Differential diagnosis of vertebral spinous process deviations in archaeological and modern domestic dogs

Dennis F. Lawler^{a,e,*}, Christopher C. Widga^a, David A. Rubin^b, Jennifer A. Reetz^c, Richard H. Evans^e, Basil P. Tangredi^f, Richard M. Thomas^g, Terrence Martin^a, Charles Hildebolt^b, Kirk Smith^b, Daniel Leib^d, Jill E. Sackman^h, James G. Averyⁱ, Gail K. Smith^c

^a Illinois State Museum, Research and Collections Center, 1011 East Ash St., Springfield, IL 62703-3500, USA

^b Mallinckrodt Institute of Radiology (Box 8131), Washington University School of Medicine, 510 S. Kingshighway Blvd, St Louis, MO 63110, USA

^c Department of Clinical Studies, School of Veterinary Medicine, University of Pennsylvania, 3900 Spruce St., Philadelphia, PA 19104, USA

^d 11506, BJCIH, Washington University in St Louis, MO 63110, USA

^e Pacific Marine Mammal Center, 20612 Laguna Canyon Road, Laguna Beach, CA 92651, USA

^f Department of Biology, Green Mountain College, Poultney, VT 05764 USA

^g School of Archaeology and Ancient History, University of Leicester, University Road, Leicester, UK, LE1 7RH

^h Numerof & Associates, Inc., Four City Place Drive, Suite 430, St. Louis, MO 63141, USA

ⁱ Department of Internal Medicine, Washington University School of Medicine, (Grant Medical Clinic, 114 N. Taylor Ave., St. Louis MO 63108, USA)

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***Corresponding author:**

CC Widga; Illinois State Museum Research & Collections Center; Springfield IL
cwidga@museum.state.il.us

Abstract

Paleopathological study of domestic animal remains can elucidate human-domesticate relationships, when all reasonable differential diagnoses are considered. Deviated spinous processes found on ancient domesticated dog vertebrae have been assumed to result from pack burdens, although consideration of diagnostic alternatives has been unclear. To more thoroughly assess the potential significance of these features, we first generated an extensive differential diagnosis of potential causes. Broad causal categories included: (i) morphological; (ii) infectious; (iii) taphonomic; (iv) life history (*in utero* to death), with numerous subcategories that sometimes overlap. We then evaluated these possibilities through an observational and radiology study of 15 ancient deliberate domestic dog burials (191 vertebrae) from the midwestern USA, dating between 10,130 and 200 years ago. **Archaeological specimens from the UK were included to evaluate for geographic uniqueness of our observations.** We characterized deviations of spinous processes of cervical (n=74), thoracic (n=51), lumbar (n=60), and sacral (n=6) vertebrae. Affected spinous processes were found in 34% of cervical vertebrae, 63% of thoracic vertebrae, 78% of lumbar vertebrae, and 50% of sacral vertebrae. Four types of spinous process deviations were observed: (a) lateral leaning from the base but not otherwise deviated; (b) lateral curving at some point above the base; (c) bowing because of multiple curves; and (d) torsion along the vertical axis. Computed tomography and micro-computed tomography were essential tools for establishing differential diagnoses.

1. Introduction

Ancient animal bones offer a unique biological record that informs upon the health of animals associated with human cultures, and indirectly addresses relationships between humans and their domesticates (Baker, J.R. Brothwell, 1980; Davies et al., 2005; Bartosiewicz and Gal, 2013). Although there is a long history of paleopathological study in archaeology (Moodie, 1923), advanced imaging technology (Chhem and Brothwell, 2008), an expanding knowledge base, and increasing academic interest (Davies et al., 2005; Miklíková and Thomas, 2008), demand clarified interpretations.

Dogs and humans have maintained a domestic relationship for at least 12,000 years. Although the exact origins of this relationship remain somewhat obscure (Miklosi, 2007; Larson et al., 2012), the close association of dogs and humans in cultural contexts lend special significance to dog evolution and behavior (Morey, 2006, 2010). Paleopathological studies can contribute new understandings of the nature of human-dog relationships through analyses of behaviorally-influenced damage to bones and joints, or diseases and injuries sustained through life activities (Snyder, 1995; Tourigny et al., 2015). Dog paleopathology specifically has the potential to inform about subsistence or mobility strategies among human groups (Warren, 2004; Lawler et al., 2015).

Previous paleopathological studies of domestic dogs have focused on opportunistic observations of gross pathologies (Warren, 2004; Walker et al., 2005; Ware, 2006). Only rarely (Tourigny et al., 2015) have such studies incorporated medical imaging (radiology and tomography) or rigorous differential diagnosis, despite example work in human paleopathology (Miller et al., 1996; Ortner, 2003; Lynnerup, 2010) and forensics (Jalalzadeh, H. et al., 2015).

Deviated spinous processes of domestic dog vertebrae have been observed with inter-vertebral osteoarthritis, presumed compression fractures of epiphyseal endplates, and scapular modification (Snyder, 1995; Warren, 2004). However, arguments that deviated spinous processes suggest use as a pack animal were made in the absence of observing associated pathologies (Warren, 2000; Darwent and Gililand, 2001; Walker et al., 2005) or providing for differential diagnosis. Thus, the interpretation became perpetuated in literature when in fact the early diagnoses actually were speculative and in need of further study.

We present a differential diagnosis of deviated vertebral spinous processes in archaeological domestic dogs. We include archaeological dog remains from ~~the midwestern USA and~~ Great Britain for comparative evaluation for geographical uniqueness of our observations, and have used computed tomography and digital radiography in selected instances. Although we narrow the range of diagnostic possibilities, limitations inherent in archaeological materials often preclude definitive diagnosis.

2. Materials and Methods

Most vertebral remains that are described in this report are curated at the Illinois State Museum Research and Collections Center, Springfield IL USA. The specimens represent both deliberate burials and isolated vertebrae recovered from nine archaeological sites in Illinois and Missouri (Fig. 1) (Fowler, 1959; Griffin and Morse, 1961; Wray and MacNeish, 1961; Parmalee et al., 1972; McMillan, 1976; Morey and Wiant, 1992). These assemblages span the Archaic to late Mississippian periods, from 10,130 – 200 cal BP (Table 1). Vertebrae from a Roman (mid-2nd to mid-3rd century AD) dog recovered from Alchester, Oxfordshire UK, were included to evaluate similar morphologies from a geographically, taphonomically, and temporally distant context.

2.1 Zooarchaeological and Taphonomic observations

2.1.1 Biological Factors

Earlier zooarchaeological observations of buried dogs were focused partly on establishing age and sex of individuals. A detailed scheme for aging *Canis lupus lupus* based on tooth wear (Nowak et al., 2000) was not used because our age categories were too coarse to account for uncertainties of diet and lifestyle influences.

We assessed age on a relative scale, considering degree of epiphyseal union of major long bones, along with dental eruption and attrition. Individuals <2 years of age were assigned to general age classes based on long bone epiphyseal closure (Newton and Nunamaker, 1985). Age estimates of individuals >2 years were assessed primarily based on dental attrition.

Shoulder height, a relative measure of body size, was calculated based on humeral length, using standard linear regression equations (Harcourt, 1974). Burials from the Stilwell and Apple Creek (Burial 3) sites lacked humeri, so shoulder height was calculated using radius and femur, respectively.

A baculum (os penis) indicated burial of a male. However, absence of a baculum did not necessarily indicate a female, considering the possibilities of non-preservation, non-recovery, or removal. Thus, burials without a baculum were categorized as female/indeterminate.

We did not assess age, sex, or body-size characteristics of disarticulated, isolated specimens, due to the possibility of mixing elements from different individuals.

2.1.2 Taphonomic Factors

A number of post-mortem taphonomic processes can affect bone integrity and appearance (Lyman, 1994; Haglund and Sorg, 1997), causing partial-to-total destruction. Physical examples of these processes include modification by scavenging animals and sub-aerial weathering that often remove osteological materials from the sedimentary record.

Chemical changes may alter bone morphology *in situ*. Low soil pH can completely remove organic materials. In moist-to-saturated depositional contexts, low pH can affect bone rigidity by promoting decalcification (Brothwell and Gill-Robinson, 2001) and predisposing bones to deformation by sedimentary forces. Carcass decomposition itself promotes a low pH environment (Gill-King, 1997), and drying creates stress on muscle and ligament attachments (Weigelt, 1989). The result can be minor warping of skeletal elements.

To evaluate these taphonomic possibilities, all specimens were examined microscopically (low power magnification) for indicators of a low pH depositional history that include exterior solution pitting and erosion (Johnson et al., 1997), gastric polish (Andrews, 1990), and root etching (Morlan, 1984).

2.2 Gross morphology

Spinous processes were recorded as normal or deviated, with the latter categorized into four types: (a) lateral leaning from the base but otherwise not malformed (Fig. 2a); (b) lateral curving at some point above the spinous base (Fig. 2b); (c) bowing because of multiple curves (Fig. 2c); (d) torsion along the longitudinal axis (Fig. 2d). Data were recorded by spinal region, deviation category and direction, and qualitative severity of pathology. All affected vertebrae were photographed and described. Vertebrae were not measured because the large size variability among ancient dogs, just as among modern dogs, precludes useful biological interpretation.

Statistical analyses (Fisher's exact test) were limited to relationships among leaning, lateral curving, and bowing, for frequency, severity, and right-left direction. Statistical analyses included only data from the Illinois sites and Rodgers Shelter MO. Additional statistical evaluations were not conducted because the data are too sparse for further sub-categorization, especially considering that they are non-independent, and that a valid negative control population cannot be identified.

2.3 Imaging studies

Four vertebrae were transported to Washington University School of Medicine (WUSM, St. Louis MO USA) for non-invasive imaging using microcomputed tomography (μ CT) with a vivaCT 40 (Scanco Medical, Switzerland) instrument, made available through the musculoskeletal structure and strength core at WUSM. These four specimens were selected because visual inspection suggested that different diagnoses would be recognized among them. Imaging parameters for these specimens were 70 kVp and 114 μ A, voxel size 21 μm^3 with an integration time of 300ms. ~~Four vertebrae were selected deliberately as examples, based on suspicion that scanning would yield different diagnoses.~~

Computed tomography (CT) images of four adult dogs (University of Pennsylvania School of Veterinary Medicine, Philadelphia PA USA) also were included to describe vertebral spinous process deviations discovered during life, for comparative evaluation of gross morphologies.

3. Results

3.1 Zooarchaeology and Taphonomy

Over 75% of dogs with available age **indication** were classified as adult or older adult.

Individuals of indeterminate sex were more numerous than known males. Shoulder height calculations ranged from 350-450 mm, approximating modern mid-sized terriers.

There are no complete axial sequences in the archaeological dataset. However, all vertebrae associated with an individual were examined, regardless of morphology. Abnormal spinous processes were noted in 25% to 100% of available vertebrae from individual dog burials. The exception was Apple Creek Burial #4, a young dog with 13% **variant** vertebrae.

Few specimens (n=15; 8%) had pH-related surface damage. Mild-to-moderate pitting was found only at Modoc (Dog #2), Koster (#2256), and ~~Putney~~-Apple Creek (Burial #4). These affected vertebrae reveal concentrations of pitting in areas of strong muscle attachments. Fourteen slightly pitted vertebrae from two individuals had very mild spinous process curving, bowing, or leaning, but pitting was not found with marked deviation of the spinous process. Root etching was found only in Modoc Dog #6090 (n=6 vertebrae), and was highly localized on each surface area <1cm². Gastric polish was not present on any specimens.

3.2 Gross morphology

We evaluated 191 domestic dog vertebrae from 15 deliberate dog burials (n=184), and isolated vertebrae (n=7). Spinous process deviations were observed in 25/74 (34%) of cervical; 32/51 (63%) of thoracic; 47/60 (78%) of lumbar; and 3/6 (50%) of sacral vertebrae. Among deviation categories, lateral leaning occurred primarily as a mild change, while lateral curving and bowing each occurred over a range of severity (Table 2). Longitudinal torsion was noted in only three specimens; these were excluded from statistical analysis. Multiple deviations in a single vertebra occurred only twice; both were combined right leaning and right torsion involving cervical vertebrae

A significant association (P=0.032, Fisher's exact test) was found between deviation category and severity, for leaning and bowing only. No statistically-significant differences were found for right-left distributions (Table 2). Spinous process deviation occurred with vertebral body left-

right (lateral) asymmetry in eleven vertebrae, and with articular facet osteophytes in eight vertebrae. Spinous process deviation did not occur with vertebral body spondylosis. The small sizes and distributions of data subsets precluded additional statistical treatment.

Vertebrae from the Alchester, UK Roman site included five thoracic, five lumbar, and one sacrum from the same individual, collectively revealing spinous process deviations (Fig. 3a-c), osteophytes, articular facet asymmetry, and erosion (Table 3). The features were visually identical to those seen from American sites, from the Archaic to recent history. The Alchester circumstances suggest convenient disposal, and cut mark patterns suggest butchery, in contrast to the deliberate burials that we evaluated from North America.

3.3 Imaging studies

3.3.1 Microcomputed tomography of archaeological specimens

μ CT was used to provide highly detailed images of the cortical and trabecular bone of the four archaeological vertebrae that were selected as examples for further evaluation. This procedure illustrates identification of specific diagnoses in some instances and facilitates recognizing that some archaeological diagnoses remain inconclusive despite advanced diagnostics. Specimens 1 and 2 were from the same dog.

Specimen 1, Apple Creek Burial 6 On the basis of full epiphyseal closure and moderate to heavy dental wear, this was an adult dog. A baculum was not recovered. This thoracic vertebra was used as a reference specimen because it showed no spinous process deviation on visual inspection (Fig. 4a). By μ CT (Fig. 4b), the trabeculae in the spinous process are uniformly distributed, of similar thickness, and arranged into an organized three-dimensional lattice. The cortex is smooth, uninterrupted, and symmetric.

Specimen 2, Apple Creek Burial 6 A lumbar vertebra showing deviation of the spinous process, same dog as *Specimen 1*. Gross examination reveals dorsal-ventral fracture of the spinous process, with obvious leaning to the right (Fig. 5a); μ CT (Fig. 5b) suggests that force was applied from a posterolateral direction, fracturing the bone, but it is not entirely impossible that a dorsal compression could have occurred. There is no visible healing or remodeling, indicating

that the fracture likely occurred either after death or shortly before. The random pattern of the fractured trabeculae is atypical for living individuals, wherein acutely fractured trabeculae usually align in straight or stellate patterns. A definitive diagnosis is not offered, but the features favor post-mortem damage over pre-mortem injury.

Specimen 3, Weaver Site This thoracic vertebra is from a general site assemblage, not a burial; estimates of age and sex were not attempted. Gross examination reveals moderate-severe spinous process lateral curving to the right (Fig. 6a). However, μ CT (Fig. 6b) reveals a trabecular pattern that is not encountered in diseased living subjects. Specifically, this trabecular pattern is not recognizable as one that occurs due to trauma, infection, metabolic, or neoplastic conditions in humans or dogs. No normal trabecular structure can be observed along the curved part of the bone; the width of the bone resembles compact bone that has been “melted” and bent. A more normal bone structure can be seen on either end of the feature.

Possible influences on this feature could involve soil moisture or chemical composition that slowly dissolved normal bone, with re-deposition by precipitation along lines of force. A second taphonomic possibility could be long-term, highly focal compressive or constrictive forces in-ground. A further possibility is that a fracture occurred postmortem, and new loading patterns were superimposed. Combined pre-mortem and post-mortem effects also cannot be ruled out. No healing process is evident, and a definitive diagnosis cannot be identified, even following μ CT evaluation.

Specimen 4, Apple Creek Burial 3 Epiphyseal closure is complete and dentition is heavily worn, indicating an older dog. Gross examination reveals significant lateral lumbar spinous process curving with only slightly increased curving of the neck of the spinous process (Fig. 7a). μ CT (Fig. 7b) reveals trabeculae that are focally very thickened and aligned in a roughly linear-to-curved pattern, with normal trabeculae at the base of the spinous process, volar to this feature. The cortex is composed of mature-looking compact bone that is thicker than normal on the concave side of the curvature. The appearance suggests mature callus formation and a completely healed-remodeled fracture that occurred during life. The amount of healing suggests that the dog lived at least 3-4 months after the injury. A separate crack along the convex surface likely occurred after death; no tissue response is visible.

3.3.2 Computed tomography (CT) of living dogs

Computed tomographic images were included from four living domestic dogs that were presented to the University of Pennsylvania Veterinary Hospital, USA. Medical records provided supporting information that aided each evaluation. In all four cases, while the contour of each spinous process is curved, the ultrastructure of the underlying cortex and trabeculae appear normal, similar to burial *Specimen 1*.

Case 1 (Fig. 8a) German shepherd dog, aged 10 years, with: acute spinal trauma, paraparesis, pneumothorax, T13-L1 subluxation and fracturing, articular facet degenerative joint disease (DJD), degenerative spondylosis, and no prior history of back pain. CT: 2.5mm slice thickness, bone algorithm, bone window (WW3750, WL 340), reveals vertebral spinous process curving at T11; cranial-dorsal articular facet margin osteophytes at T10; and right cranial articular facet ventromedial enlargement at T10, with mild encroachment on the vertebral canal.

Case 2 (Fig. 8b) Dachshund, aged 8 years, with: back pain; T3-L3 spinal cord myelopathy, paraparesis with deep pain present, compressive herniated disc at L2-3, and no prior history of back pain. CT: 1.25mm slice thickness, bone algorithm, bone window (WW 2650, WL 250), reveals vertebral spinous process curving at T11.

Case 3 (Fig. 8c) Mixed breed dog, aged 10 years, with: neck pain and otherwise normal neck evaluation, brain-related neurological signs, pulmonary mass, and no prior history of thoracolumbar pain. CT: 0.63mm slice thickness, bone algorithm, bone window (WW 5900, WL 235), reveals vertebral spinous process curving at T12.

Case 4 (Fig. 8d) Bernese mountain dog, aged 22 months, with urinary incontinence and no prior history of back pain. CT: 2.5mm slice thickness, soft tissue algorithm, bone window (WW 2050, WL 195), reveals vertebral spinous process curving at L3.

3.4 Summary of Findings

3.4.1 Findings were observationally independent of chronological period, site, and **probably** culture; further statistical evaluation would be scientifically tenuous in the study circumstances.

3.4.2 Multiplanar reconstruction and volume-rendering of cross-sectional images provided excellent spatial resolution for tomography (Robertson and Thrall, 2011; Viera et al., 2009). The μ CT results for two selected ancient vertebrae revealed postmortem fracture (Fig. 5b) and possible slow taphonomic change (Fig. 6b). The healed fracture (Fig. 7) was distinguished readily by μ CT.

3.4.3 Observations of living dogs included: acute trauma with prior pathology (Case 1); acute intervertebral disc disease and spinous process deviation proximate to localized clinical signs (Case 2); spinous process deviation distant from localized clinical signs (Case 3); and unassociated spinous process deviation (Case 4).

3.4.4 These data confirm that (a) domestic dog vertebral spinous process deviations occur with varying structure, but usually not in combinations; (b) primary or secondary pathology can be represented causally; (c) spinous process deviations can occur before or after death; (d) there is no evident association with sex or age.

4. Discussion

The origins of deviated vertebral spinous processes can be complex, potentially resulting from many processes that can operate over time. The differential diagnosis format presented below elaborates four primary etiological groupings. The differentials are not mutually exclusive, nor are they equally testable in archaeological contexts. Multiple interacting causes also must be considered.

We recognize that our data raise a number of questions about considering new studies of potential taphonomic influences; climatic factors post-deposition; broad-scope imaging studies, and relationships to other observed pathology. These ideas, while beyond the scope of the present report, do indicate the need to consider the contributors to thorough differential diagnosis, which we now present. The types of damage that occur during storage (breakage,

polish) are clearly distinguishable and unrelated to spinous process deviations, and are not considered further here.

4.1 Abnormal spinal morphology

4.1.1 Bone morphogenesis is diffusely regulated; *purely* genetic causes of isolated vertebral spinous process anomalies are relatively implausible. The developing mammalian fetus is protected *in utero* by a thickened gravid uterine wall and by fetal fluids (Evans and Christensen, 1979), but usually is not protected from biochemical damage. Biochemical events that occur *in utero* and during early life may be diagnostically obscure, but should be considered nonetheless for impact on differential diagnoses.

4.1.2 Hemivertebrae occur primarily in small dogs, especially brachycephalic breeds (Done et al., 1975; White, 2013). Pain, muscle atrophy, abnormal gait, and weakness can be observed in life, but some affected individuals display no overt distress. Regional co-presenting kyphosis or scoliosis may be either secondary or independent events, and a short “screw tail” often is present.

4.1.3 Syringomyelia is a painful condition caused by a large, long, or asymmetrical syrinx in the cervical spinal cord (Rusbridge et al., 2007), and malformation of the caudal occipital bone leads to cerebellar crowding and herniation of brain tissue, obstructing normal flow of cerebrospinal fluid (Rusbridge et al., 2007).

4.1.4 Vertebral malformations may result from unilateral damage causing lateralized loss of paraspinal muscle function, with subsequent atrophy (Van Biervliet et al., 2004) and focal spinal deformity due to unbalanced muscle forces. Or, an upper motor neuron lesion could create lateralized paraspinal muscle dysfunction and result in uniform curving of several vertebral spinous processes.

4.1.5 Mucopolysaccharidosis-I is a lysosomal storage metabolic disease that causes vertebral dysplasia, odontoid hypoplasia of the axis, and intervertebral disk disease. Kypho-scoliosis and spinal cord compression also may be observed (Chiaro et al., 2013).

4.1.6 Scoliosis is a common spinal abnormality among humans, occurring less frequently among dogs. Brachycephalic ‘screw-tailed’ dogs are predisposed; the cervical and thoracic spine are affected most frequently (Grenn and Lindo, 1969; Sponenberg and Bowling, 1985; Breit and

Kunzel, 2002; Guevar et al., 2014). Association with hydromyelia and syringomyelia has been reported (Child et al., 1986; Takagi et al., 2005).

By contrast to domestic dogs, in human scoliosis, the spinous processes of C2-C6 are virtually always bifid, and often bifid at C7. Unilateral hyperplasia at C5, C6, or C7 may be observed (Reinhardt, 1956; Seibert-Daiker, 1975). Thoracic spinous processes usually deviate obliquely from the midline (Freyschmidt et al., 2001). Spinal torsion occurs in the axial plane, and the scoliotic curve in the coronal plane. The spinous processes bend towards the convex side (Wever et al., 1999; Kotwicki and Napiontek, 2008).

4.1.7 Species-independent, non-pathological influences on spinal rotation occur as well. Normal mid-lower (below T5) thoracic spinal rotation to the right has been reported in humans without scoliosis (Kouwenhoven et al., 2006). The same investigators identified a T1-T13 right rotation in the spine of a normal dog. The course of the descending aorta relates closely to the left aspect of the vertebral column in the thoracic region of both species. Rightward rotational forces during development could associate with the position of the aorta (Kouwenhoven et al., 2006a; 2006b), and any subsequent directional change may be dictated by this pre-existing, non-pathological spinal rotation.

4.2 Infection

4.2.1 Most canine spondylitis occurs as diskospondylitis, thus also involving intervertebral disks (Burkert et al., 2005). Diskospondylitis is thought to result from vascular supply to vertebral end plates, transporting infectious agents. Originating sources include the urinary bladder, endocarditis, periodontal disease, respiratory infections, and wounds or migrating foreign bodies such as grass awns (LeCouteur and Grandy, 2000).

4.2.2 Many offending infectious agents have been associated with canine diskospondylitis. Staphylococci are the most common, but Streptococci, *E. coli*, and *Brucella canis*, also are identified with some frequency. Relatively uncommon isolates include *Klebsiella*, *Pseudomonas*, *Proteus*, *Actinomyces*, *Pasteurella*, *Candida*, *Mycobacterium* species, *Aspergillus*, and *Paecilomyces* (LeCouteur and Grandy, 2000). Mixed bacterial infections also are common in animals. The critical diagnostic implication is that genomic testing to identify offending microorganisms must include all possible agents to be credible.

4.3 Taphonomic or post-depositional origin

4.3.1 Carcass burials undergo decomposition phases that simultaneously alter carcass pH and subject the skeleton to internal and external stresses through differential drying. Production of organic acids associated with decay and putrefaction occurs, along with carcass de-fatting, potentially: (a) causing reduced rigidity of vertebral processes in a low pH environment; and (b) subjecting these same elements to directional stresses from drying muscles and ligaments (Weigelt, 1989). **The clarity provided by imaging or histological studies will support ruling in or out at least some post-depositional causes for spinous process deformity.**

4.3.2 Frequencies and interactions among postmortem changes are important aspects of differential diagnosis that must be evaluated as possible causal or influential variables. For instance, pitting of the bone surface in Modoc dog burial #2 occurs in association with robust muscle attachments along the ventral surface of the spinous process, and with mild deviation of spinous processes. However, no cause-effect relationship is clearly supported. Although surface damage from pitting and root etching is uncommon in our dataset, these factors may impact burials in other contexts.

4.4 Life history

4.4.1 Early-life injury resulting in asymmetrical development of axial muscles can lead to secondary asymmetry of back muscles, vertebral spinous process deviation, and degrees of pain (McGill, 2009).

The origins, attachments, and functional interconnections of oblique abdominal and spinal muscles comprise a ‘core strength’ that varies highly among individuals (McGill, 2009). Core muscle weakness or pain results in reduced load-bearing strength and spinal instability, with ultimate secondary bone deformity. Diagnostic criteria include deviation of spinous processes at gross observation, with “normal” trabecular microstructure.

4.4.2 Analysis of skeletal indicators for work-related behaviors (running, carrying loads, grinding corn) is common in bioarchaeology (Larsen, 1987). Long-term, low-level stresses on the skeleton affect bone shape through asymmetrical development of muscle attachments and subsequent remodeling processes.

4.4.3 Trauma causing fracture of a spinous process can result from mistreatment or carrying loads that are too heavy at a young age (prior to development of supporting musculature and bone strength) (Snyder, 1995; Warren, 2000; Darwent and Gililand, 2001; Walker et al., 2005). Diagnostic criteria include formation of a callus-type response (healing bone) and associated re-organization of trabeculae.

Conclusion

It is our view that pathology studies of ancient animals can provide valuable information with respect to animal health and the nature of the human-animal bond, although differential diagnosis must be thorough if interpretations are to be accurate. While definitive diagnosis may not be possible in many instances, imaging studies can produce a narrowed field of possibilities that are most plausible in a given circumstance. **In the case of domestic dog vertebral spinous process deviations, it is evident that earlier causal explanations would need to be re-evaluated in differential diagnosis formats, or discarded.**

We have **indicated a** range of **possible** explanations that could account for deviations of vertebral spinous processes in dogs. **We have provided both specific imaging examples and a discussion of how investigators can use an orderly and detailed process to approach differential diagnosis. Comparative study of vertebrae from a geographically distant site yielded similar observations, indicating that our North America observations are not unique geographically, but also demonstrating that new studies in broader scope are desirable.**

Macroscopic and radiographic analyses, supplemented by computed and microcomputed tomography, along with awareness of rigorous differential diagnosis, are requirements for confident archaeological interpretations. **Our report did not include histology, but increasing use of histological methods will be useful in future diagnostic processes as well.** Another critical factor is to correctly separate taphonomic from biological influences; our observations suggest that this is not uniformly possible, **leading thus to a realization that some differential diagnoses will proceed only as far as a narrowed list of alternatives.**

Supplemental Materials

Computed tomography imagery of the four archaeological specimens will be provided through an online data repository upon acceptance.

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References

- Andrews, P., 1990. Owls, Caves and Fossils: Predation, Preservation and Accumulation of Small Mammals Bones in Caves. University of Chicago Press, Chicago.
- Baker, J.R., Brothwell, D.R., 1980. Animal diseases in archaeology. Academic Press, London.
- Bartosiewicz, L., Gal, E., 2013. Shuffling Nags, Lame Ducks: The Archaeology of Animal Disease. Oxbow Books, Oxford, UK.
- Breit, S., Kunzel, W., 2002. Shape and Orientation of Articular Facets of Cervical Vertebrae (C3-C7) in Dogs Denoting Axial Rotational Ability: An Osteological Study. Eur. J. Morphol. 40, 43–51. doi:10.1076/ejom.40.1.43.13953
- Brothwell, D.R., Gill-Robinson, H., 2001. Taphonomic and Forensic Aspects of Bog Bodies, in: Haglund, W., Sorg, M.H. (Eds.), Advances in Forensic Taphonomy: Method, Theory, and Archaeological Perspectives. CRC Press, New York, pp. 119–131.
- Burkert, B.A., Kerwin, S.C., Hosgood, G.L., Pechman, R.D., Fontenelle, J.P., 2005. Signalment and clinical features of diskospondylitis in dogs: 513 cases (1980-2001). J. Am. Vet. Med. Assoc. 227, 268–275. doi:10.2460/javma.2005.227.268
- Chhem, R., Brothwell, D.R., 2008. Paleoradiology: Imaging mummies and fossils, Paleoradiology: Imaging Mummies and Fossils. Springer Berlin Heidelberg.
- Chiaro, J.A., Baron, M.D., Del Alcazar, C.M., O'Donnell, P., Shore, E.M., Elliott, D.M., Ponder, K.P., Haskins, M.E., Smith, L.J., 2013. Postnatal progression of bone disease in the cervical spines of mucopolysaccharidosis I dogs. Bone 55, 78–83. doi:10.1016/j.bone.2013.03.014
- Child, G., Higgins, R.J., Cuddon, P.A., 1986. Acquired scoliosis associated with hydromyelia and syringomyelia in two dogs. J. Am. Vet. Med. Assoc. 189, 909–912.
- Darwent, C.M., Gililand, J.E., 2001. Osteological Analysis of Domestic Dogs from Burials in Southern Missouri. Missouri Archaeol. 62, 149–169.
- Davies, J., Fabis, M., Mainland, I., Richards, M., Thomas, R., 2005. Diet and health in past

- 440 animal populations : current research and future directions, in: Proceedings of the 9th ICAZ
441 Conference, Durham. Oxbow Books, Oxford, UK.
- 442 Done, S., Drew, R., Robins, G., Lane, J., 1975. Hemivertebra in the dog: clinical and
443 pathological observations. *Vet. Rec.* 96, 313–317. doi:10.1136/vr.96.14.313
- 444 Evans, H.E., Christensen, G.C., 1979. Miller’s anatomy of the dog, 2nd ed. WB Saunders,
445 Philadelphia.
- 446 Fowler, M.L., 1959. Modoc Rock Shelter: An Early Archaic Site in Southern Illinois. *Am. Antiq.*
447 24, 257–270.
- 448 Freyschmidt, J., Brossmann, J., Wiens, J., Sternberg, A., 2001. Borderlands of normal and early
449 pathological findings in skeletal radiography, 5th ed, George Thieme Verlag.
- 450 Gill-King, H., 1997. Chemical and ultrastructural aspects of decomposition, in: Haglund, W.D.,
451 Sorg, M.H. (Eds.), *Forensic Taphonomy: The Postmortem Fate of Human Remains*. CRC
452 Press, New York, pp. 93–108.
- 453 Grenn, H.H., Lindo, D.E., 1969. Hemivertebrae with severe kypho-scoliosis and accompanying
454 deformities in a dog. *Can. Vet. J.* 10, 214–6.
- 455 Griffin, J., Morse, D., 1961. The Short-Nosed God from the Emmons Site, Illinois. *Am. Antiq.*
456 26, 560 – 563.
- 457 Guevar, J., Penderis, J., Faller, K., Yeaman, C., Stalin, C., Gutierrez-Quintana, R., 2014.
458 Computer-assisted radiographic calculation of spinal curvature in brachycephalic “screw-
459 tailed” dog breeds with congenital thoracic vertebral malformations: reliability and clinical
460 evaluation. *PLoS One* 9, e106957. doi:10.1371/journal.pone.0106957
- 461 Haglund, W., Sorg, M.H., 1997. *Forensic taphonomy : the postmortem fate of human remains*.
462 CRC Press, Boca Raton.
- 463 Harcourt, R., 1974. The dog in prehistoric and early historic Britain. *J. Archaeol. Sci.* 1, 151–
464 175.
- 465 Jalalzadeh, H., Giannakopoulos, G.F., Berger, F.H., Fronczek, J., van de Goot, F.R., Reijnders,
466 U.J., Zuidema, W.P., 2015. Post-mortem imaging compared with autopsy in trauma victims
467 - A systematic review. *Forensic Sci. Int.* 257, 29–48.
- 468 Johnson, E., Gutierrez, M., Politis, M., Martinez, G., Hartwell, T., 1997. Holocene Taphonomy
469 at Paso Otero 1 on the Eastern Pampas of Argentina, in: Hannus, L.A., Rossum, L.,
470 Winham, R.P. (Eds.), *Proceedings of the 1993 Bone Modification Conference*, Hot Springs,
471 South Dakota. Archeology Laboratory, Augustana College: Occasional Publication No. 1,
472 Sioux Falls, SD, pp. 105–121.
- 473 Kotwicki, T., Napiontek, M., 2008. Intravertebral deformation in idiopathic scoliosis: a
474 transverse plane computer tomographic study. *J. Pediatr. Orthop.* 28, 225–9.
475 doi:10.1097/BPO.0b013e3181647c4a
- 476 Kouwenhoven, J.-W.M., Vincken, K.L., Bartels, L.W., Castelein, R.M., 2006. Analysis of
477 preexistent vertebral rotation in the normal spine. *Spine (Phila. Pa. 1976)*. 31, 1467–1472.
- 478 Kouwenhoven, J.-W.M., Vincken, K.L., Bartels, L.W., Meij, B.P., Oner, F.C., Castelein, R.M.,

2006. Analysis of preexistent vertebral rotation in the normal quadruped spine. *Spine (Phila. Pa. 1976)*. 31, E754–8. doi:10.1097/01.brs.0000240209.85498.01
- Larsen, C.S., 1987. Bioarchaeological interpretation of subsistence economy and behavior from human skeletal remains. *Adv. Archaeological Method Theory* 10, 27–56.
- Larson, G., Karlsson, E.K., Perri, A., Webster, M.T., Ho, S.Y.W., Peters, J., Stahl, P.W., Piper, P.J., Lingass, F., Fredholm, M., Comstock, K.E., Modiano, J.F., Schelling, C., AgoulNIK, A.I., Leegwater, P.A., Dobney, K., Vigne, J.-D., Vila, C., Andersson, L., Lindblad-Toh, K., 2012. Rethinking dog domestication by integrating genetics, archaeology, and biogeography. *PNAS* 109, 8878–8883.
- Lawler, D.F., Reetz, J.A., Sackman, J.E., Evans, R.H., Widga, C., 2015. Suspected hypertrophic osteopathy in an ancient canid: Differential diagnosis of possible etiologies. *Int. J. Paleopathol.* 9, 52–58. doi:10.1016/j.ijpp.2015.02.001
- LeCouteur, R.A., Grandy, J.L., 2000. Diseases of the Spinal Cord, in: Ettinger, S.J., Feldman, E.C. (Eds.), *Textbook of Veterinary Medicine*. Saunders, Philadelphia, pp. 608–657.
- Lyman, R.L., 1994. *Vertebrate Taphonomy*. Cambridge University Press.
- Lynnerup, N., 2010. Medical imaging of mummies and bog bodies - a mini-review. *Gerontology* 56, 441–448.
- McGill, S., 2009. *Ultimate back fitness and performance*. Backfit Pro, Inc., Waterloo, ON, Canada.
- McMillan, R.B., 1976. Rodgers Shelter: A Record of Cultural and Environmental Change, in: McMillan, R.B., Wood, W.R. (Eds.), *Prehistoric Man and His Environments: A Case Study in the Ozark Highland*. Academic Press, New York, pp. 111–122.
- Miklíková, Z., Thomas, R., 2008. Current research in animal palaeopathology. *BAR International Series* 1814., Oxford, UK.
- Miklósi, A., 2007. *Dog behaviour, evolution, and cognition*. Oxford University Press, Oxford.
- Miller, E., Ragsdale, B., Ortner, D.J., 1996. Accuracy in Dry Bone Diagnosis : a Comment on Palaeopathological Methods. *Int. J. Osteoarchaeol.* 6, 221–229. doi:10.1002/(SICI)1099
- Moodie, R.L., 1923. *Paleopathology: An Introduction To the Study of Ancient Evidence for Disease*. University of Illinois Press.
- Morey, D.F., 2010. *Dogs: Domestication and the development of a social bond*. Cambridge University Press. doi:10.1017/CBO9780511778360
- Morey, D.F., 2006. Burying key evidence: the social bond between dogs and people. *J. Archaeol. Sci.* 33, 158–175. doi:10.1016/j.jas.2005.07.009
- Morey, D.F., Wiant, M.D., 1992. Early Holocene Domestic Dog Burials From the North American Midwest. *Curr. Anthropol.* 33, 224. doi:10.1086/204059
- Morlan, R., 1984. Toward the Definition of Criteria for the Recognition of Artificial Bone Alterations. *Quat. Res.* 22, 160–171.
- Newton, C.D., Nunamaker, D.M., 1985. *Textbook of Small Animal Orthopaedics*. J. B.

- 517 Lippincott Company.
- 518 Nowak, R.M., Mech, L.D., Gipson, P.S., Ballard, W.B., 2000. Accuracy and precision of
519 estimating age of gray wolves by tooth wear. *J. Wildl. Manage.* 64, 752–758.
- 520 Ortner, D.J., 2003. Identification of pathological conditions in human skeletal remains.
521 Academic Press.
- 522 Parmalee, P.W., Paloumpis, A.A., Wilson, N., 1972. Animals Utilized by Woodland Peoples
523 Occupying the Apple Creek Site, Illinois. Illinois State Museum, Reports Investig. 23.
- 524 Reinhardt, K., 1956. Eine ungewöhnliche Anomalie an den Dornfortsätzen des 5, 6, und 7.
525 Halswirbels *Fortschr Rontgenstr* 85, 253–255.
- 526 Robertson, I., Thrall, D.E., 2011. Imaging dogs with suspected disc herniation: pros and cons of
527 myelography, computed tomography, and magnetic resonance. *Vet. Radiol. ultrasound* 52,
528 S81–84. doi:10.1111/j.1740-8261.2010.01788.x
- 529 Rusbridge, C., Carruthers, H., Dubé, M.-P., Holmes, M., Jeffery, N.D., 2007. Syringomyelia in
530 cavalier King Charles spaniels: the relationship between syrinx dimensions and pain. *J.*
531 *Small Anim. Pract.* 48, 432–6. doi:10.1111/j.1748-5827.2007.00344.x
- 532 Seibert-Daiker, F., 1975. Über eine halbseitige Dornfortsatzhyperplasie des 5. Halswirbels
533 *Fortschr Rontgenstr* 122, 366–377.
- 534 Snyder, L.M., 1995. Assessing the role of the domestic dog as a Native American food resource
535 in the Middle Missouri Subarea A.D. 1000-1840 (Book, 1995) [WorldCat.org]. University
536 of Tennessee.
- 537 Sponenberg, D.P., Bowling, A.T., 1985. Heritable syndrome of skeletal defects in a family of
538 Australian shepherd dogs. *J. Hered.* 76, 393–395.
- 539 Takagi, S., Kadosawa, T., Ohsaki, T., Hoshino, Y., Okumura, M., Fujinaga, T., 2005. Hindbrain
540 decompression in a dog with scoliosis associated with syringomyelia. *J. Am. Vet. Med.*
541 *Assoc.* 226, 1359–1363. doi:10.2460/javma.2005.226.1359
- 542 Tourigny, E., Thomas, R., Guiry, E., Earp, R., Allen, A., Rothenberger, J.D., Lawler, D.,
543 Nussbaumer, M., 2015. An Osteobiography of a 19th-Century Dog from Toronto, Canada.
544 *Int. J. Osteoarchaeol.* DOI: 10.1002/oa.2483
- 545 Upex, B., Dobney, K., 2012. More Than Just Mad Cows: Exploring Human-Animal
546 Relationships through Animal Paleopathology, in: Grauer, A.L. (Ed.), *A Companion to*
547 *Paleopathology*. Blackwell Publishers, pp. 191–213. doi:10.1002/9781444345940.ch11
- 548 Van Biervliet, J., DeLahunta, A., Ennulat, D., Oglesbee, M., Summer, B., 2004. Acquired
549 cervical sclerosis in six horses associated with dorsal grey column chronic myelitis. *Equine*
550 *Vet. Journal* 2 36, 86–92.
- 551 Viera, R.L.R., Arora, R., Schewitzer, M.E., 2009. Radiologic Imaging of Spinal Deformities, in:
552 Errico, T.J., Lonner, B.S., Moulton, A.W. (Eds.), *Surgical Management of Spinal*
553 *Deformities*. Saunders Elsevier, Philadelphia, pp. 45–60.
- 554 Walker, R.B., Morey, D.F., Relethford, J.H., 2005. Early and Mid-Holocene Dogs in
555 Southeastern North America: examples from Dust Cave. *Southeast. Archaeol.* 24, 83–92.

- Ware, C.S., 2006. Disease, Skeletal Injury and Trauma as Possible Behavioral Modifiers in the Fossil Dire Wolf *Canis dirus* (Canidae: Carnivora) from Rancho La Brea, California. Union Institute & University, Cincinnati, OH.
- Warren, D.M., 2004. Skeletal Biology and Paleopathology of Domestic Dogs from Prehistoric Alabama, Illinois, Kentucky and Tennessee. University of Indiana.
- Warren, D.M., 2000. Paleopathology of Archaic Dogs from the North American Southeast, in: Crockford, Susan, J. (Ed.), *Dogs Through Time An Archaeological Perspective*. BAR International Series 2000, pp. 93–104.
- Weigelt, J., 1989. Recent vertebrate carcasses and their paleobiological implications. University of Chicago Press, Chicago.
- Wever, D.J., Veldhuizen, A.G., Klein, J.P., Webb, P.J., Nijenbanning, G., Cool, J.C., v. Horn, J.R., 1999. A biomechanical analysis of the vertebral and rib deformities in structural scoliosis. *Eur. Spine J.* 8, 252–260. doi:10.1007/s005860050169
- White, D., 2013. Screening for hemivertebra in pugs. *Vet. Rec.* 173, 24. doi:10.1136/vr.f4289
- Wray, D.E., MacNeish, R.S., 1961. The Hopewellian and Weaver Occupations of the Weaver Site: Fulton County, Illinois, Scientific Papers 7. Illinois State Museum.

Figure Legends

Fig. 1. Map of sites included in this study.

Fig. 2a. Koster, Feature 2256. Cervical: Spinous process near normal, but with very mild lean to left (white arrow); mild periarticular rim of right anterior articular facet (grey arrow)

Fig. 2b. Apple Creek, Burial 6. Lumbar: Spinous process severe right curving (white arrow); very mild asymmetry anterior articular facets (grey arrows)

Fig. 2c. McDonough Lake. Lumbar: Spinous process bowlike deformity (short white arrows) with visible crack anterior margin; asymmetry and proliferation on mamillary processes (long white arrows); small osteophyte cranioventral margin (short grey arrow)

Fig. 2d. Koster, Feature 2256. Thoracic: Mild right torsion spinous process (grey indicator lines)

Fig. Alchester, England. 3a. Lumbar: Spinous process left bow (white arrow), with mild right torsion (short grey arrows)

Fig. 3b. Alchester, England. Thoracic: Spinous process mild right curving (larger white arrow); anterior articular facets rough margins (short white arrows); anterior & posterior end plates severe ventral & lateral osteophytes (short grey arrows)

Fig. 3c. Alchester, England. Thoracic: Spinous process mild right curving (long white arrow); posterior articular facet asymmetry; mild transverse process osteophytes; anterior articular facets rough margins and mild asymmetry (short white arrows)

Fig. 4a. Apple Creek, Burial 6, Specimen 1. Thoracic: Normal spinous process.

Fig. 4b. Apple Creek, Burial 6, Specimen 1. Thoracic μ CT: Spinous process demonstrates normal cortex and trabeculae.

Fig. 5a. Apple Creek, Burial 6, Specimen 2. Lumbar: Spinous process visible cracking and moderate curving to the right (long grey arrow); dorsal arch asymmetry (short grey arrows); small ventromedial and ventrolateral osteophytes (white arrows)

Fig. 5b. Apple Creek, Burial 6, Specimen 2. Lumbar μ CT: Fracturing, no healing or remodeling (short grey arrow); irregular trabecular pattern (long white arrows); probable post-mortem trauma

Fig. 6a. Weaver Site, Specimen 3. Thoracic: Spinous process severe right curving (arrow)

Fig. 6b. Weaver Site, Specimen 3. Thoracic μ CT: ‘Blurring’ of detail consistent with post-mortem slow taphonomic mineralizing change possibly resulting from compressive or constrictive forces *in situ* (arrows), but an open diagnosis

619 Fig. 7a. Apple Creek, Burial 3, Specimen 4. Lumbar: Spinous process severe right curving
620 (arrow)

621 Fig. 7b. Apple Creek, Burial 3, Specimen 4. Lumbar μ CT: Callus formation consistent with
622 fracture during life; healing and remodeling (white arrows); artifact cracking postmortem (short
623 grey arrow)

624 Fig. 8a. German Shepard (modern), age 10 yr. Thoracic CT: Spinous process right curving
625 (medium arrow); osteophytes dorsal margins of cranial articular facets (short arrows); focal
626 enlargement ventromedial right cranial articular facet (long arrow)

627 Fig. 8b. Dachshund (modern), age 8 yr. Thoracic CT: Spinous process right curving (white
628 arrow)

629 Fig. 8c. Mixed Breed (modern), age 10. Thoracic CT: Spinous process right curving (white
630 arrow)

631 Fig. 8d. Bernese Mountain Dog (modern), age 22 months. Lumbar CT: Spinous process right
632 curving, lumbar vertebra (white arrow)

633

634

Table 1. Age, Sex, body-size, and gross pathology of dog remains included in this study.

Period	Site	Age (cal BP)	ID	Age	Shoulder Ht (mm)	Sex	Tot ₁	N ²	Ab ₃
Archaic	Modoc Shelter, Randolph Co., IL	8560-8200	Burial 2	Adult, old	453.66	Male	16	7	9
		5720-5330	6090	Adult	385.06	Female/Indeterminate	7	3	4
	Stilwell, Calhoun Co., IL	10,190-9630	Burial	Adult, old	450.33(rd)	Female/Indeterminate	8	2	6
	Koster, Greene Co., IL	10,130-9680	2256	Adult	446.8	Female/Indeterminate	18	7	11
			222	Adult	388.49	Female/Indeterminate	7	4	3
			2407	Adult	453.66	Male	16	5	11
Hopewell	Apple Creek, Greene Co., IL	2000-1600	Burial 6	Adult, old	371.34	Female/Indeterminate	18	7	11
	Raker Mound, Fulton Co., IL	2000-1600	Assemblage				11	0	11
	Weaver Village, Fulton Co., IL	2000-1600	Assemblage				7	4	3
Late Woodland	Apple Creek, Greene Co., IL	1550-900	Burial 2	6mo to 1 year		Female/Indeterminate	7	3	4
			Burial 4	6mo to 1 year	350.76	Female/Indeterminate	15	13	2
			Burial 1	Adult	415.93	Female/Indeterminate	4	3	1
			Burial 3	Adult, old	429.78 (fm)	Female/Indeterminate	10	2	8
			Burial 5	Adult, old	415.93	Female/Indeterminate	9	6	3
			Burial 7				6	4	2
			Assemblage				7	4	3
Mid-Mississippian	Emmons, Fulton Co., IL	600-540	Hillside burial	Adult	433.08	Female/Indeterminate	12	4	8
			Burial 3	Adult	419.36	Female/Indeterminate	3	1	2
Mississippian	McDonough Lake	900-560	Assemblage				8	4	4
Late Prehistoric	Rodgers Shelter, Benton Co., MO	850-200	Assemblage				2	1	1

¹Total vertebrae from individual or assemblage²Number of normal vertebrae³Number of abnormal vertebrae

636 **Table 2. Vertebral Spinous Process Deviations in Archaeological Domestic Dogs [n (%)]**

	Lean	Curve	Bow	Torsion
Degree				
Mild	24 (80%) ^{ab}	27 (45%)	9 (56%)	3 (100%)
Moderate	3 (10%)	14 (23%)	4 (25%)	
Severe	3 (10%)	19 (32%)	3 (19%)	
Direction				
Right	15 (50%)	34 (57%)	7 (44%)	
Left	15 (50%)	26 (43%)	9 (56%)	

637 ^a Percents refer to column only

638 ^b Significant difference morphology x severity, P=0.032

Table 3. Observations from Roman Domestic Dog Vertebrae, Alceister Site, England

Thoracic 4: Anterior articular facets mild asymmetry & rough margins; transverse process osteophytes.

Thoracic 5: Anterior & posterior end plate osteophytes, posterior osteophytes are severe; anterior articular facets rough margins & mild asymmetry; transverse process osteophytes.

Thoracic 7: Spinous process mild right curve; posterior articular facet asymmetry; mild transverse process osteophytes; anterior articular facets rough margins & mild asymmetry (Fig. 2c).

Thoracic 9: Anterior & posterior end plate osteophytes; posterior end plate fine pitting and oval focus of eburnation; anterior articular facet rough margins & mild asymmetry; anterior & posterior end plate osteophytes not visible in photograph.

Thoracic 13: Spinous process mild right bow; anterior articular facets rough margins; anterior & poster end plates severe ventral & lateral osteophytes (Fig. 2b).

Lumbar 3: Spinous process mild right curve; anterior end plate severe lateral & ventral osteophytes.

Lumbar 4: Anterior & posterior articular facets mild asymmetry and mild anterior osteophytes; lateral and ventral anterior end plate mild osteophytes.

Lumbar 5: Spinous process bow to left, with mild right torsion; posterior articular facets asymmetry (Fig. 2a).

Lumbar 6: Spinous process curve left.

Lumbar 7: Spinous process broken (post-mortem); posterior end plate ventral & lateral osteophytes.

Sacrum: Anterior end plate ventral & lateral osteophytes.