Although the pathogenesis of injuries involving the distal end of the third metacarpal bone in horses is complex, mechanical overload has been suggested as an important contributing factor. Mechanical overload may be acute, resulting from a single event that culminates in catastrophic injury, or chronic, resulting from cumulative damage over an extended period. However, despite the clear relationship between mechanical loading and the pathogenesis of injuries involving the distal end of the third metacarpal bone, little is known about the specific mechanisms of bone loading. In particular, the loads exerted by the proximal phalanx and proximal sesamoid bones on the distal end of the third metacarpal bone during locomotion are not well understood, even though these loads likely have an important role in the net mechanical loading of this bone.

Several in vitro studies have investigated the mechanical properties of the third metacarpal bone in horses and have provided information regarding the types of mechanical loads that it may be able to support. In these studies, it was found that the third metacarpal bone in horses could withstand large axial loads but only moderate bending and torsional loads, suggesting that this bone is loaded mainly in axial compression. Similarly, results of in vivo measurements of surface strain on the third metacarpal bone in horses, in conjunction with results from an in vitro study in which an end-loaded, beam-column model was used to calculate loading of the third metacarpal bone under a variety of conditions, suggested that the bone is primarily loaded in axial compression during locomotion, with only small loads producing bending in the sagittal and transverse planes.

A separate study involving the application of strain gauges to the third metacarpal bone also found that the third metacarpal bone was loaded primarily in axial compression of the distal end of the third metacarpal bone in horses during walking and trotting.

## Objective
To assess the net mechanical load on the distal end of the third metacarpal bone in horses during walking and trotting.

## Animals
3 Quarter Horses and 1 Thoroughbred.

## Procedures
Surface strains measured on the left third metacarpal bone of the Thoroughbred were used with a subject-specific model to calculate loading (axial compression, bending, and torsion) of the structure during walking and trotting. Forelimb kinematics and ground reaction forces measured in the 3 Quarter Horses were used with a musculoskeletal model of the distal portion of the forelimb to determine loading of the distal end of the third metacarpal bone.

## Results
Both methods yielded consistent data regarding mechanical loading of the distal end of the third metacarpal bone. During walking and trotting, the distal end of the third metacarpal bone was loaded primarily in axial compression as a result of the sum of forces exerted on the metacarpal condyles by the proximal phalanx and proximal sesamoid bones.

## Conclusions and Clinical Relevance
Results of strain gauge and kinematic analyses indicated that the major structures of the distal portion of the forelimb in horses acted to load the distal end of the third metacarpal bone in axial compression throughout the stance phase of the stride. (Am J Vet Res 2010;71:508–514)
compression. In contrast, in that same study, analysis of data obtained by filming horses when the forelimbs passed over a force plate indicated that the third metacarpal bone was loaded in sagittal bending. The investigators suggested that the discrepancy in metacarpal loading indicated by the 2 methods may have been attributable to the fact that the force plate analysis did not account for the force exerted by the proximal sesamoid bones on the distal end of the third metacarpal bone.

A hypothetical mechanism for axial loading of the third metacarpal bone was described in a study that investigated the structure of the bone. It was suggested that the paired proximal sesamoid bones exerted a force on the metacarpal condyles that partially opposed the force exerted by the first phalanx. The vector sum of these 2 forces was suggested to act along the axis of the third metacarpal bone. Although this hypothesis was supported by the trabecular structure of the third metacarpal condyles, no analysis was performed to determine that the structures of the distal portion of the limb could produce the necessary balance of forces during locomotion while simultaneously satisfying all other requirements of a normal gait.

Many recent biomechanical studies of the forelimb in horses have examined tendinous structures, whereas others have examined the role of muscles during locomotion. A few studies have evaluated joint reaction forces as they pertain to the distal sesamoid bone. Several studies have evaluated contact areas and pressures within the metacarpophalangeal joint by analyzing cadaver limbs under artificial loading conditions. However, results of in vivo studies have not been reported, and mechanical loading of the third metacarpal bone in horses is still not clearly understood. Therefore, the purpose of the study reported here was to assess net mechanical load on the distal end of the third metacarpal bone in horses during walking and trotting. We hypothesized that forces exerted by the paired proximal sesamoid bones and the proximal phalanx would produce a resultant force directed along the shaft of the third metacarpal bone that acted to load the bone primarily in compression.

Materials and Methods

Strain gauge analysis—Surface strain data acquired from the third metacarpal bone of a single Thoroughbred gelding during walking and trotting were incorporated in an analytic beam-column model and FEA model to calculate the net force applied to the distal end of the third metacarpal bone. Strain data were acquired at the University of Melbourne Veterinary Clinical Center, and the study protocol was approved by the Animal Experimentation Ethics Committee of the University of Melbourne. The horse was 21 years old and weighed 450 kg at the time of the study. Results of a complete physical examination, including lameness examination, were unremarkable, and radiographic examination of the forelimbs prior to the study did not reveal any abnormalities.

Procedures for measurement and analysis of bone strains have been described previously. Briefly, three 350-Ω strain gauge rosettes were implanted on the lateral, dorsal, and medial aspects of the mid-diaphysis of the left third metacarpal bone. A strain gauge was not applied to the palmar aspect of the bone because of concerns regarding access to that location and previous findings that application of a strain gauge to the palmar aspect was desirable but not essential for full resolution of loading. Following the implant surgery, the horse was given 1 g of phenylbutazone/d.

Strain gauge data were acquired with custom-made data acquisition hardware. The gauges were zeroed with the horse standing quietly with the 4 limbs arranged approximately square. The horse was then exercised on a flat treadmill at a walk (5 km/h) and at a trot (10 km/h), and bone strain recordings were obtained. The horse was then euthanatized by IV administration of an overdose of pentobarbital sodium, and the left forelimb was removed at the level of the carpus. Computed tomography of the third metacarpal bone was performed, with a single transverse image acquired at the approximate level of the implanted strain gauges.

For each gait, portions of the strain data when the horse had performed at least 5 regular strides in succession were selected for analysis. Data were filtered by use of forward-reverse, low-pass Butterworth filters with cutoff frequencies of 5 Hz for the walking data and 12 Hz for the trotting data and analyzed by use of a model described previously for analysis of data acquired from horses during walking. The third metacarpal bone was treated as an end-loaded member subject to potential axial compression, shear forces in the dorsal plane, and torsion about the long axis. The model of the third metacarpal bone incorporated subject-specific geometry derived from the computed tomographic image and previously published bone material properties.

During the stance phase of the stride, the inertia forces on the distal portion of the limb resulting from acceleration of the limb segments are thought to be relatively small. Therefore, the third metacarpal bone was modeled in quasistatic equilibrium with the proximal end fixed. Loading was modeled by use of 3 orthogonal forces and 3 orthogonal moments that represented the sum of all forces applied to the distal end of the third metacarpal bone. Similarly, the reaction forces and moments at the proximal end of the third metacarpal bone represented the sum of all forces at the proximal end. Given the assumption of quasistatic equilibrium, all reaction components at the proximal end of the bone were determined by loading components at the distal end. Therefore, only 6 components were required to describe loading of the third metacarpal bone.

An analytic beam-column model and an FEA model were used to determine the load-strain relationships for the third metacarpal bone, allowing loads applied to the distal end of the bone to be determined on the basis of surface strains recorded at the mid-diaphysis. Both models were expressed by use of the equation e = MF, where e is an N × 1 column matrix of strains, F is an M × 1 column matrix of scalar forces and moment components, and M is an N × M transformation matrix that yields strain components from the model as a linear combination of mechanical loads.

For the analytic beam-column model, the transformation matrix (M) was approximated analytically as a series of transformations applied in sequence. First, a
model matrix (X) was identified that transformed the applied loads to bone-aligned stresses at each rosette site. A constitutive matrix (C) was then derived to transform bone-aligned stresses at each rosette site to bone-aligned strains. The bone material was modeled as transversely orthotropic, with the principal material axes aligned with the anatomic axis of the third metacarpal bone, and the Young modulus in the axial direction was assigned a value of 14.3 GPa on the basis of the mean Young modulus calculated from the FEA model. Material properties in the other directions were determined by scaling the previously reported properties for bovine Haversian femoral compact bone.22 Finally, a strain transformation matrix (T) was used to find the normal strain along the direction of each gauge of each rosette. The full transformation matrix (M) was then identified as the matrix product of T, C, and X.

The FEA model was developed by manually segmenting the computed tomographic image of the third metacarpal bone to identify regions containing bone, and area properties of the bone section were calculated from these data. Reported distribution of the axial Young modulus20 was interpolated to determine Young modulus as a function of angle, with reference to the axes of the principal geometric second moments of area. The other material properties were calculated as described for the analytic beam-column model. With the segmented computed tomographic image as a template, an open source software program was used to create a mesh model of the bone. The mesh was then exported for analysis with an FEA program.27 Meshes containing 4,800 and 38,400 elements were analyzed, but because results for both meshes were similar, results for only the 38,400-element model are reported. The model was fully constrained at all nodes at the proximal end, simulating rigid fixation, while successive loading components were applied to the distal end. The transformation matrix (M) was populated directly by calculating the normal strains caused by each load component in each gauge. The analytic beam-column model and the FEA model were both solved with custom-written software.28

Force plate and kinematic analyses—Force plate and kinematic data acquired from 3 Quarter Horses during walking and trotting were incorporated in a computational model of the distal portion of the forelimb to allow calculation of the forces applied by the paired proximal sesamoid bones and the proximal phalanx. Horses were 2, 2, and 3 years old and weighed 500, 500, and 545 kg, respectively. All of the horses were geldings. In all horses, results of a complete physical examination, including a lameness examination, prior to the study were unremarkable. Methods for data collection have been described.28A Briefly, reflective markers were placed on segments of the distal portion of the right forelimb. Kinematic data were acquired with a commercial system, and GRF data were acquired with a commercial force plate.2 Data were acquired for the stance phase of the stride during walking and trotting. The stance phase was defined as the time when the force plate measured vertical reaction force > 50 N. Data were collected at the Orthopedic Research Center, College of Veterinary Medicine and Biomedical Sciences, Colorado State University; the experimental protocol was approved by the Colorado State University Institutional Animal Care and Use Committee.

Sagittal-plane joint moments were calculated by use of a massless, quasistatic analysis,21,23 in which the gravitational mass and inertial parameters of each segment were set at zero. A 2-D mathematical model of the musculoskeletal system of the distal portion of the forelimb was then applied to calculate loading of the limb.28 Tension in the interosseous (suspensory) ligament was calculated by use of a previously published strain-force relationship.21 Net joint moments at the distal interphalangeal and metacarpophalangeal joints were calculated on the basis of tension in the superficial and deep digital flexor tendons, as described.23,16,20 Joint reaction forces were then calculated for the distal interphalangeal and metacarpophalangeal joints by assuming static equilibrium of all forces acting on the limb segments. The first and second phalanges were treated as a single rigid body in this model because the proximal interphalangeal joint was assumed to be a low-motion joint. Because the deep digital flexor tendon exerts a compressive force on the distal sesamoid bone, which articulates with the second phalanx, and the superficial digital flexor tendon, deep digital flexor tendon, and interosseous ligament compress the proximal sesamoid bones against the condyles of the third metacarpal bone, these compressive forces were considered in the calculation of joint reaction forces. At the metacarpophalangeal joint, the forces exerted by the proximal sesamoid bones and proximal phalanx were added to calculate the resultant force applied to the distal end of the third metacarpal bone. Detailed information regarding calculation of joint moments and tendon and ligament forces has been described elsewhere.4

Results

Analysis of analytic beam-column and FEA models for surface strain data from the single Thoroughbred indicated that the third metacarpal bone was loaded primarily in axial compression (F_x), with only small shear components (F_y and F_z) acting to cause bending (Figure 1). The calculated axial compressive force was negative during the swing phase because strain gauges were zeroed while the horse was bearing weight and thus at a time when the third metacarpal bone was under some axial load. In the FEA model, this had the effect of adding a constant offset of approximately 5 N/kg to all axial compression values. The calculated shear load components did not have any clear pattern, and peak values were < 5% of the calculated peak axial compressive force. The torsion load component (M_y) acted to pronate the limb during the first half of the stance phase and to supinate the limb during the second half.

Analysis of force plate and kinematic data indicated that the third metacarpal bone was loaded primarily in axial compression during walking and trotting (Figure 2). The calculated force acting to cause bending in the sagittal plane had a peak value < 4% of the calculated peak axial compressive force.
Results of the present study indicated that the third metacarpal bone in horses was loaded primarily in axial compression during the stance phase of walking and trotting. These findings support our hypothesis that the balance of the forces exerted by the proximal sesamoid bones and proximal phalanx produces a resultant force directed along the shaft of the bone. We theorize, therefore, that the superficial and deep digital flexor tendons and interosseous muscles.

**Discussion**

Results of the present study indicated that the third metacarpal bone in horses was loaded primarily in axial compression during the stance phase of walking and trotting. These findings support our hypothesis that the balance of the forces exerted by the proximal sesamoid bones and proximal phalanx produces a resultant force directed along the shaft of the bone. We theorize, therefore, that the superficial and deep digital flexor tendons and interosseous muscles...
intact interosseous ligament compress the sesamoid bones against the palmar aspect of the third metacarpal bone, whereas the proximal phalanx exerts a force in the opposing direction. Owing to the geometry of the limb during the stance phase of gait, the dorsopalmar components of these forces could be expected to cancel each other, producing a resultant force that acted along the axis of the third metacarpal bone. This mechanism operated throughout the stance phase of the stride, despite varying magnitudes and directions of the forces involved (Figure 3).

The shape and material properties of the third metacarpal bone in horses suggest that it may be more sensitive to bending than to axial compression, with greater mechanical stress developing per unit shear force than per unit axial compressive force. This implies that disruptions to the balance between forces exerted by the proximal sesamoid bones and proximal phalanx could be responsible for large changes to the stress state of the third metacarpal bone secondary to increased bending. These hypothesized interrelated changes in load may provide a theoretical basis for such clinical phenomena as the association between injury to the interosseous ligament and third metacarpal bone injuries such as condylar fractures.

There were a number of limitations to the present study. First, different horses were used to obtain strain...
gauge versus force plate and kinematic data. Therefore, results for the 2 methods of analysis cannot be directly compared. Second, the study population was small with strain data obtained from a single horse and force plate and kinematic data obtained from only 3 horses. Third, the strain gauge analysis was limited because of imprecise knowledge of the true strain-force relationship. Fourth, the musculoskeletal model used for analysis of force plate and kinematic data was 2-D and did not account for frontal plane asymmetry in limb anatomy or loading. Frontal plane asymmetry may be relevant to the study of the forelimbs of horses because certain injuries are known to predominantly affect either the medial or lateral aspect of the limb. Fifth, the musculoskeletal model included only the largest structures in the limb, neglecting many smaller structures that likely exert additional loads. Sixth, both the bone strain and musculoskeletal models assumed quasi-static conditions. Nevertheless, we believe that the fact that analysis of different models (the bone strain model vs the musculoskeletal model) incorporating different formulations and different input data yielded similar results supports our contention that the third metacarpal bone is loaded primarily in axial compression.

The musculoskeletal model used in the present study supported the mechanical validity of the hypothesis that axial loading of the third metacarpal bone can arise from the forces applied by the proximal sesamoid bones and proximal phalanx. Although this loading has been described previously and has been reported to be able to produce axial loading under certain conditions, to our knowledge, it has not been previously determined that hypothesized loads could be generated during locomotion or that their vector sum would resolve in the direction of the long axis of the third metacarpal bone. Results of the present study suggest that these conditions could be met and that the function of the involved structures was consistent during walking and trotting, despite variations in limb configuration and load magnitude.

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