles in an assemblage, tends to inflate the Number of Identified Specimens (NISP) through the addition of new identifiable fragments or whole bone parts (e.g., unfused epiphyses) to the tallies. To counter these potential biases, Watson developed a new counting method focused on "diagnostic zones," using sub-regions of a bone as a basis for quantification instead of the entire element. Watson suggested that a reliable diagnostic zone should "be as species-specific and as commonly preserved as possible, suitable for unfused as well as fused material, as free as possible from age-biases and as rarely as possible broken or split" (Watson 1979:129). Key to this approach

is the notion that specimens are only recorded when they comprise more than 50% of a diagnostic zone, which prevents the same element from being counted twice. This means that any fragment lacking a diagnostic zone, or containing less than 50% of the zone's cortical surface, is not counted. Among other advantages, Watson (1979:135–136) emphasized that this recording method allows considerable flexibility in interpretation and improves comparability of results.

Following Watson's lead, other archaeozoologists have refined his approach or developed similar recording methods based on diagnostic zones and the "greater than 50%" rule (e.g., Bogucki 1982; Rackham 1986; Dobney and Rielly 1988; Davis 1992; Outram et al. 2005; Russell and Martin 2005). The approach has also been extended to human (Knüsel and Outram 2004; Mack et al. 2016) and bird (Cohen and Serjeantson 1996) remains. Although some of these approaches—hereafter referred to as zone-based recording methods—have been used for generating specimen counts (e.g., Davis 1992; Russell and Martin 2005), many of them appear to have served as scaffolds for deriving more traditional measures such as the MNE or MNI (the Minimum Number of Individuals) and for improved recording of patterns of preservation, fragmentation and bone surface modification, as is the case for the system put forward by Dobney and Rielly (Dobney and Rielly 1988; Outram et al. 2005; Marom 2016). These emphases, combined with the fact that the approaches have not diffused widely beyond the British school of Neolithic specialists, probably explain why these recording systems have received only limited attention in discussions of faunal quantification, including popular textbooks (e.g., Lyman 2008; Reitz and Wing 2008; Gifford-Gonzalez 2018).

The Number of Distinct Elements

Like zone-based recording methods, the NDE builds on the notion that a specimen is only counted when more than 50% of a given landmark is present—the greater than 50% rule. However, the NDE differs from previous approaches drawing on the same principle in its exclusive focus on specimen counts and in being a landmark- rather than a zone-based method. In addition, unlike some recording systems (e.g., Dobney and Rielly 1988; Münzel 1988), the NDE was not specifically designed for the examination of patterns of preservation or the study of mark distribution, although the approach may be used for this purpose as well. In general, NDE landmarks correspond to easily identifiable features of skeletal elements, such as nutrient foramina and strong muscle attachments. When possible, we selected landmarks that are relatively small and robust to increase the chance of finding them complete, even on highly fragmented elements. For example, the *Fovea capitis* and the nutrient foramen constitute two distinct landmarks (#18 and 19, respectively) for the proximal femur of bovids and cervids, both of which can be identified on small specimens.

NDE counts are based exclusively on a specific list of landmarks. All skeletal elements are covered by the approach, including small and fragile bones (e.g., hyoid, sesamoids). In determining NDE, any bone or tooth fragment containing more than 50% of the cortical surface of a given landmark adds one to the NDE count for that landmark. For instance, Figure 1 shows how to count the NDE for a bovid or cervid talus ("astragalus" in the earlier nomenclature, landmark #72). The NISP and MNE for this assemblage are the same, while the value of the NDE is smaller by 1. This is because

landmark #72 is too incompletely represented on the rightmost specimen to be added to the NDE count. This counting procedure prevents the same osteological feature from the same original skeletal element from being counted twice, resolving the problem of specimen interdependence that affects NISP in fragmented assemblages. To reduce subjectivity, we suggest using a square cutout made of flexible material (e.g., solid fabric, thin plastic) to assist in evaluating the coverage of an incomplete landmark, as illustrated in Figure 1. The size of the cutout varies to accommodate differences in body size: an internal side of 10 mm is used for small species (<50 kg), 15 mm for moderate-sized species (50–250 kg), and 25 mm for large species (>250 kg). The landmark must be placed at the center of the cutout to determine its completeness.

To account for the tendency of larger elements to become more fragmented than smaller ones, the number of landmarks used for the NDE generally scales with the size of the element. For instance, in our list of landmarks for bovids and cervids, we provided four landmarks for long bones, two for vertebrae (except for the caudal vertebrae, which have only one), and one each for carpals and the minor tarsals. A single specimen from a larger element could therefore potentially contribute to the NDE count for multiple landmarks. Having a greater number of landmarks for large elements increases the odds of accurately estimating the abundance of a skeletal part, by compensating for differential representation of bone portions due to variable preservation or sampling error. This problem is of lesser concern in small elements, as they are, at least in prehistoric contexts, frequently recovered relatively complete (e.g., Watson 1979; Morin et al. 2017). The landmarks provided for long bones cover the main bone regions typically considered in

ethnoarchaeological analyses and utility indices (i.e., proximal end, proximal shaft, distal shaft and distal end).

Counting and Norming NDE

When quantifying skeletal abundance for elements with a single landmark, the count for the landmark gives the NDE. In elements with several landmarks (e.g., long bones), abundance estimates can be derived from the NDE simply by taking the largest NDE count for any landmark listed for that skeletal part, as shown in Figure 2. To account for variation in the number of skeletal elements in different species, NDE counts per element can be normed using the abundance of an element in a skeleton (Normed NDE, or NNDE), in a manner similar to the NNISP (Normed NISP, Grayson and Frey 2004) and MAU (Minimum Number of Animal Units, Binford 1984) routines. For instance, an NDE tally of 24 for the femur would give an NNDE of 12 because there are two femora in the vertebrate skeleton. Moreover, side can be included in the NDE counts for paired elements by simply entering an “L” (for left) or an “R” (for right) in a spreadsheet column.

Like NISP, NDE counts can be summed by species and used to evaluate differences in taxonomic abundances over time and space (note again that when summing the values, only the highest NDE count is retained for an element with two or more landmarks). However, to counter the problem of inter-species variation in the number of skeletal elements, it may sometimes appear preferable to sum NDE counts that have been normed. This strategy may be particularly productive when, for instance, comparing

monodactylous (e.g., equids) with pentadactylous species (a feature common in carnivores). In this situation, we suggest taking the sum of normed NDE values (∑NNDE) to generate a total standardized element count for each taxon. One advantage of this taxonomic approach is that it can be used to assess the robustness of patterns of rank order derived with different measures of abundance, regardless of whether the tallies are normed or not (i.e., ∑NISP versus ∑NDE, see Morin and Soulier 2017 for an example). Although in general we suggest that NDE counts should be used alongside NISP, identification based only on NDE landmarks is also an efficient alternative to NISP for rapid assessment of the skeletal and taxonomic abundances of large assemblages (e.g., for preliminary study).

Because it provides an estimate for a "minimum" number of elements in a sample, the NDE can serve many of the same purposes than the MNE. For example, NDE counts may be used for comparisons with utility indices (Binford 1978), for measuring species richness and evenness (Faith and Du 2018) or in analyses of bone mineral density (Lam et al. 2003). In the latter case, however, the fit between scan sites and landmarks may not always be perfect. In such cases, the count for the nearest landmark should be used.

The NDE can easily be integrated into spreadsheet-based recording methods currently employed by faunal analysts. For NISP-based spreadsheets, NDE information can be entered by simply adding a column in which to record the landmark number(s) observed on a specimen. Analysts might alternatively prefer to have each row in the spreadsheet represent a unique NDE identification instead of a single identified specimen. In such cases, NDE data on individual specimens may be contained in as many as four

(or five, in the case of metapodials in cervids) rows when the specimen is a complete long bone.

Despite its advantages, the NDE is not without limitations. For instance, in contexts where a very specific type of analysis must be considered—such as calculating proportions of dry-bone fractures for long bone shaft fragments—other metrics such as NISP or the total number of shaft fragments may prove more practical. Likewise, the NDE is less than an optimal approach when sample sizes are small, a problem that also plagues MNE. In these situations, NISP remains the best available alternative. Despite these caveats, we believe that the NDE constitutes a productive method for recording taxonomic, skeletal and taphonomic information in most archaeozoological contexts.

Differences between the NDE, MNE and zone-based methods

As pointed out above, a number of issues make MNE a problematic measure of abundance. In this section, we examine how the NDE differs from the MNE and other recording methods regarding these problems.

One notorious issue with MNE is that counts may be derived differently depending on the analyst's training. For instance, some record elements as fractions of complete bones (e.g., Klein and Cruz-Uribe 1984), while others prefer to count them as integers (e.g., Bunn and Kroll 1986; Morlan 1994). Another point of disagreement centers on the issue of whether counts should focus on articular ends or both articular ends and shaft portions (Turner 1989; Bunn 1991; Marean and Kim 1998; Stiner 2002; Pickering et al. 2003; Yravedra and Domínguez-Rodrigo 2009). A further source of

concern is that analysts vary widely in their use of criteria of age, sex, size and idiosyncrasies for “matching” (distinguishing) elements; some use several or all of these criteria, whereas other analysts simply ignore them (Klein and Cruz-Uribe 1984; Lyman 1994; Reitz and Wing 2008). The NDE avoids these problems because the approach is based on a standard list of landmarks that precludes matching using criteria of age, sex, size, or other unique features of the animal. Regardless of these characteristics, a specimen only contributes to the NDE for a landmark when it is at least 50% complete.

Just as MNI exaggerates the representation of rare species (Ducos 1968), the MNE approach inflates the representation of rare elements (Morin et al. 2017). This is because MNE typically uses *any* zone of overlap, and sometimes any idiosyncrasy, for the identification of a new element. In small samples, one can often easily find a new zone of overlap that provides a larger MNE count, particularly when criteria such as age or size are considered. However, as sample size gets larger, it becomes progressively harder to find a fragment showing a zone that can raise the count, while criteria such as age and size become increasingly difficult to apply. This results in MNE tallies increasing at a decelerating rate relative to NISP, creating a curvilinear relationship. There is no such relationship between the NDE and sample size, because NDE landmarks are invariant and independent of previous identifications. The only issue that matters with the NDE is whether more than 50% of the landmark is preserved.

Another serious limitation of MNE is the problem of aggregation. As is the case with MNI, MNE counts for a given site can vary depending on how the stratigraphic or spatial boundaries are defined, because skeletal elements are unlikely to be evenly distributed between aggregates (Grayson 1984). NDE tallies are not affected by this

problem, as they are based on landmarks that do not vary with the boundaries of the sample. Consequently, NDE counts for each landmark are additive. However, for NDE counts to be fully additive, it is important to report all counts for all landmarks identified in the collection of interest, preferably in table format.

Despite the need for several lists of landmarks—one for each of the main groups of taxa (e.g., cervids/bovids, equids)—to implement the NDE, trained archaeozoologists can quickly learn how to use this measure. Our experience with students indicates that it can be mastered within a few hours. The gain in time is quite substantial when compared to traditional approaches such as MNE because the measure does not require additional handling of the material as, for instance, when one needs to lay out the specimens on a table to look for physical overlap. In addition to decreasing variation between analysts, the additivity of NDE counts makes the approach well-suited to analyses of faunal material from sites with ongoing excavations (Gifford-Gonzalez 2018). Moreover, the approach can be fruitfully applied to the counting of very large assemblages (NISP>5,000), contexts in which the MNE is very impractical.

One criticism of the NDE raised since the publication of our original article is that the approach decreases the power of statistical tests because it tends to provide slightly smaller counts than MNE (Lyman 2018). While the NDE will indeed often produce somewhat lower tallies than MNE (as illustrated in Figure 1), this critique does not take into account the fact that MNE *tends to inflate the representation of rare elements*, a problem with sample size that should be of far greater concern to faunal analysts than a slight decrease in absolute count (and therefore, in statistical power). In other words, the non-linear behavior of MNE with increasing sample size—an issue accentuated when

sex, size and other idiosyncrasies are considered, as these are more easily assessed in certain categories of elements than in others—seems far more problematic than the possibility of producing a Type II error. By focusing on invariable landmarks and by precluding matching, the NDE gives values that are more similar in terms of numerical behavior across samples. The result is that statistical analyses based on the NDE approach should produce more accurate and more reproducible results *irrespective of sample size* than those based on MNE, even though tests using the NDE may have marginally reduced power due to slightly smaller counts.

While quite different from MNE, the NDE is relatively close in its construction to zone-based recording methods (e.g., Watson 1979; Bogucki 1982; Rackham 1986; Dobney and Rielly 1988; Davis 1992; Outram et al. 2005). Although it is beyond the scope of the present study to proceed with a systematic comparison of these recording systems, it is worth emphasizing a few important points that distinguish the zone-based methods from the NDE. A first notable difference is that the NDE focuses on relatively small landmarks (e.g., nutrient foramen, medial malleolus) rather than on broadly defined zones. Figure 3 provides examples of these differences for two of the better-known zone-based approaches. As shown in this figure, the NDE landmarks cover smaller surfaces on large elements, such as the femur and mandible, than the other two methods. Given this feature, the NDE should, assuming large sample sizes and substantial fragmentation, yield higher counts for these parts than the other two approaches, as the landmarks under scrutiny are smaller, and therefore, more likely to be fully preserved on small fragments. This problem has real field implications, as noted by Russell and Martin (2005:38) in their application of Bogucki's (1982) variant of Watson's approach: "The use of

diagnostic zones is somewhat problematic for an assemblage such as that of Çatalhöyük, where the bones are so fragmented that it is relatively rare to encounter more than half of a diagnostic zone." Rackham (1986:189) also raised this issue in his discussion of computerized approaches to faunal tallies. Because its landmarks are small, the NDE should generally be less susceptible to undercounting than the zone-based methods.

Another distinction between the NDE and zone-based methods concerns the range of elements considered. Some zone-based recording systems ignore certain categories of elements (Figure 3, lower). For instance, Watson's (1979) recording system omits parts that are considered difficult to identify to species, such as vertebrae and ribs. Likewise, the protocols devised by Dobney and Rielly (1988) and Davis (1992) ignore some elements (e.g., skull, minor tarsals, vestigial metapodials and phalanges). Although these authors provided entirely valid justifications for their decisions, including these skeletal parts can provide valuable insights into an assemblage. For instance, the relative abundance of carpals and tarsals may inform the study of carnivore ravaging (Marean 1991) and shed light on the selective use of bone as fuel (Castel 1999; Morin 2010). Moreover, certain bone portions that are now the center of much attention—the shaft of long bones particularly—are disregarded in certain recording systems (e.g., Watson 1979; Davis 1992). In contrast, the NDE includes landmarks for all skeletal parts and all major long bone portions because we believe that quantification measures should not make any a priori assumptions about the identifiability or analytical importance of skeletal elements and bone parts. The points made above suggest that the design of zone-based methods may make them less effective in some assemblages and, consequently, less generalizable than a method that covers the entire skeleton.

Landmarks for other taxa

By definition, NDE landmarks are taxon-specific. The initial list of landmarks that we assembled focused on cervids and bovids (Morin et al. 2017, Table 4), because these taxa are similar in terms of skeletal morphology and are commonly encountered in the archaeological contexts with which we are most familiar (North America and Europe). In extending the approach to other taxa, we made efforts to use the same or equivalent landmarks and the same landmark numbers to make it easier to record patterns of skeletal representation across taxa and to facilitate memorization of the landmarks. However, the landmark numbers for birds and turtles/tortoises had to be substantially adjusted due to the considerable anatomical differences observed in these taxa relative to mammals.

Terrestrial ungulates

Figures 4–5 provide landmarks for equids. The list, which is presented in Table 1, includes landmarks 1–87 (#64 and 77 were duplicated to account for the presence of different bones in equids), which is similar to the list of 87 landmarks published for bovids and cervids. Landmarks were also identified for suiformes (suids and tayassuids, Figures 6–7). In this case, the list of landmarks (#1–87, Table 2) shows, in comparison to cervids and bovids, several minor changes for the metapodials, carpals, and tarsals. The supporting information provides landmarks for four additional herbivore taxa that have

more limited geographic and temporal distribution in the archaeological record: camelids (Supporting Figures S1–S2, Supporting Table S1), tapirids (Supporting Figures S3–S4, Supporting Table S2), rhinocerotids (Supporting Figures S5–S6, Supporting Table S3) and proboscideans (Supporting Figures S7–S8, Supporting Table S4).

Carnivores and glires (rodents and lagomorphs)

The list of landmarks for carnivores (Supporting Table S5) can be applied to canids, felids and hyaenids (Supporting Figures S9–S10) and should also apply well to mustelids and procyonids. The number of landmarks for these taxa (#1–89) is comparable to the list produced for ursids (#1–88, Supporting Figures S11–S12, Supporting Table S6). Ursids were separated from other carnivores because they are much larger, and consequently, have a slightly different skeletal anatomy. The landmarks for glires (Supporting Table S7, #1–89) should be applicable to most species attributed to this clade, including beaver (*Castor* spp.), rabbit (*Oryctolagus* spp., *Sylvilagus* spp.), hare (*Lepus* spp.), agouti (*Dasyprocta* spp.), paca (*Cuniculus paca*) and porcupine (e.g., *Erethizon dorsatum*). As is the case for birds and turtles/tortoises (see below), no illustrations were made for glires, as we believe that the list is self-explanatory in the case of small animals.

Birds and turtles/tortoises

Because their skeletal anatomy differs substantially from that of mammals, the list of landmarks is different for birds (#1–68, Supporting Table S8). For turtles and tortoises, we created a list that includes landmarks #1–87 (Supporting Table S9). In this case, we made an effort to cover terrestrial, freshwater, and marine species. Table 3 provides a summary of the NDE models available at the moment and how they can be applied to various taxa.

Conclusions

The NDE was developed in an effort to increase accuracy and reproducibility in faunal analysis. With the expanded list of taxa presented here, the NDE approach should now be applicable to a broad range of archaeological contexts, including most sites from North America, Eurasia and Africa. The important advantages of the NDE are that the measure: i) is more standardized than MNE, ii) is not influenced by sample size nor by the boundaries of the sample, iii) can easily be applied to large assemblages, and iv) does not necessitate assessing physical overlap between specimens, which results in substantial time gains. The NDE also improves on zone-based recording methods in that it focuses on a set of small diagnostic landmarks and considers all elements of the skeleton. In addition, we note that the NDE can be fruitfully used in teaching, for instance for emphasizing features that play a crucial role in identification.

We encourage other archaeozoologists to develop and share standardized landmark lists for taxa they encounter in their research area that are not covered by our published lists (e.g., fish, reptiles, primates, marine mammals, marsupials, xenarthrans).

The guiding principles for producing such lists are simple: one should focus on small, easily identified landmarks that can be identified even when the specimens are fragmented. To minimize confusion when switching from a list to another, attention should be paid to using landmarks that correspond as closely as possible to those already included in the published lists.

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Supporting information

Figure S1. Location of landmarks for camelid long bones.

Figure S2. Location of landmarks for camelid non-long bones.

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Tables

Ldmk#	Landmarks
	humerus
1	Lmk1 (juncture between the *Caput humeri* and the greater tubercle)
2	Lmk2 (base of the *Tuberositas teres major*)
3	Lmk3 (foramen)
4	Lmk4 (fossa of the *Capitulum*)
	radius
5	Lmk1 (proximal portion of the *Tuberositas radii*)
6	Lmk2 (proximal surface of the articular surface with the ulna)
7	Lmk3 (medial anterior ridge of the distal radius)
8	Lmk4 (radial styloid process, rudimentary in equids)
	ulna
9	Lmk1 (proximo-anterior section of the *Tuber olecrani*)
10	Lmk2 (proximo-medial portion of the trochlear notch)
11	Lmk3 (lateral coronoid process)
12	Lmk4 (ulnar styloid process, rudimentary in equids)
	metacarpal
13	Lmk1 (anterior portion of the ridge separating the two main proximal articular surfaces)
14	Lmk2 (articular surface for metacarpal II)
15	Lmk3 (proximo-anterior portion of the intermediate ridge)
16	Lmk4 (fossa of the medial condyle + fossa of the lateral condyle)/2
17	Not relevant for equids
	femur
18	Lmk1 (*Fovea capitis*)
19	Lmk2 (proximal portion of the third trochanter)
20	Lmk3 (foramen)
21	Lmk4 (posterior portion of the facet on the axial face of the lateral condyle)
	tibia
22	Lmk1 (*Sulcus extensorius*)
23	Lmk2 (distal portion of the foramen)
24	Lmk3 (constriction of the lateral ridge)
25	Lmk4 (medial malleolus)
	metatarsal
26	Lmk1 (anterior portion of the ridge separating the two anterior articular surfaces)
27	Lmk2 (articular surface for metatarsal II)
28	Lmk3 (proximo-anterior portion of the intermediate ridge)
29	Lmk4 (fossa of the medial condyle + fossa of the lateral condyle)/2
30	Not relevant for equids
	indeterminate metapodial
31	(fossa of the medial condyle + fossa of the lateral condyle)/2
	other bones
32	not relevant for equids
33	cranium (worn or unworn UD4 + worn UM3)/2; mesial lobe[a]
34	(petrosal, >50%)/2
35	mandible (worn or unworn LD4 + worn LM3); mesial lobe[a]
36	(*Foramen mentale*)
37	(mandibular condyle)

38	hyoid (proximal section of the stylohyoideum, >50%)
39	(epihyoideum, >50%)
40	(basihyoideum, proximal section, >50%)
41	atlas (cranial view, left articular surface)
42	(caudal view, inter-articular notch)
43	axis (central portion of the *Dens axis*)
44	(dorsal section of the cranial articular surface, left side)
45	other cervical vertebrae (base of the spinous process, anterior side)
46	(cranial articular process, left side)
47	thoracic vertebrae (cranial articular surface, left side)
48	(cranial *Fovea costalis*, left side)
49	lumbar vertebrae (cranial articular surface, left side)
50	(medio-anterior portion of the transverse process)
51	sacrum (left portion of the cranial surface of the centrum)
52	(dorsal extremity of the spinous process of the 2nd sacral vertebrae)
53	caudal vertebrae (centrum, cranial side)
54	rib (proximal end)
55	(distal end)
56	sternebrae (>50% of the bone)
57	scapula (cranial portion of the glenoid cavity)
58	(proximal portion of the *Spina scapulae*, rising section)
59	(constricted portion of the distal axillary border)
	carpals
60	scaphoid (>50%)
61	lunatum (>50%)
62	triquetrum (>50%)
63	pisiform (>50%)
64cap	capitatum (>50%)
64tra	trapezoid (>50%)
65	hamatum (>50%)
66	innominates (foramen on the lateral side of the ilium)
67	(acetabulum: ischium portion)
68	(acetabulum: pubis portion)
69	patella (anterior view, central portion)
70	(posterior view, apex)
71	fibula (=malleolus in bovids/cervids) (proximal portion)
	tarsals
72	talus (distal portion of the anterior side of the groove of the trochlea)
73	(proximal portion of the articular surface for the calcaneus)
74	calcaneus (proximo-anterior portion of the *Tuber calcanei*)
75	(anterior portion of the articular surface for the talus)
76	(distal extremity, articular surfaces for the cuboid and talus)
77cub	cuboid (>50%)
77nav	navicular (posterior portion of the articular surface, dorsal view)
78	smaller cuneiform (>50%)
79	greater cuneiform (posterior articular surface, dorsal view)
80	phalanx 1 (portion of the proximal articular surface near the anterior aspect)
81	phalanx 2 (portion of the proximal articular surface near the anterior aspect)
82	phalanx 3 (portion of the proximal articular surface near the anterior aspect)
83	not relevant for equids
84	not relevant for equids
85	not relevant for equids
86	vestigial metapodial (>50%)
87	sesamoids (>50%)

[a]Only teeth showing more than 50% of the occlusal surface for the mesial lobe are counted.

Table 1. NDE landmarks for equids.

Ldmk#	Landmarks
	humerus
1	Lmk1 (base of the greater tubercle)
2	Lmk2 (base of the *Tuberositas teres major*)
3	Lmk3 (foramen)
4	Lmk4 (fossa of the *Capitulum*)
	radius
5	Lmk1 (*Tuberositas radii*)
6	Lmk2 (proximal surface of the articular surface with the ulna)
7	Lmk3 (distal surface of the articular surface with the ulna)
8	Lmk4 (radial styloid process)
	ulna
9	Lmk1 (proximo-anterior portion of the olecranon)
10	Lmk2 (proximo-medial portion of the trochlear notch)
11	Lmk3 (lateral coronoid process)
12	Lmk4 (ulnar styloid process)
	metacarpal
13	Lmk1 (>50% of the proximal portion)
14	Not relevant for suiformes
15	Not relevant for suiformes
16	Lmk4 (>50% of the distal portion)
17	Not relevant for suiformes
	femur
18	Lmk1 (*Fovea capitis*)
19	Lmk2 (foramen)
20	Lmk3 (proximal portion of the *Fossa supracondylaris*)
21	Lmk4 (posterior portion of the facet on the axial face of the lateral condyle)
	tibia
22	Lmk1 (*Sulcus extensorius*)
23	Lmk2 (distal portion of the foramen)
24	Lmk3 (constriction of the lateral ridge)
25	Lmk4 (medial malleolus)
	metatarsal
26	Lmk1 (>50% of the proximal portion)
27	Not relevant for suiformes
28	Not relevant for suiformes
29	Lmk4 (>50% of the distal portion)
30	Not relevant for suiformes
	indeterminate metapodial
31	distal epiphyses (>50%)
	other bones
32	not relevant for suiformes
33	cranium (worn or unworn UD4 + worn UM3)/2; mesial lobe[a]
34	(petrosal, >50%)/2
35	mandible (worn or unworn LD4 + worn LM3); mesial lobe[a]
36	(*Foramen mentale*, immediately caudal to the canine)
37	(mandibular condyle)
38tymp	hyoid (tympanohyoideum, >50%)
38styl	(stylohyoideum, >50%)
39	(epihyoideum, >50%)
40cera	(ceratohyoideum, >50%)
40basi	(basihyoideum, proximal section, >50%, generally fused with thyrohyoideum)
41	atlas (cranial view, left articular surface)
42	(caudal view, inter-articular notch)

43	axis (central portion of the *Dens axis*)
44	(dorsal section of the cranial articular surface, left side)
45	other cervical vertebrae (base of the spinous process, cranial side)
46	(cranial articular process, left side)
47	thoracic vertebrae (cranial articular surface, left side)
48	(cranial *Fovea costalis*, left side)
49	lumbar vertebrae (cranial articular surface, left side)
50	(medio-anterior portion of the transverse process)
51	sacrum (left portion of the cranial surface of the centrum)
52	(dorsal extremity of the spinous process of the 2nd sacral vertebrae)
53	caudal vertebrae (>50%)
54	rib (proximal end)
55	(distal end)
56	sternebrae (>50% of the bone)
57	scapula (cranial portion of the glenoid cavity)
58	(base of the spinous process)
59	(constricted portion of the distal axillary border)
	carpals
60	scaphoid (>50%)
61	lunatum (>50%)
62	triquetrum (>50%)
63	pisiform (>50%)
64trap	trapezium (>50%)
64trapd	trapezoid (>50%)
64cap	capitatum (>50%)
65	hamatum (>50%)
66	innominates (insertion surface for the sacrum, caudal part, >50%)
67	(acetabulum: ischium portion)
68	(acetabulum: pubis portion)
69	patella (anterior view, central portion)
70	(posterior view, apex)
	fibula (=malleolus in bovids/cervids)
71pe	(proximal end, >50%)
71ps	(proximal shaft, >50%)
71ds	(distal shaft, >50%)
71de	(distal end, >50%)
	tarsals
72	talus (proximal portion of the lateral surface)
73	(proximal portion of the medial surface)
74	calcaneus (posterior portion of the *Tuber calcanei*)
75	(anterior portion of the articular surface for the talus)
76	(distal extremity, articular surface for the cuboid)
77cub	cuboid (anterior portion of the articular surface for the calcaneus)
77nav	navicular (>50%, articular surface for the medial and intermediate cuneiforms)
78int	intermediate cuneiform (>50%) (smaller cuneiform in cervids and bovids)
78med	medial cuneiform (>50%) (smaller cuneiform in cervids and bovids)
79	lateral cuneiform (>50%) (greater cuneiform in cervids and bovids)
80	phalanx 1 (>50% of the proximal portion)
81	phalanx 2 (>50% of the proximal portion)
82	phalanx 3 (>50% of the proximal portion)
83	vestigial phalanx 1 (digits II & V) (>50% of the distal portion)
84	vestigial phalanx 2 (digits II & V) (>50% of the distal portion)
85	vestigial phalanx 3 (digits II & V) (>50% of the distal portion)
86	vestigial metapodial (digits II & V) (>50% of the proximal portion)
87	sesamoids (>50%)

[a]Only teeth showing more than 50% of the occlusal surface for the mesial lobe are counted.

Table 2. NDE landmarks for suiformes.

Class/Order	Family	Model
Artiodactyls	Bovidae (e.g., cattle)	"Bovids, cervids" (Morin et al. 2017)
	Cervidae (e.g., red deer)	"
	Giraffidae (e.g., giraffe)	"
	Antilocapridae (e.g., pronghorn)	"
	Suidae (e.g., pig)	"Suiformes" (Fig. 6–7)
	Tayassuidae (e.g., peccary)	"
	Camelidae (e.g., camel)	"Camelids" (Fig. S1–S2)
Perissodactyls	Equidae (e.g., horse)	"Equids" (Fig. 4–5)
	Tapiridae (e.g., tapir)	"Tapirids" (Fig. S3–S4)
	Rhinocerotidae (e.g., rhinoceros)	"Rhinocerotids" (Fig. S5–S6)
Proboscideans	All families (e.g., elephant)	"Proboscideans" (Fig. S7–S8)
Carnivores	Felidae (e.g., lion)	"Carnivores" (Fig. S9–S10)
	Hyaenidae (e.g., hyena)	"
	Canidae (e.g., dog)	"
	Mustelidae (e.g., badger)	"
	Procyonidae (e.g., raccoon)	"
	Ursidae (e.g., bear)	"Ursids" (Fig. S11–S12)
Glires	All families (e.g., rabbits, beaver)	"Glires" (Table S7)
Birds	All families (e.g., duck, grouse)	"Birds" (Table S8)
Testudines	All families (e.g., turtle, tortoise)	"Turtles/Tortoises" (Table S9)

Table 3. Taxonomic groups and the equivalent NDE model that can be used for counting faunal remains.

Figure captions.

Figure 1. Example of how NDE values are counted, in comparison to NISP and MNE.

Figure 2. Derivation of NDE values for complete elements with multiple landmarks.

Figure 3. Comparisons of the NDE with the recording methods of Watson (1979) and Dobney and Rielly (1988) for the femur and mandible. Illustrations for Watson's approach are based on his descriptions, whereas those for Dobney's and Rielly's system are modified from their paper (Dobney and Rielly 1988, Figures 7 and 12).

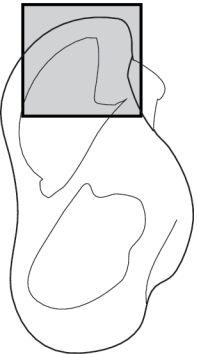
Figure 4. Location of landmarks for equid long bones. The model for the bones is the horse (*Equus caballus*). The landmarks are described in Table 1. All images of elements are from the left side.

Figure 5. Location of landmarks for equid non-long bones. The model for the bones is the horse (*Equus caballus*). The landmarks are described in Table 1. All images of elements are from the left side.

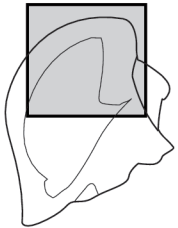
Figure 6. Location of landmarks for suiforme long bones. The model species is the pig (*Sus scrofa*). The landmarks are described in Table 2. All images of elements are from the left side.

Figure 7. Location of landmarks for suiforme non-long bones. The model species is the pig (*Sus scrofa*). The landmarks are described in Table 2. All images of elements are from the left side.

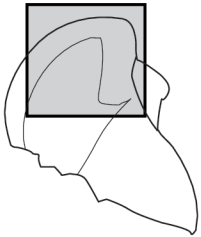
NISP =1
MNE =1
NDE =1



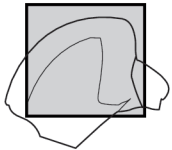
NISP =1
MNE =1
NDE =1



NISP =1
MNE =1
NDE =1



NISP =1
MNE =1
NDE =1



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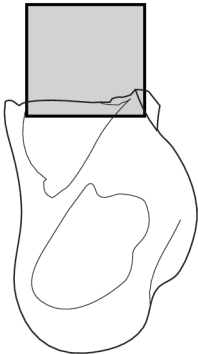
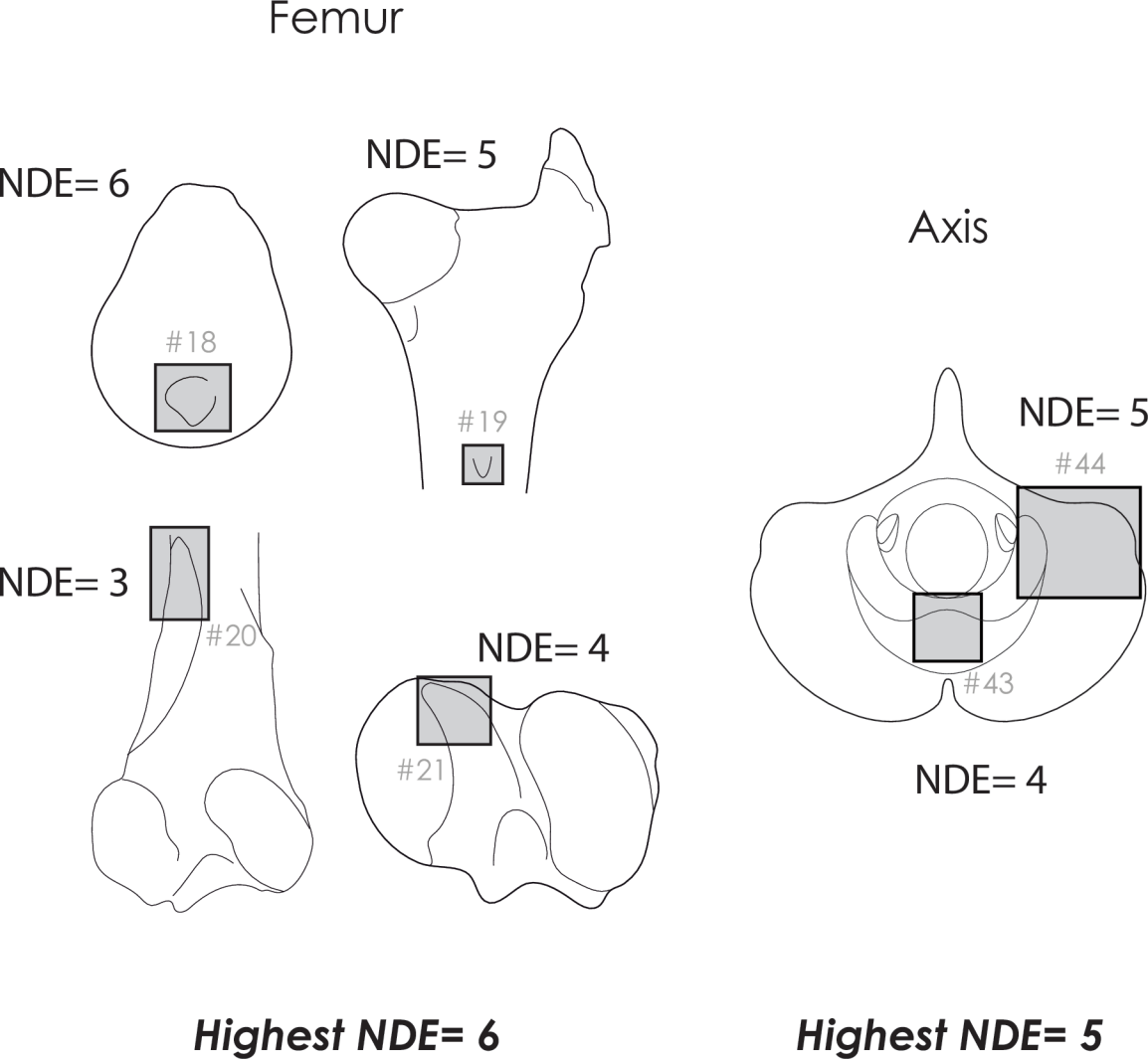
MNE =1
NDE =0



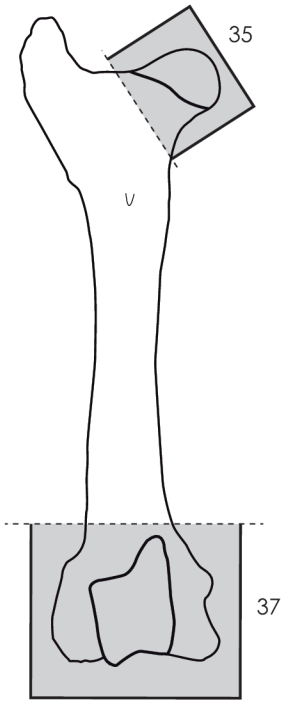


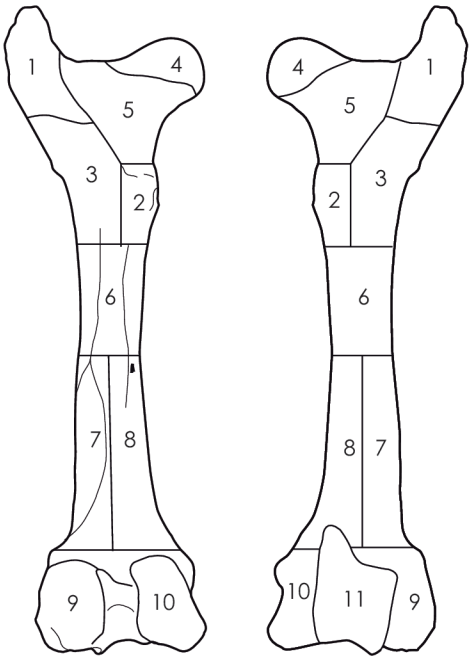
Highest NDE= 6

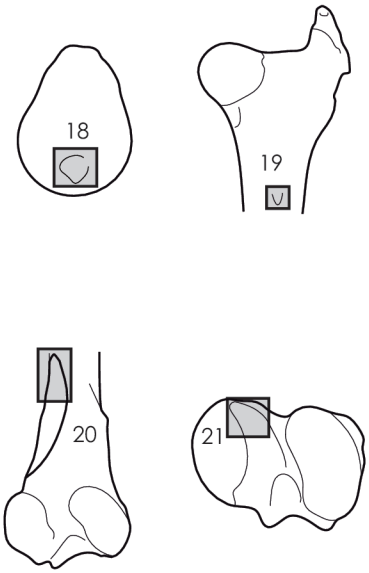
Highest NDE= 5

Watson (1979) | Dobney and Rielly (1988) | This study

Femur

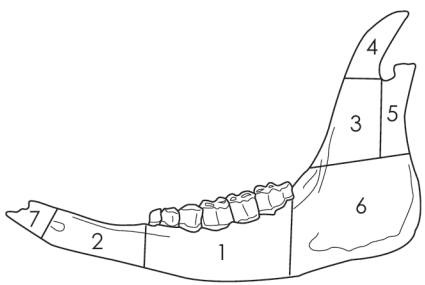


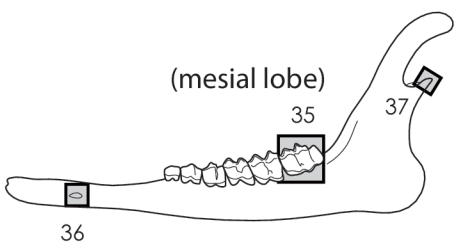




Mandible

>50%

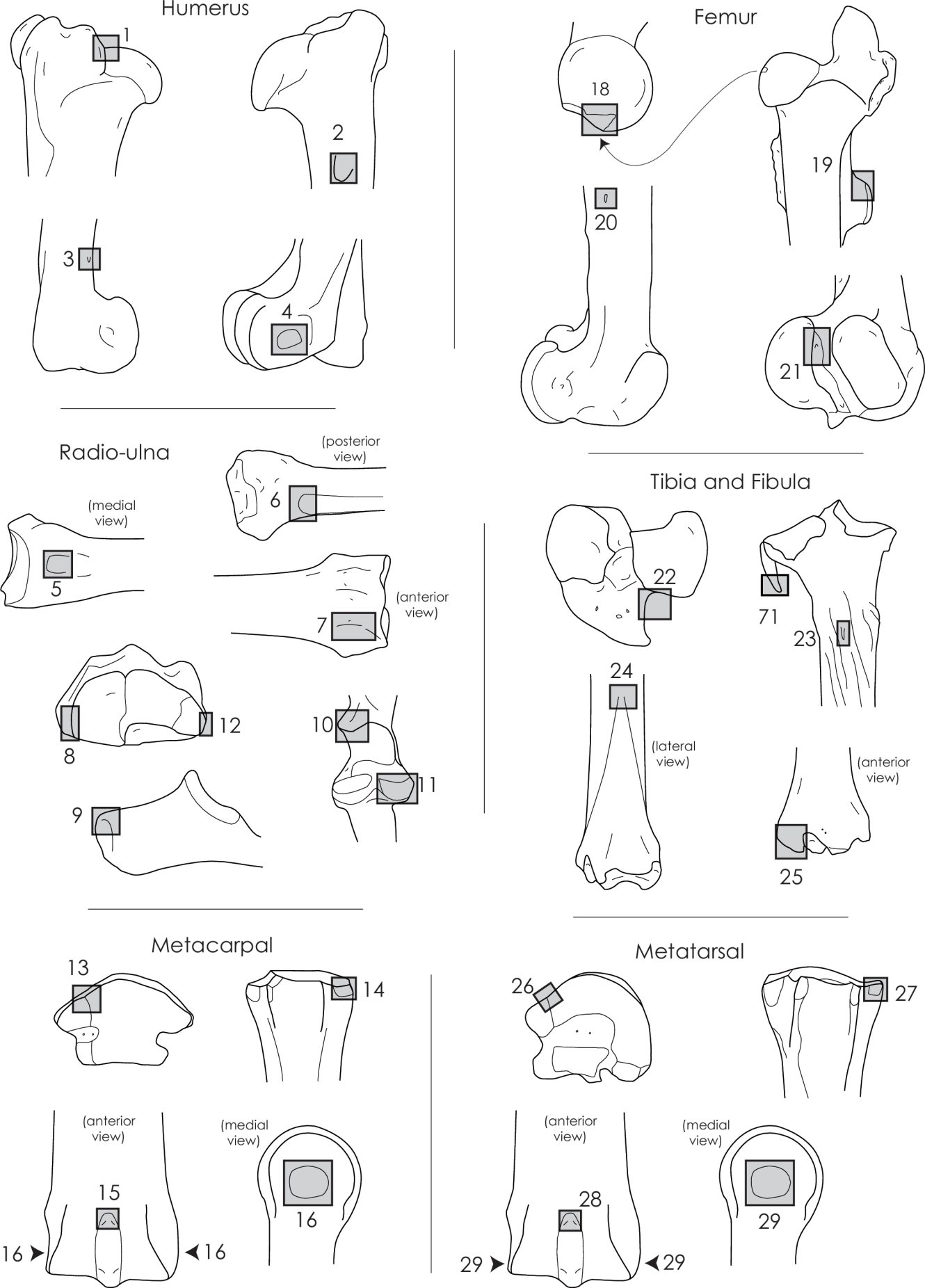


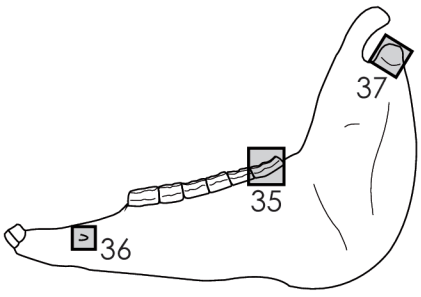


Parts excluded: antler/horn, hyoid, ribs, vertebtrae, sternebrae, sacrum, fibula, minor tarsals other than cuboid, sesamoids, vestigial metapodials and phalanges

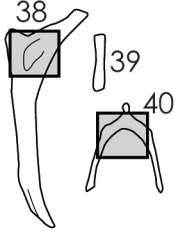
Parts excluded: skull, antler/horn, hyoid, sternebrae, sacrum, patella, lateral malleolus, fibula, carpals and minor tarsals, sesamoids, vestigial metapodials and phalanges

Parts excluded: none


Humerus
1
2
3
4
Femur
18
19
20
21
Radio-ulna
(posterior view)
6
(medial view)
5
(anterior view)
7
12
8
10
11
9
Tibia and Fibula
22
71
23
24
(lateral view)
(anterior view)
25
Metacarpal
13
14
(anterior view)
15
16
16
(medial view)
16
Metatarsal
26
27
(anterior view)
28
29
29
(medial view)
29

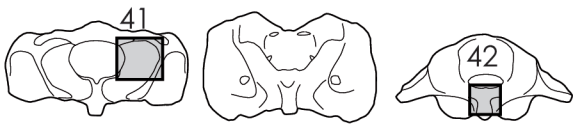


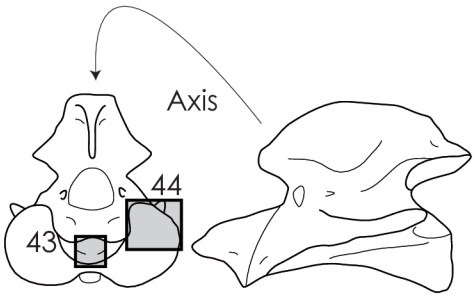
Mandible

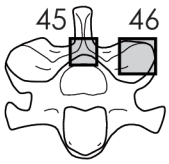


Hyoid

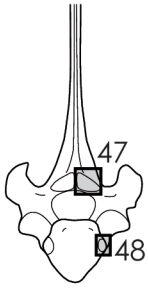
Atlas



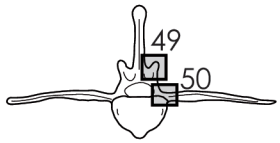




Other cervical vertebrae

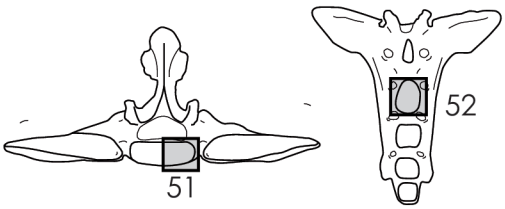


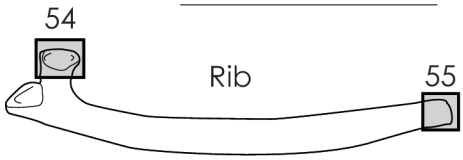
Thoracic vertebrae



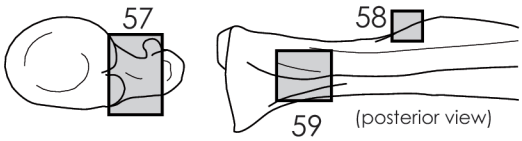
Lumbar vertebrae

Sacrum

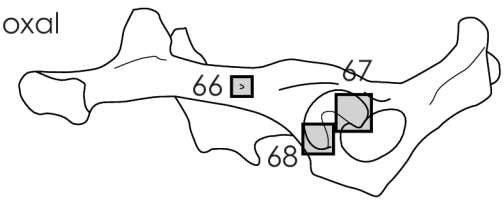




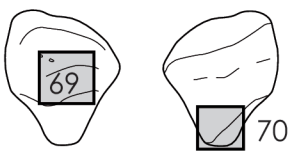
Scapula



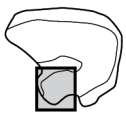
Coxal



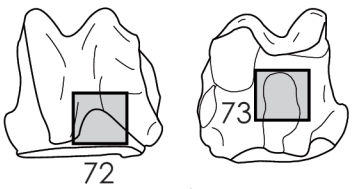
Patella



Navicular

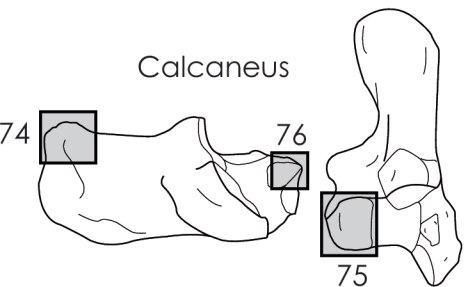


77nav

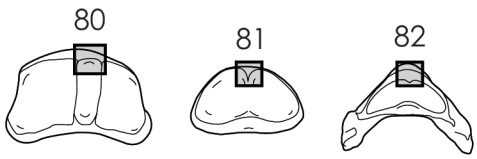


Talus

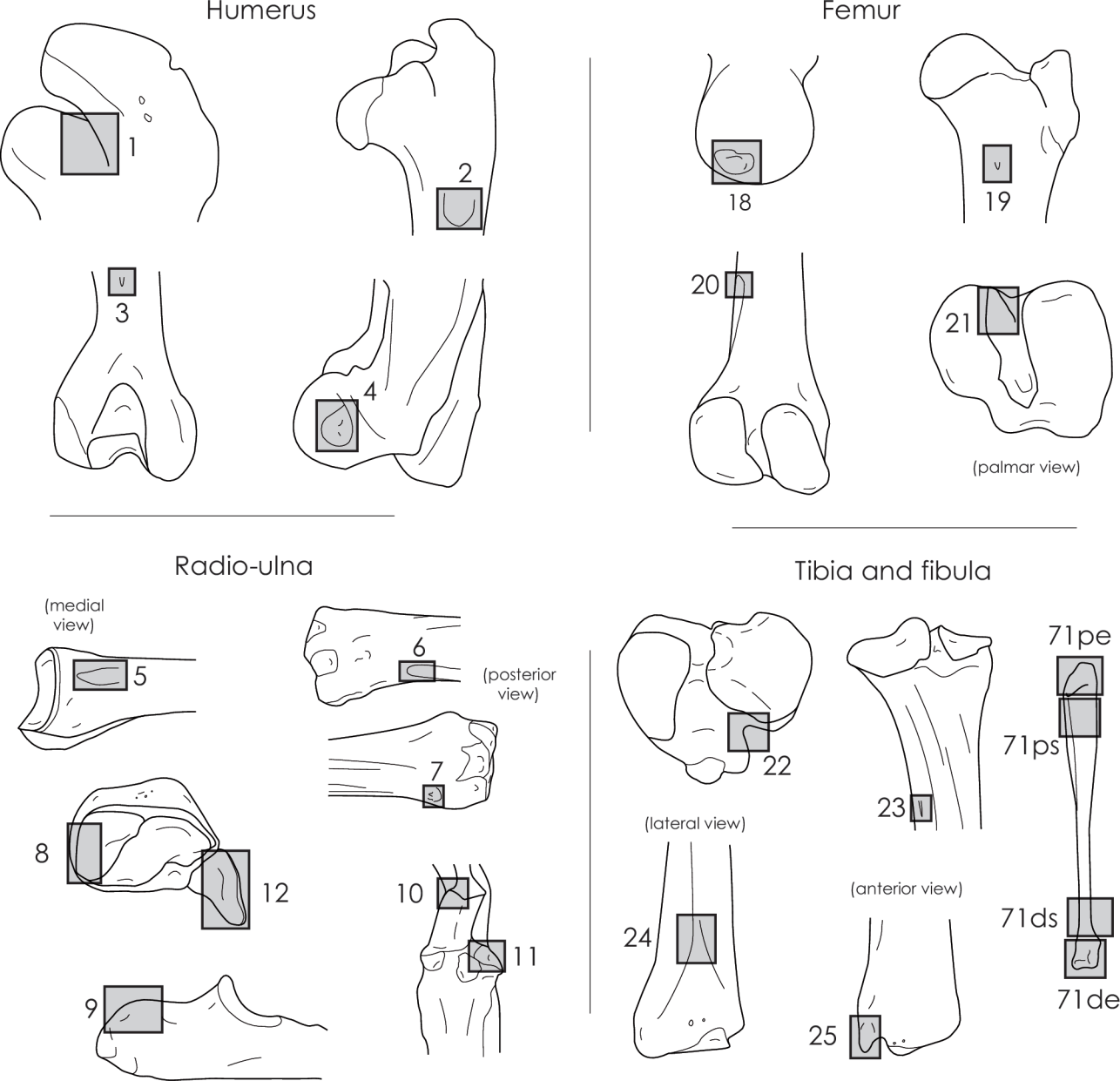
Calcaneus

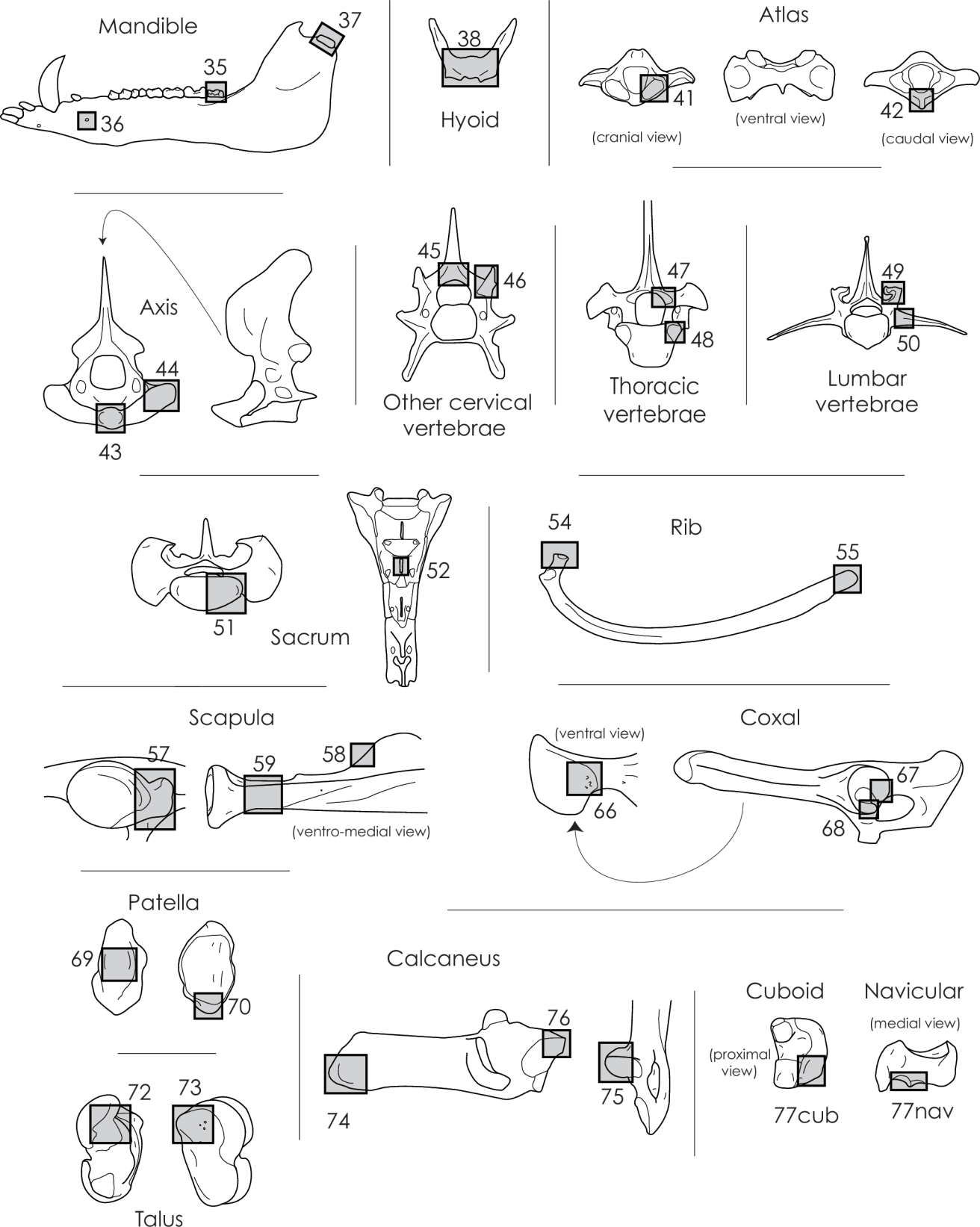


Greater cuneiform



Phalanx 1 Phalanx 2 Phalanx 3


Humerus
1
2
3
4
Femur
18
19
20
21
(palmar view)
Radio-ulna
(medial view)
5
6
(posterior view)
7
8
12
10
11
9
Tibia and fibula
22
23
71pe
71ps
71ds
71de
(lateral view)
24
(anterior view)
25


Mandible
37
35
36
38
Hyoid
Atlas
41
(cranial view)
(ventral view)
42
(caudal view)
Axis
44
43
45
46
Other cervical vertebrae
47
48
Thoracic vertebrae
49
50
Lumbar vertebrae
51
Sacrum
52
54
Rib
55
Scapula
57
59
58
(ventro-medial view)
(ventral view)
66
Coxal
67
68
Patella
69
70
72
73
Talus
Calcaneus
74
76
75
Cuboid
(proximal view)
77cub
Navicular
(medial view)
77nav