FRONT MATTER

Title
Tracing horseback riding and transport in the human skeleton

Short Title
Horseback riding and the human skeleton

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Abstract
Among the most widely-employed methods for understanding human-horse relationships in the archaeological record is the identification of human skeletal pathologies associated with mounted horseback riding. In particular, archaeologists encountering specific bony changes to the hip, femur, and lower back often assert a causal link between these features and prolonged periods of mounted horseback riding. The identification of these features have recently been used to assert the early practice of mounted horseback riding among the Yamnaya culture of western Eurasia during the 3rd and 4th millennium BCE. Here, we summarize the methodological hurdles and analytical risks of using this approach in the absence of valid comparative datasets and outline best practices for using human osteological data in the study of ancient animal transport.

Teaser
Human skeletal pathologies are unreliable indicators of early mounted horseback riding without careful comparison.

Introduction

Few events in human history have been as impactful as the domestication of the horse (*E. caballus*), which revolutionized human transport, communication, subsistence, and culture. While the impacts of domestic horse transport are well-chronicled, particularly in later periods of human history, understanding the earliest chapters of the human-horse story through reliable archaeological proxies for domestication and horse transport has proven challenging. Although recent, innovative animal genomics work has recently suggested that the origin of modern domestication lies towards the final 3rd and early 2nd millennium BCE (1), other highly publicized scholarship analyzing human skeletal pathologies has revived earlier arguments for the use of mounted horseback riding in eastern Europe during the late 4th millennium BCE among the Yamnaya culture (2). Here, we summarize the available osteological tools used to identify early horse transport and outline methodological pitfalls from basing such assertions on human skeletal pathologies in the absence of corroborating data from faunal contexts. We propose the need for systematic comparisons of skeletal changes in human remains associated with different types of animal transport, including wagon-driving and horse chariotry.

Hypotheses for early horse domestication

One of the core questions in the study of horse domestication is the challenge of how to trace horse riding and transport in archaeological assemblages from the grassland regions of Europe and Asia. Because of the general lack of written records or unequivocal archaeological indicators for horseback riding, researchers interested in early domestication have long made due with indirect proxies such as burial styles (3), grave goods (4), or changes in the frequency or variability of equid remains in archaeological assemblages (e.g. 5, 6) to model hypothesized changes in the human-horse relationship.

One of the most influential models for horse domestication, often known as the "kurgan hypothesis", links horse riding with an expanding wave of cultural changes including the construction of above-ground funerary mounds or *kurgans* in the northern Black Sea region during the final Neolithic (6th-4th millennia BCE), that eventually radiated outwards into central Europe and Central Asia. Perhaps most famously articulated by Gimbutas (3) and Anthony (7), proponents of the kurgan hypothesis argue that early Yamnaya pastoralists and their predecessors domesticated horses, used them for riding, and dispersed across much of western Eurasia, spreading Indo-European language and culture in the process. Recognition by archaeologists that certain kinds of horse equipment, especially metal mouthpieces or bits, could produce lasting modification of the teeth of a horse (e.g. 8) led to the initial identification of an apparently bitted horse from the pre-Yamnaya site of Deriyevka, supporting association between Yamnaya and horse domestication (9).

When radiocarbon dating subsequently revealed the Deriyevka horse to be much more recent than originally assumed, belonging to the first millennium BCE (10), interest grew in another site known as Botai in Kazakhstan. This site boasted an enormous assemblage of horse bones dating to the 4th millennium BCE ca. 3500-3000 BCE (11, 12). Despite some initial disagreement on the matter, links between Botai and early horse domestication reached near-consensus status in the first decade of the new millennium, with isotope values from pottery sherds showing seasonal exploitation of horse fats and apparent bit damage to the anterior margin of one premolar (13). Located to the east of the core Yamnaya area, Botai seemed to nonetheless fit the same general chronological framework as the Yamnaya model. Because Botai restored the basic assumptions of the kurgan hypothesis, subsequent evidence showing the dispersal of Yamnaya people into Europe and Inner Asia were once again commonly linked with horse riding or domestication (14, 15).

However, the expansion of biomolecular tools over the last two decades has undercut many of the core assumptions of the kurgan hypothesis, and has destabilized consensus belief in the Botai model. For one, problems have emerged in connecting Botai and Yamnaya as new human genomic data show little or no connectivity between the two populations (16). Even more problematically, animal genetic data show that the horses found at Botai are not the progenitors of domestic horses at all, but instead a different taxon altogether, the Przewalski's horse (*E. przewalskii*) (17). Although these genetic datasets do not themselves say anything about human-horse interactions at Botai, they provide a general timeline for horse domestication that is fundamentally inconsistent with the Yamnaya/kurgan model.

In the years since the Yamnaya model was first configured, osteological techniques for tracing horse transport have both proliferated and matured, producing a diverse analytical toolkit that is integrated with knowledge of equine development and physiology. Scholars have increasingly recognized that tracing horse transport requires careful consideration and identification of non-anthropogenic health problems and developmental challenges observed in wild horses, such as malocclusion, natural cementum banding, and enamel hypoplasia (12, 18-20). Instead of looking to individual skeletal indicators as a "smoking gun" for riding or bit use, best practices now often include a consideration of whole-skeleton patterning in pathological features like entheses, osteophytes, and arthritis, including consideration of pathology symmetry, severity, and frequency (21). Most importantly, inferences about ancient horse transport have been developed through robust comparisons between ancient specimens and modern collections of known life and work histories (including wild animals, zoo animals, and domestic horses used with different kinds of equipment or in different types of transport), which have helped to reveal the underlying causes of some skeletal features and to identify cases of equifinality. Archaeologists now recognize that particular kinds of horse equipment impact the skeleton in different ways. Control systems like lip rings (22), leverage and curb bits (23), and organic mouthpieces (24, 25) each leave different and often recognizable osteological traces. Successfully identification of horse riding in the archaeozoological record, and distinguishing it from other modes of ancient transport, is no longer a question of presence or absence – it requires careful consideration of each of these lines of evidence among well-preserved horse remains (26).

Chronological patterning in evidence for animal transport

The archaeozoological record provides little or no evidence to support Yamnaya links with horseback riding. The faunal record of the Black Sea region provides strong indication of important changes in human-animal relationships during the 4th millennium BCE, but little or no direct evidence linking these changes with horses. Burial features from the 3rd and 4th millennia BCE in the northern Caucasus sometimes include heavy wagons and wagon parts, along with the skeletal remains of cattle controlled by nose or lip rings (27). South of the Caucasus, both iconography and archaeofauna show clear evidence for use of donkeys and hybrids in light cart transport and riding as early as the mid-3rd millennium BCE, including pathological changes to equid skeletons consistent with the use of lip rings (22).

To the east, as well, despite compelling evidence for transcontinental movement, there is no evidence of the domestic horse in Yamnaya-associated contexts. Populations with genetic links to the Yamnaya, who produced an archaeological culture known as the Afanasievo, reached the Russian Altai and even central Mongolia by the end of the 4th millennium BCE (28). However, the archaeofaunal record in the region shows no evidence so far that they used, raised, or even brought domestic horses with them on this tremendous journey, which have yet to be identified in the region before the late 2nd millennium BCE.

In fact, across all of Eurasia, no directly-dated horse skeletons have been reported in association with transport equipment, or exhibiting transport-linked pathology until after 2000 BCE, when they appear in sites of the Sintashta culture of the trans-Ural region (29). These earliest domestic horse assemblages are paired with obvious and novel transport technology, including the first bridles, first bridle mouthpieces, and the earliest spoked wheels (30). Importantly, these archaeological and faunal patterns mirror the new evidence emerging from animal genomics: a recent large-scale genomic survey of hundreds of ancient horse specimens from across Eurasia demonstrated that the very first identifiable ancestors of the lineage leading to domestic horses (the so-called "DOM2" horses) appear in the Black Sea Steppes and eastern Europe only at the tail end of the 3rd millennium BCE (1). At the time of writing, neither genomically-identified animals of the DOM2 lineage, nor any animal paleopathological data linked with horse transport, have been recovered in association with Yamnaya cultural features.

Indeed, so far the only direct scientific indicators that horse domestication might meaningfully precede ca. 2000 BCE comes from human dental calculus at the site of Krivyanskiy-2, located in western Russia along the Don River (31). In burials from this site, researchers recovered milk proteins reported as *Equus*, and reported as dating to the late 4th or early 3rd millennium BCE. However, a recent large-scale study of burials from a similar region across the Neolithic-Bronze Age transition failed to replicate these finds (32), making it difficult to confidently link this report with any widespread adoption of domestic horses, even if they faithfully reflect consumption of horse milk.

Despite the erosion of these key underpinnings for the kurgan hypothesis, renewed interest in the idea has accompanied the findings of Trautmann et al. (2), who reported a number of interesting pathological markers in human skeletal remains from Yamnaya sites across eastern Europe dating to the late 4th millennium BCE. These skeletal traits include entheseal changes on the pelvis and femur, ovalization of the acetabulum, morphological alterations to the femur or acetabulum, anteroposterior flattening of the femoral shafts, vertebral degeneration, and patterns of accidental trauma. Assuming these traits to be collectively diagnostic of horseback riding, Trautmann et al. (2) developed a scoring system to evaluate skeletal remains for likelihood of riding activity. Here, we assess the literature underpinning the identification of mounted horseback riding in human skeletal assemblages.

Tracing riding in the human skeleton:

The posture and position of a human rider on horseback, as well as the biomechanical stress of the motion and impact of riding, have the potential to alter the human skeleton. Changes at musculoskeletal insertion sites and morphological variation have been scrutinized for several decades to determine a variable suite of skeletal characteristics often referred to as “horseman’s” or “horse-riding” syndrome (33-36). The most widely agreed upon traits are musculoskeletal changes to the pelvis and upper femur and morphological changes to the hip joint. Others include pathologies of the lower spine, certain trauma patterns, and degenerative changes to the hip, knee, and ankle.

The position of a rider on horseback requires the flexion of the coxofemoral joints, resulting in potential morphological changes to the acetabulum and anterior femoral neck. Shape changes to the acetabulum, variously described as anterosuperior elongation or ovalization, have been one of the few potential skeletal markers of riding to be quantifiably assessed via a vertical/horizontal index (37). The position of the femur in hyperflexion of the hip joint may also result in femoroacetabular impingement, causing morphological changes to the anterior surface of the femoral head and neck. These changes are frequently noted in osteological studies of horseback riding in the form of Poirier’s facets, Allen’s fossae, and anteroiliac plaque (38-40), however the various etiologies of these different features are often not considered (41).

Horseback riding requires the use of muscle groups in the back and legs to support the rider’s posture and seated position on the horse. The adductor muscle group (*adductor brevis, adductor longus, adductor magnus, adductor minimus, pectineus, gracilis,* and *obturator externus*) is of particular importance, as riders, especially those without stirrups or saddle, must keep their legs pressed to the horse’s side to maintain their mount (41). Skeletal changes at the attachment sites, or entheses, of the tendons associated with these muscles are often considered to be the strongest skeletal evidence of riding (2, 40, 42-44). The involvement of other muscle groups of the hips and legs, including the gluteals, the iliopsoas, and triceps surae, are also included in some studies as notable riding markers (2, 38, 39, 44, 45).

Other skeletal characteristics have been intermittently linked to the consequences of riding, particularly spinal pathologies. While intervertebral disk degeneration and osteoarthritis of vertebral joint facets have multifactorial etiologies, these degenerative changes are frequently noted in relation to the biomechanical stressors of horseback riding on the human spine. Likewise, pathologies to the lower spine such as Schmorl's nodes, lesions indicative of intervertebral disc tissue herniation, and spondylolysis, a defect in the neural arch, have been categorized as possible riding markers (2, 34, 40, 44, 46). Other degenerative joint changes, the result of inflammation and microtrauma due to repetitive mechanical loading, have been identified in the hips, knees, and ankles of suspected riders. Osteoarthritis in these joint areas, while admittedly nonspecific, may relate to different riding styles and equipment placing stress on various joints (44, 47-49). Finally, certain patterns of skeletal trauma have also been linked to riding on the basis of modern clinical studies of injuries related to riding. These patterns typically include "fall type" fractures to the ribs, forearms and clavicle, as well as non-specific blunt trauma to the cranium (37, 44, 46, 50).

Limitations and challenges

Despite a growing number of studies examining indicators of riding in various cultural contexts, there is no universally acknowledged system of evaluation and the skeletal traits assessed in individual studies vary. As such, the constituent symptoms of "horse-riding syndrome" differ from study to study, making accurate comparisons difficult. Cultural variation in riding style and equipment may impact our ability to identify a universal set of riding markers (41, 43, 45, 48). For example, riding bareback in a "chair seat" position requires more forceful and sustained adduction of the legs than a "split seat" position more commonly used with some types of saddles (2, 45). Likewise, the use of stirrups may result in more biomechanical loading to the knee joint, as seen in degenerative changes to the superior patellar surface in probable Avar riders (47). Limited sample sizes, a common issue in archaeological contexts, affect scholars' ability to determine either culturally specific or universally applicable riding markers. Several notable case studies represent one or a few skeletons with possible evidence of riding, but these preclude statistical analyses or even repeated observable skeletal changes that could indicate a pattern within a particular population (35, 44, 46, 47, 50).

Flawed comparative research designs

A number of studies have attempted a population-based approach to identifying riding markers by comparing modern populations with ancient assemblages. Some of these compare different populations based on presumed lifestyle or technological differences (45, 51, 52). For example, Djukic et al. (42) consider the presentation of entheseal changes in a group of presumed Avar horse riders and a contemporary agricultural population. Others use modern reference collections as a control group of 'non-riders' based on documentation about life histories (37). Importantly, though, there are no modern skeletal reference collections of humans whose primary mode of transport is mounted riding, meaning that skeletal changes in modern riders are accessed only through clinical literature on riding injuries. Even when carefully performed, such studies rarely consider other habitual activities that may mimic the biomechanical stress of horseback riding.

Another common but flawed comparative research design is to assess presumed riders and non-riders within the same ancient population on the basis of mortuary contexts (37, 39, 48). This method requires a direct association between the presence or absence of burial objects with lived occupations and activities. However, burials with equestrian equipment such as spurs or bridles may have reflected masculine identity and mythologized ideals of combat performatively represented in mortuary treatment, particularly in elite burials (53-55). At the same time, the absence of equestrian objects in a burial context does not definitively mark an individual as a non-rider in a cultural context in which riding was prevalent (52).

The multifactorial etiology of many skeletal traits is another limiting factor in assessing the presence of horseback riding. In addition to mechanical stress, entheseal and osteoarthritic changes can be heavily influenced by genetics, age, sex, body weight, height, and ancestry (56-59) as well as pathological changes and trauma at particular sites in the body (60). Trautman et al. (2) acknowledge this problem by creating a weight system for their observed traits, assigning lower scores to traits that cannot be conclusively linked to riding, including trauma and vertebral degeneration. Indeed, fractures commonly associated with falls such as clavicle, rib, and forearm fractures may occur in many other contexts besides a fall from horseback (61). Likewise, pathologies to the lower spine such as osteoarthritic joint changes, Schmorl's nodes, and spondylolysis have also been associated with nonspecific mechanical loading and/or stress fractures (62).

Coxofemoral changes

Perhaps the greatest limitation to reconstructing riding activity is the nonspecific nature of activity-related musculoskeletal changes in humans, a well-recognized issue in the field (63, 64). Few, if any, osteological studies of horseback riding seriously consider other activities that could result in the skeletal traits more confidently associated with riding, such as ovalization of the acetabulum and entheseal developments on the pelvis and femur.

Stress on the coxofemoral joints due to flexion and the motion of the rider on the back of the horse are noted to cause shape changes to the acetabulum and the anterior surface of the femoral neck. However, these changes are broadly linked to a habitual seated position and the pressure of the femoral heads on the anterosuperior rim of the acetabulum (41). Horseback riding is far from the only activity that involves the flexion of the coxofemoral joints. Indeed, other prolonged activities in a seated or squatting position have the potential to produce similar bony reactions and must be accounted for before horseback riding can be inferred. For example, Mann et al.

(65) report the common presence of facets and/or fossae on the anterior femoral neck in diverse archaeological contexts unrelated to horseback riding, notably in young adults and adolescents.

Adductor-related changes

Often cited as the most compelling skeletal evidence of riding are entheseal changes at the insertion sites of the adductor muscle group due to their role in keeping the legs pressed to the horse's side to maintain a mounted position (41). Researchers often assert that these muscles are not typically used in a strenuous manner in other daily activities, giving this skeletal trait primacy in nearly all "horse-riding syndrome" variations (2, 41, 42). However, so far no studies have systematically evaluated adductor changes across activities, particularly the range of human transport activities practiced in antiquity. The clinical studies cited in archaeological literature center exclusively on modern horseback riding injuries.

Recognition of adductor changes in these contexts is used to bolster their inferred association with horse riding without considering any other culturally-relevant activities that may result in similar skeletal alterations. As a case in point, sports medicine literature notes common microtrauma, acute strains, and overuse injuries to the adductor group in athletes engaged in sports involving acceleration, repetitive movements, and pivoting, including ice hockey and soccer (66, 67). These injuries, classified broadly as 'groin strains,' are not clinically distinguished from adductor injuries that occur in horseback riding. Due to the non-specific nature and multifactorial etiology of entheseal changes, non-riding activities that involve adduction of the lower limbs, pivotal movements, and changes in speed must also be considered as causal mechanisms. Indeed, archaeologists have identified specific activities expected to impact adductor attachment sites, including chariotry (68), barrel making, basketry (2), and preparing potter's clay by treading (69). Clearly, the relevance of activities such as these to any particular pathology must be corroborated by the archaeological record, but these examples illustrate the problems of cherry picking case-centered clinical literature that has thus far guided archaeological investigations.

Other forms of animal transport

Most importantly, skeletal features associated with other forms of animal transport (Fig. 1, Tables 1 and 2) must be considered as possible sources of patterns linked with horseback riding, particularly in light of the associated faunal and archaeological data from the 4th millennium BCE. For example, in the search for the earliest evidence of horseback riding among the Yamnaya, cattle-drawn wagon transport that has been clearly demonstrated in burials dating to the 3rd and 4th millennia BCE in the northern Caucasus (27, 70) provides a compelling alternative explanation for these skeletal markers. In the rare but instructive case in which a possible driver was found in direct archaeological association with a wagon, results show antemortem "fall"-type fractures, degenerative spinal changes, and entheseal changes in various muscle attachment sites of the hips and legs (70). A seated position on a wagon or cart may achieve similar levels and types of biomechanical stress from the jolting and bouncing of the structure in motion (68, 70). In particular, the coxofemoral flexion and stress on the pelvic joints from a prolonged and habitual seated position on the front of a moving wagon could result in similar hip changes to those identified in horseback riders, including ovalization of the acetabulum and changes to the anterior surface of the proximal femur. Degenerative spinal changes from repetitive mechanical loading should also be considered as potential consequences of habitual wagon driving (70), although the more passive use of hip and leg muscles in this mode of transport would seem to preclude substantial stress on the adductor muscles.

Chariotry, which appears to have been the predominant mode of horse transport during the second millennium BCE, involves a person standing on a moving cart drawn by horses. In terms of human posture, horse-drawn chariots share key similarities with earlier cart systems drawn by donkeys, hemiones, or hybrids (71). Balancing on a chariot or similar ancient two-wheeled vehicle requires a slightly crouched standing position with a wide stance of the legs. This position, and the responsive, quick movement required to maintain balance, necessitate strenuous use of the adductor muscles (68), potentially mimicking the osteological changes seen in presumed horseback riders. A rare example of a burial of a likely vehicle driver from Ur in Mesopotamia was reported by Molleson and Hodgson (68) to have well-developed adductor muscle attachment sites in addition to arthritic changes in the knees and ankles. For activity patterns that maintained a standing crouch, like chariot-driving, acetabular ovalization and alterations to the anterior surface of the femur would seem less likely, though not impossible. The near-absence of detailed human osteological data reliably associated with chariot-driving highlights the urgent need for further research to establish the osteological signatures of alternative modes of transport in relation to horseback riding.

Other osteological evidence frequently cited as indicative of horseback riding must also be systematically evaluated in other transport systems, or discarded. For example, degenerative changes to the lower back occur with loading stress in many different contexts. Likewise, skeletal fractures associated with fall injuries or kicks from large animals could result from any form of animal transport, not just horseback riding (70).

Discussion

In analyzing the use of human skeletal pathology in the assessment of horseback riding, it is clear that under the current paradigm, these assessments are made primarily through the lens of a presence/absence approach without a full understanding of alternative processes that could produce similar patterns. Although in animal paleopathology it has become increasingly common to conduct population-level assessments of factors like severity and frequency when assessing skeletal changes, these considerations are largely omitted from the analysis of horseback riding in humans. Most problematically, populations of humans that can be confidently associated with other animal transport strategies in the archaeological record, such as wagon-driving or horse chariotry, have never been characterized in terms of their paleopathological patterning at a population level.

In order to confidently identify horseback riding in novel contexts, including those that predate the known domestication of the horse such as the argument by Trautmann et al. (2), it will be essential to first conduct robust comparisons between human populations of known transport strategy. The archaeological record is replete with groups that could help build strong comparative samples, including skeletal populations from steppe cultures in later eras when riding was ubiquitous, such as during the Mongol Empire or Turkic Khaganate. Although chariot driving may be harder to isolate as an activity in human populations, chariot drivers from early China prior to the historically-documented adoption of mounted riding in the late first millennium BCE provide a compelling option (26). Similarly, a detailed skeletal characterization of non-Yamnaya populations associated with strong evidence of wagons or cattle transport (e.g. 27) might serve as a useful counterpoint to assess the hypothesis of Yamnaya horsemanship.

When performing comparisons between transport systems, it will be necessary to A) characterize the degree of pathological change in a given location, B) assess the frequency of such changes at the population level, C) understand the specific anatomical mechanisms generating these pathologies and, crucially, D) characterize whether these pathological indicators differ in any meaningful way from those caused by wagon-driving, chariotry, or riding of non-horse animals already proven to be used for this purpose in adjoining regions, namely cattle, donkey, and hemione. We recognize that this set of recommendations presents a steep challenge and may not be easy to conduct quickly.

This preliminary review of available osteological data associated with other transport systems nonetheless points to promising avenues of future inquiry that may help resolve the serious methodological issues with existing diagnoses of horseback riding-related changes to the human skeleton. Based on the biomechanics of riding, we note that the *co-occurence* of acetabular ovalization and entheseal changes in the pelvis and femur may have greater analytical value than individual traits. These two 'diagnostic' traits were given the highest weights in the scoring system developed by Trautmann et al. (2), but less than a third of the hypothesized 'riders' exhibited both traits. The frequency of co-occurrence of these two traits has not yet been tested in skeletal assemblages confidently linked with chariots or wagon-driving. Moreover, given the significance of mounted riding to domestication narratives, it is crucial that archaeologists examine the preponderance of evidence rather than a 'threshold' or individual diagnosis approach, using population-level data and robust comparisons between known groups to demonstrate the presence of riding in ancient contexts.

Most importantly, a preponderance of evidence approach should also include careful assessment of the rest of the archaeological, archaeofaunal and biomolecular records. Recent scholarship from ancient horse genomics now demonstrates that there is little or no connection between horses found at Yamnaya sites and the ancestors of modern domestic horses, and that genomic indicators of domestication do not emerge in the Black Sea region until well into the 3rd millennium BCE (72). These new findings exacerbate a serious discrepancy between the evidence offered from human skeletal pathology and all other known lines of evidence for horse domestication, including radiocarbon dating and genomic identification of the earliest members of the DOM2 lineage, the appearance of horse equipment in dated archaeological contexts, and animal paleopathological indicators of horse transport. As a result, the burden of proof for linking human skeletal pathologies observed in Yamnaya populations with horseback riding rather than alternative forms of animal transport should, we argue, be quite high.

As one of the most impactful events in human history, understanding the origins of mounted horseback riding is a key task for understanding both the ancient and modern world. Powerful findings from equine genomics align with results from archaeology and archaeozoology, placing the earliest horse transport at the turn of the second millennium BCE or in the centuries immediately preceding. Existing methodology from human osteology suffers from considerable issues in research design, including the lack of comparative datasets, the risk of equifinality from alternative activities (especially other forms of animal transport), and major discrepancies with findings from archaeozoology and archaeological data. While some of these issues can be addressed by targeted analysis of relevant modern and ancient populations with known life histories and specific activity associations, the available data do not support the argument for early horseback riding in Yamnaya culture based on human skeletal remains.

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All data needed to evaluate the conclusions in the paper are present in the paper.

Figure Caption

Figure 1. ***The posture and position of a human rider.*** *Body areas of interest from Table 1 are highlighted in red for A) horseback riding without stirrups, B) horseback riding with saddle and stirrups, C) horse, donkey, or hemione-driven chariot, and D) cattle-drawn wagon [Figure drawings produced by Daria Chechushkova].*

Tables and Captions

Transport system	Positions and potential stressors	Hypothesized skeletal responses
Horse riding	Seated position on horse	Flexion of the coxofemoral joints and pressure of the femoral head on the anterosuperior rim of the acetabulum resulting in acetabular elongation Femoroacetabular impingement resulting in changes to anterior aspect of the femoral neck
	Legs gripping horse	Entheseal changes in the pelvis and femur (including adductor tubercle and linea aspera) reflecting development of and/or strain to adductor muscle

		group
	Mechanical loading and impact stress on lower spine	Schmorl's nodes and degenerative changes to the spine, particularly lumbar vertebrae
	Fall from horseback	"Fall" type fractures, including to the forearms, clavicle, cranium
Equipment variations in horse riding	Impact stress on knees and ankle from use of stirrups	Developed anterior cruciate ligament attachment, osteoarthritis in knee joint Degenerative changes in the feet, including osteoarthritis of the first metatarsal Entheseal changes at calcaneal tuberosity reflecting development of *triceps surae*
	Reduced use of gripping muscles from use of saddle	Reduced/fewer entheseal changes on the pelvis and femur
Chariotry	Standing on chariot with legs semi-flexed	Slight flexion of the coxofemoral joints and some pressure of the femoral heads on the anterosuperior rim of the acetabulum resulting in possible acetabular elongation Some femoroacetabular impingement resulting in possible changes to anterior aspect of the femoral neck
	Legs in wide stance stabilizing and/or gripping	Entheseal changes in the pelvis and femur (including adductor tubercle and linea aspera) reflecting development of and/or strain to adductor muscle group
	Mechanical loading and impact stress on lower spine	Schmorl's nodes and degenerative changes to the spine, particularly lumbar vertebrae
	Fall from/crash of chariot	"Fall" type fractures and more extensive blunt-force trauma
	Semi-flexed knee with impact stress	Developed anterior cruciate ligament attachment, osteoarthritis in knee joint
	Semi-flexed ankle	Degenerative changes in the feet, including

	with impact stress	osteoarthritis of the first metatarsal Entheseal changes at calcaneal tuberosity reflecting development of *triceps surae*
Wagon/cart driving	Seated position on wagon or cart	Flexion of the coxofemoral joints and pressure of the femoral head on the anterosuperior rim of the acetabulum resulting in acetabular elongation Femoroacetabular impingement resulting in changes to anterior aspect of the femoral neck
	Mechanical loading and impact stress on lower spine	Schmorl's nodes and degenerative changes to the spine, particularly lumbar vertebrae
	Fall/kicks from draft animals	"Fall" type fractures and other blunt-force trauma

Table 1 ***. Biomechanical stressors of different animal transport strategies.*** *The potential or hypothesized skeletal responses are based on recent scholarship (38, 41, 46, 47, 51, 68, 70).*

Skeletal pathology	Horse riding	Horse chariotry	Wagon/cart driving
Acetabular elongation (os coxa)	+	?	+
Changes to the anterior aspect of the femoral neck	+	?	+
Development of adductor muscle group (Os coxa and femur)	+	+	-

Vertebral pathologies, particularly lumbar	+	+	+
Acute trauma (fractures or dislocations)	+	+	+
Changes to the knee and ankle joints	?	+	-

Table 2. ***Associated or hypothesized skeletal traits for ancient transport strategies.*** *Osteological manifestations are (+): likely skeletal response; (?): possible response; (-): unlikely response.*