

NOTEWORTHY HEALED FRACTURES IN SOME NORTH AMERICAN ARTIODACTYLA

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ABSTRACT

The authors examined four medium-sized wild North American artiodactyl skeletons, all of which show limb bone pathologies that presumably affected the animal's locomotor ability. One of these animals (a white-tailed deer) lived in an urban park, and might have survived a serious limb fracture due to absence of predators. The other three (a second white-tailed deer, a mule deer, and a pronghorn) were collected in rural environments. Both white-tailed deer were collected in eastern states from which most native predators have been extirpated, but where unconfined domestic dogs might sometimes act as predators on small artiodactyls. The mule deer and pronghorn were collected on range lands in northern plains states. The two white-tailed deer display fractures of major weight-bearing limb bones in which the bone pieces had completely fused prior to the animal's death. The mule deer shows extensive osteomyelitis in the hock region. The pronghorn suffered an injury to the epiphyseal plate which resulted in a left metatarsal that is shorter than the right metatarsal. Considered as a group, these specimens demonstrate the resiliency of injured artiodactyls in wild populations with few large predators. Each of these four individuals was able to survive its injury for long enough to allow significant healing of the fractured leg bones essential to locomotion in a cursorial prey species.

INTRODUCTION

Wild artiodactyls have a remarkable ability to survive seemingly crippling injuries, despite the apparent rarity of survivable long bone fractures in wild primates (Bulstrode 1990; Bulstrode et al. 1986) and also in wolves and coyotes (Wobeser 1992). It is not uncommon to find healed fractures in cervids killed by car impacts or some other cause. In this paper we describe limb injuries in four artiodactyls which probably seriously reduced the mobility of these animals. The animals studied lived in both open western plains habitats and heavily urbanized eastern habitats. These specimens demonstrate that deer and pronghorn can survive long enough to allow their injuries to heal, and that fairly long periods

of survival are possible even in relatively undisturbed environments where one might expect predators to quickly remove injured animals.

The notable ability of cervids to survive injuries has been documented in various reports (summarized by Rothschild and Martin 2006), although there have been few published illustrations of skeletal pathologies in wild cervids (see Bartosiewicz and Gál 2013, chapter 8; Chaplin 1971, Figure 15; Grimm 2008, Figures 5, 7; Moodie 1918, Figure 7). It might be presumed that few individuals with severe skeletal injuries would escape predation, and that animals living in parklands and reservations, most of which are predator-free, are the most likely to survive (Chapman and Chapman 1969). Here we describe skeletal materials from three cervids that record very debilitating injuries which did not result in immediate death. Indeed, these animals seem to have lived for a considerable time, since their injuries had healed (at least in so far as the broken bones having fused) prior to death. We also describe herein an injury in another artiodactyl genus (an antilocaprid) from North America.

METHODS

This study was prompted by the discovery of a single skeletal specimen (NJSM-B-466) found by one of us (E.D.) while walking dogs in an urban park. Our study eventually grew to include three other pathological artiodactyls, all of which reside in the collections of the New Jersey State Museum, and all of which exhibit injuries to major weight-bearing limb bones. The three cervid specimens that we describe here were all initially surface-collected as skeletal remains. The striking deformity of the broken and healed tibia in the Clifford Park deer prompted a search for more of the same skeleton, and additional bones were recovered by digging and screening in the area where the surface finds had been made. The bones, already free of soft tissue, were cleaned by simple washing. Broken bones were reassembled with acetone-based glue. Unlike the three cervids described herein, the antilocaprid was found freshly dead in a Kansas pasture over a kilometer from the nearest road. The cadaver exhibited no wounds or obvious injuries. It was recovered by two of us (B.S.G and D.C.P), gutted, and skeletonized by burial in a large lidded garbage can filled with soil. The metatarsal pathology was discovered only after the animal had been skeletonized.

Most measurements included in this study were made using a 300mm Mitutoyo Absolute digimatic bar caliper accurate to 0.1mm. The sole exception is length of the normal tibia from the Clifford Park deer, which exceeds the length of the bar caliper. All skeletal elements were compared to a mounted white-tailed deer skeleton in the collection of the School of Veterinary Medicine to confirm side of body and to evaluate how much morphological change had occurred to each. All photographs in this study were taken in the anatomy laboratories of the School of Veterinary Medicine at the University of Pennsylvania with a Panasonic DCM-TZ4 Lumix digital camera.

RESULTS

Pennsylvania white-tailed deer (*Odocoileus virginianus*)—This profoundly affected specimen is a partial skeleton of a fully mature white-tailed deer (*Odocoileus virginianus*, NJSM-B-466), consisting of a complete scapula, one complete right and one partial left humerus, a complete left ulna, a complete left and a partial right radius, a left metacarpal cannon bone (fused metacarpals III and IV), a rib, a lumbar vertebra (possibly the second), the sacrum, the right femur (pathological), the left tibia (complete with fused proximal fibula), and the right tibia (pathological). All epiphyses of the bones are fully fused, as would be the case in an adult of more than 42 months age (Reitz and Wing 1999). The bones were discovered in Clifford Park, a unit of the Fairmount Park System, near the Tulpehocken Train Station in Philadelphia County, Pennsylvania, late in the year 2009. The animal is presumed to have died earlier that same year. The bones are no longer greasy, but are unweathered (Behrensmeyer 1978) and have not been gnawed by rodents.

The most striking pathology in this skeleton involves the right tibia (Figure 1a), which was fractured and healed with the proximal and distal ends at a right angle to each other. The fusion was accompanied by substantial proliferation of periosteal bone, and the tibia was barely recognizable as a tibia when found. The associated osteomyelitis is strikingly evident as exostosis which covered much of the fractured area, and was variously expressed as encrustations, stabilizing secondary development, and offshoot strands of bone. A large part of the diaphysis appears to have been lost, possibly by remodeling, so that the pathologic right tibia is much shorter than the normal left tibia (Figure 1b, c; Table 1). The tibial plateau retains recognizable articular surfaces, but their surfaces are not as smooth as those on the normal left tibia. The fibula appears to have been rotated caudally at its distal end (Figure 1c), possibly by traction from soft tissues connecting it to the tibial diaphysis.

The right femur was not fractured, but shows considerable pathology related to the tibial articulation. The surfaces of both the articular condyles and patellar groove of the right femur are irregular rather than smooth, suggesting that mobility of the stifle joint was probably limited. The distal end shows significant exostosis in the area where the joint capsule attached. This exostosis conceals the extensor fossa in cranial view. A deep pit, 28.5mm wide and 37.3 mm long, on the cranial surface of the distal femoral shaft (Figure 1d) may have been occupied during life by the right patella, which was not found with the specimen. This pit has a rugose elevated rim, and lies proximal to and essentially in line with the patellar groove.

It may be presumed that the right hind limb of this animal was essentially non-functional, being significantly shorter than its counterpart. However the healing, unguided as it was, seems to have been complete or nearly so. This urban animal presumably suffered a broken leg as a result of being struck by a motor vehicle. It clearly survived for some time after the leg was broken. Its survival probably was facilitated by the fact that this animal lived in an urban park setting. Philadelphia does have a feral dog population, and feral dogs could have harassed the animal even in this urban setting. To date, no coyotes have been reported in Fairmount Park.

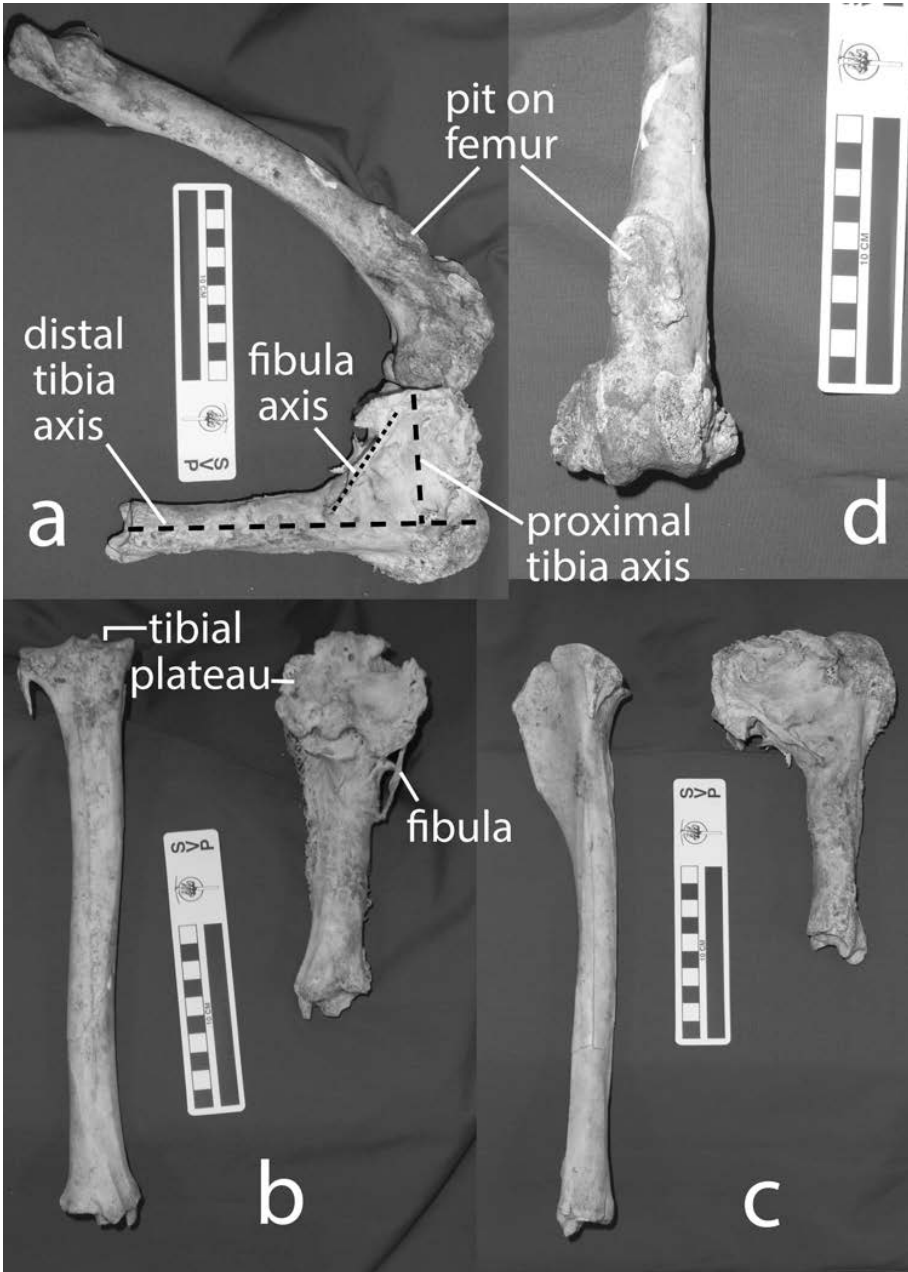


Figure 1. Clifford Park deer (NJSM-B-466). **a.** articulated right femur and tibia in lateral view. Long (proximal to distal) axes of the tibial shaft pieces are indicated with dashed black lines; the long axis of the fibula is indicated with a dotted black line. **b.** normal left tibia and pathologic right tibia in caudal view. The proximal articular surface of the right tibia is rotated so as to be visible when the shaft of the right tibia is viewed from the caudal aspect. **c.** normal left and pathological right tibiae in lateral view. **d.** distal end of right femur in cranial view. Note the pit above the patellar groove on its cranial surface. Scale bar is in centimeters.

Table 1. Measurements of the Clifford Park, Philadelphia deer (NJSM-B-466) tibia, and of the Kansas pronghorn (NJSM-B-443) metatarsals. Proximal and distal widths and anterior to posterior measurements were taken at the articular ends of the bone; the metatarsal cannon was also measured at the fused physis to show how much distortion there is in this part of the pathological metatarsal. All measurements are in millimeters. Each measurement shown is an average of three to five repetitions. Abbreviations: MT = metatarsal. a-pt = anterior to posterior dimension.

Specimen	Bone	Length	Proximal end			Distal end			MT physis	
			width	a-pt	width	width	a-pt	width	a-pt	
PA deer	Normal tibia	327.5*	62.75	52.14	36.52	30.66	-	-		
	Pathological tibia	204.25	72.58	60.21	39.03	30.54	-	-		
Pronghorn	Normal cannon	220.73	26.03	29.59	29.98	20.11	27.96	16.03		
	Pathologic cannon	214.25	25.47	29.59	30.46	20.59	34.34	19.33		

*The normal white-tailed deer tibia was longer than the 300mm capacity of the metric bar caliper, and was therefore measured using a metric ruler. This measurement is accurate to 1.0mm.

New Jersey whitetail deer (*Odocoileus virginianus*)—A second specimen is the fused tarsus and metatarsus of a white-tailed deer (NJSM-B- 459). This 227mm long specimen was found at the Merrill Creek Reservoir in Harmony Township, Warren County, New Jersey. The principal portion of the specimen is the right metatarsal cannon bone (normally the fusion of Metatarsals III and IV). The proximal end of the metatarsal cannon was displaced medially relative to the talus (astragalus), and its cranial surface was rotated laterally 59 degrees (Figure 2a) prior to fusion with the distal end of the tarsus (figure 2b-d). While the animal's foot would have pointed somewhat laterally, the distal end of the metatarsal cannon bone lies nearly under the proximal trochlea of the talus (and

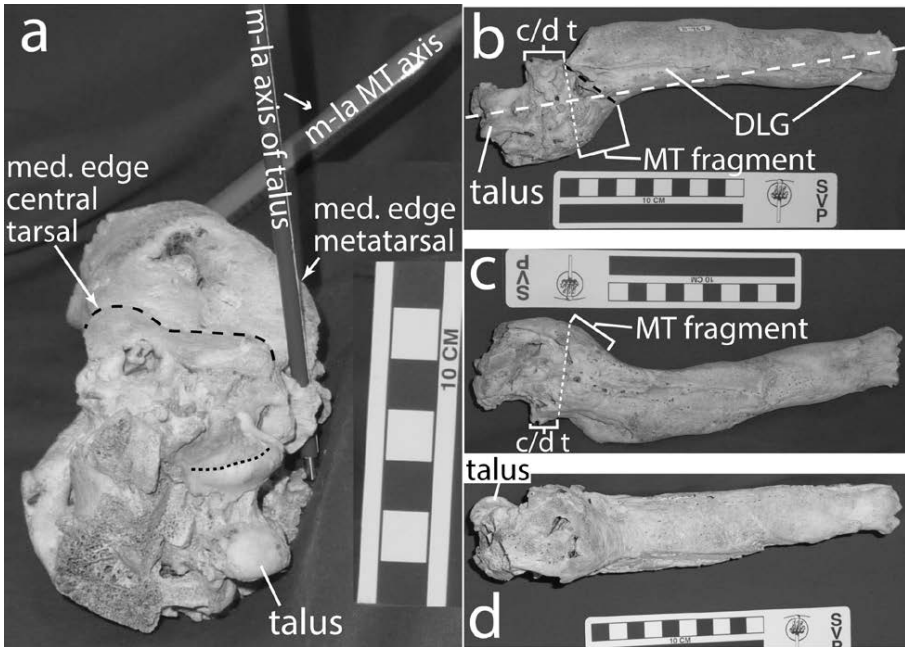


Figure 2. Merrill Creek deer foot (NJSM-B-459). **a.** Proximal view. The medial-to-lateral orientations of the talus (astragalus) and distal end of the metatarsal cannon bone are indicated by the markers (see labels). The medial edge of the proximal trochlea of the talus is indicated by a dotted black line. The medial edge of the central tarsal bone is indicated by a dashed black line. The medial edge of the metatarsus is overlain by the marker for the medial to lateral axis of the talus, but is otherwise visible against the background. Note that the distal end of the metatarsus is rotated with respect to the orientation of the proximal trochlea of the talus; the white arrow indicates the direction in which the metatarsus has been rotated. Most of this rotation appears to have occurred at the level of the fracture in the proximal metatarsus. Anterior is to the left, medial is toward the top. **b.** Merrill Creek specimen in cranial view. Note that the distal end of the metatarsus lies almost on the proximal-to-distal axis of the talus (white dashed line) even though the proximal end of the metatarsus is offset medially relative to the tarsus. Only a small lateral fragment of the metatarsus remains associated with the tarsus. The fracture of the metatarsus is indicated by the dashed black line. **c.** Merrill Creek deer foot in caudal view. **d.** Merrill Creek specimen in lateral view. The level of the tarso-metatarsal joint is indicated by the white dotted line in both **b** and **c**. In **b-d** proximal is to the left, and distal is to the right. All scale bars are in centimeters. ABBREVIATIONS: c/d t = central and distal tarsal bones; DLG = dorsal longitudinal groove marking the contact between the third and fourth metatarsal bones; MT = metatarsus.

hence the talocrural joint) when the specimen is balanced on its distal end. This suggests that the foot could have been weight-bearing, and that the animal may have been able to use its right hind limb after the fracture had healed.

The exact position of displacements in the middle and distal rows of the tarsus and of breaks in the proximal metatarsus are no longer clear due to complete fusion of the tarsals and base of the metatarsus. It is not possible to distinguish the individual tarsal bones, apart from the proximal talus and parts of the calcaneus. The only mobile joints that will have remained in this deer foot are at the proximal trochlea of the talus (the talocrural joint), the metatarsophalangeal joints, and presumably the interphalangeal joints. Mobility of the hock would have been restricted because no motion was possible on the distal trochlea of the talus. It may also have been limited by the bony callus on the hock and metatarsus. The injury could have resulted from a predator attack directed at the deer's hind leg, or from a miss-step on a rocky hillside that trapped its foot and resulted in a metatarsal fracture.

This animal survived despite living in a rural area where free-ranging, unrestrained domestic dogs might have chased it. Coyotes are known to live in this part of New Jersey, and can also be expected to prey on injured deer. It is of interest that the metatarsal epiphyses had not even begun to fuse to the diaphysis in this animal, suggesting the animal was injured as a fawn and died before reaching maturity. Fusion of the metatarsal epiphyses begins at an age of 17 months in male and 20 months in female white-tailed deer (Purdue 1983), indicating that the Merrill Creek deer was less than two years old when it died. Nonetheless, it had lived long enough for the tarsus and metatarsus to fuse completely before its death.

South Dakota mule deer (*Odocoileus hemionus*)—The desiccated, nearly complete skeleton of a mule deer doe (*Odocoileus hemionus*) was found by one of us (D.C.P.) in Oacoma, Lyman County, South Dakota, in 2005. This specimen (NJSM-B-444) shows evidence of an injury to a distal portion of the right hind leg, which affected the distal right tibia, tarsus, and proximal metatarsus (Figure 3a) and resulted in osteomyelitis at the junction of the distal tibia and tarsal bones (the talocrural joint). Substantial exostosis resulted, with considerable development on the tibia, resorption of much of the calcaneum, and fusion of the central and distal tarsal bones. The astragalus (talus) was not found. The individual seems to have lived for some time after the injury, presumably limed by its injury, but was at least moderately functional.

An additional observation in this skeleton is a thoracic vertebra in which an injury had fractured the spinous process (Figure 3b) While the complete vertebral column is not preserved, morphology of the transverse processes indicates that the fracture involved the 6th thoracic vertebra. The healing process did not restore the spinous process with a firm connection, but instead resulted in a pseudo-articulation (pseudarthrosis), essentially a hinge-like false joint that had some kinesis, primarily in the anterior to posterior direction. Pseudarthroses (false joints) develop when stresses on the broken bone result in significant motion across the break during the early soft (noncalcified) callus stage. Excessive motion will prevent calcification of the callus, and thereby prevent the bony union of the fracture. Instead, the central part of the soft tissue callus will develop into



Figure 3a. South Dakota mule deer tarsus (NJSM-B-444) in lateral view. Proximal is to the top, caudal to the left. White arrows indicate remnants of soft tissue still adhering to the bones. Note extensive development of periosteal proliferative bone on the distal tibia, tarsus, and proximal metatarsal cannon bone. The remaining tarsals are largely fused to the proximal end of the metatarsus, except for the calcanean tuber, which was present as a free element separate from the articular end of the calcaneum. No other tarsal bone is distinguishable in the fused mass that includes the proximal metatarsus. Scale is in centimeters.



Figure 3b. South Dakota mule deer vertebral column. The black arrows point to a pseudarthrosis (false joint) in the neural spine near the center of the picture. Note the small pits flanking the black arrowhead on the distal fragment of the neural spine, just above the false joint. Cranial is to the left, dorsal to the top. Scale bar is in centimeters.

a joint capsule in a manner that is analogous to joint formation in the embryo (Carter and Beaupré 2001). The epaxial muscles which insert on vertebral neural spines are active during locomotion (Ritter et al. 2001; Schilling and Carrier 2010), and these spines are therefore an excellent candidate for the development of false joints.

Kansas pronghorn (*Antilocapra americana*)—An adult male pronghorn (*Antilocapra americana*) was recovered by two of us (D.C.P. and B.S.G.) in Logan County, Kansas, shortly after its death, which we speculate may have been the result of internal injuries sustained when the animal was struck by a vehicle on a nearby road. When skeletonized, this individual (NJSM-B-443) was found to have suffered an injury to the left metatarsal cannon bone that had healed with considerable exostosis on the medial side just proximal to the distal articular condyles, but no fusion with other elements (Figure 4). No other bones of this animal show any signs of healed fractures.

The left metatarsal bone (Figure 4b, d) of this pronghorn is 6.5mm shorter than its normal right counterpart (Table 1; Figure 4a, c). The matter of greatest interest for this specimen is that the injured metatarsal bone was weight-compensated during healing. The weight (70.6 g) of the injured and healed left metatarsus is precisely matched by the weight of the corresponding right meta-

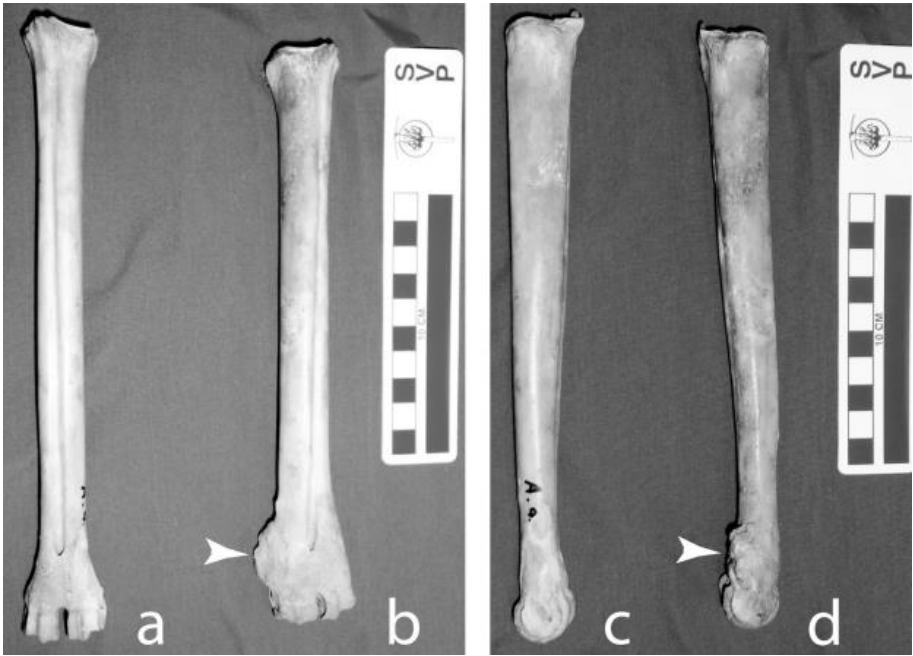


Figure 4. Normal right (a, c) and pathological left (b, d) metatarsals of the Kansas pronghorn (NJDM-B-443) in cranial view (a, b); and medial view (c, d). Note that the pathological left metatarsal is shorter than the normal right metatarsal. The overgrowth of bone on the medial side of the physeal region of the pathological left metatarsal cannon bone is indicated by the white arrows. Proximal is to the top for all images. The medial sides of the metatarsal bones face each other in the cranial view (a, b); caudal surfaces of the metatarsal bones face each other in the medial view (c, d). Scale bar is in centimeters.

tarsus. This would have preserved considerable cursorial ability in the individual; the species is noted for sustained running capabilities.

The pathology in this left metatarsus affects the distal end of the third metatarsal bone, close to the location of the epiphyseal plate. However, fusion of the diaphysis and epiphysis is so complete that no vestige of the growth plates can be seen on the normal right metatarsus. It is notable that the nutrient artery enters the caudal surface of the diaphysis just proximal to the metaphyseal region on the right metatarsal. The nutrient foramen is not visible in caudal view in the pathological left metatarsal because it lies deep to a thin shelf of bone. It can be seen when the left metatarsal is examined in oblique caudo-proximal view. It is possible that, before epiphyseal fusion, the animal suffered damage to the physis of its left metatarsal that resulted in shortening of the metatarsal length in the adult. Orientation of the metatarsophalangeal joint surface was not significantly disrupted by the pathology, and the proximal phalanges do not show any indication that they were affected. One way in which a young pronghorn might injure just one side of its metatarsus would be for its foot to be snagged while the animal was going under or through a barbed-wire fence. Pronghorns are known to suffer injuries from barbed-wire (Jones 2014; Jones et al 2015).

DISCUSSION

Fracture healing has been extensively studied in humans and domestic animals. The biologic mechanisms of fracture healing are fairly well understood, as is the course of healing in humans or animals receiving medical care. Healing proceeds from an early inflammatory phase, through a phase of fracture repair (characterized by development of a connective tissue callus and its subsequent replacement by a bony callus), and finally to remodeling of the new bone to fine-tune the repair to the biomechanical needs of the patient (Marsh and Li 1999; Kierdorf et al. 2012). Development of a hematoma at the fracture site occurs within hours (McCall et al. 2003). In domestic cats, granulation tissue replaces the hematoma within one week, and calcification (formation of the bony callus) begins within 14 to 17 days. Domestic cats achieve clinical union (bridging of the fracture by bone) in three to four weeks, and the bone callus is completely formed within six to twelve weeks (McCall et al. 2003). Tibial fractures in some cattle, particularly in young animals, can sometimes be successfully treated by confining the animal to a stall (Martens et al. 1998), confirming that even relatively large animals can recover without surgical intervention as long as they have adequate access to food and water.

Animals can survive with little or no food for longer than it would take a broken long bone to begin bearing some weight. Domestic cats can survive between six and 23 weeks of near starvation before they are unable to maintain body temperature under cold stress. Humans have survived hunger strikes for periods as long as 79 days (McCall et al. 2003). Surviving a broken leg bone probably depends most on access to water, and on luck in avoiding predators.

Further case descriptions of healed fractures in modern wild animals are of obvious interest in the fields of medicine (human or veterinary) and wildlife management. They will also be of interest in the fields of archaeology and vertebrate paleontology, since pseudarthroses (Osborn and Wortman 1895) and healed fractures (McCall et al. 2003; Kierdorf et al. 2012) are preserved in some fossil vertebrates. The biomechanical effects of fractures have been studied in domestic artiodactyls (Seebeck et al. 2005) and healing has been monitored in captive wild cervids (Bailey et al. 1983). Experiments using sheep show that fractures which are less stabilized take longer to heal (Epari et al. 2006). It has also been shown experimentally that unstable fractures are more likely to become infected (Friedrich and Klaue 1977; Lindsey et al. 2010). However, little is known about how skeletal injuries affect the ability of wild artiodactyls to function in their natural habitats (Gilbert and Hill 1956). We advocate additional detailed analyses and descriptions of such specimens. An additional potential analysis method, described by Anne (2010), represents a contribution from excavation sciences with potential usefulness to medicine.

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