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Hoof position during limb loading affects dorsoproximal bone strains on the equine proximal phalanx

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ABSTRACT

Sagittal fractures of the proximal phalanx (P1) in the racehorse appear to be associated with turf racing surfaces, which are known to restrict forward slide of the foot at impact. We hypothesized that restriction of forward foot slip would result in higher P1 bone strains during metacarpophalangeal joint (MCPJ) hyperextension. Unilateral limbs from six equine cadavers were instrumented with strain gauges and bone reference markers to measure dorsoproximal P1 bone strains and MCPJ extension, collateromotion and axial rotation during *in vitro* limb loading to 10,500 N. By limiting movement of the distal actuator platform, three different foot conditions (forward, free, and restricted) were applied in a randomised block design. Bone reference markers, recorded by video, were analyzed to determine motion of P1 relative to MC3. Rosette strain data were reduced to principal and shear magnitudes and directions. A mixed model ANOVA determined the effect of foot position on P1 bone strains and MCPJ angles. At 10,000 N load, the restricted condition resulted in higher P1 axial compressive ($p=0.015$), maximum shear ($p=0.043$) and engineering shear ($p=0.046$) strains compared to the forward condition. The restricted condition had higher compressive ($p=0.025$) and lower tensile ($p=0.043$) principal strains compared to the free condition. For the same magnitude of principal or shear strains, axial rotation and collateromotion angles were greatest for the restricted condition. Therefore, the increase in P1 principal compressive and shear bone strains associated with restricted foot slip indicate that alterations in foot: ground interaction may play a role in fracture occurrence in horses.

1. Introduction

Sagittal fractures of the equine proximal phalanx (P1) are thought to result from an acute biomechanical event in which articulation of the sagittal ridge of the third metacarpal bone (MC3) within the sagittal groove of the P1 induces compressive and torsional forces (Markel and Richardson, 1985; Holcombe et al., 1995; Ellis et al., 1987; Singer et al., 2013). At extreme hyperextension the dorsoproximal margin of P1 impinges on MC3 (Brama et al., 2001; Pool, 1996) which likely coincides with the rapid increase in principal compressive and shear strains, observed *in vitro* at the dorsoproximal aspect of P1 (Singer et al., 2013). Therefore, athletic endeavors, shoeing characteristics, or surfaces that promote rapid increases in bone strains during exercise may promote fracture of P1.

Specific racing surfaces present a higher risk for metacarpophalangeal joint (MCPJ) fractures, with P1 sagittal fractures more common on turf compared to synthetic surfaces in the UK (Parkin et al., 2004). MCPJ and metatarsophalangeal joint (MTPJ) biomechanics differ among race surfaces (Setterbo et al., 2012; Symons et al., 2013). Further, MCPJ biomechanics are modulated by interaction of the digit with the ground. Surface deformability and coefficient of friction affect biomechanics of the foot–surface interaction (Setterbo et al., 2013, 2012, 2009, 2008; Orlande et al., 2012; Thomason and Peterson, 2008; Wilson and Pardoe, 2001). Foot slip, ground reaction forces, hoof acceleration and vibration varied on different racing surfaces (Crevier-Denoix et al., 2013; Setterbo et al., 2009; Robin et al., 2009; Chateau et al., 2009) which highlights the influence of racing surface characteristics on limb kinetics and kinematics.

The transfer of forces from the ground to the hoof can also be modulated by the horseshoe (Pardoe et al., 2001; Wilson and Pardoe, 2001). Toe grabs on the shoes of Thoroughbred racehorses are thought to modulate foot slip and increase the risk of musculoskeletal injury (Kane et al., 1996). The use of shoe studs to increase grip on turf surfaces shortens foot slip duration in fore

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and hind hooves during gallop (Harvey et al., 2012). A better understanding of the effect alterations in hoof slip have on MCPJ biomechanics would facilitate our understanding of injury aetiopathogenesis.

Our goal was to demonstrate the potential effects of alterations in hoof slip, as represented by hoof position, on P1 bone strains and MCPJ angles during *in vitro* limb loading. We hypothesized that restricting forward slide of the foot during loading would result in higher bone strains during MCPJ hyperextension.

2. Materials and methods

2.1. Study design

Proximal phalangeal bone strains and MCPJ angles were measured in equine cadaveric forelimbs during *in vitro* loading to simulate walk, trot, and gallop loads, while hoof motion was either facilitated or constrained in the horizontal plane. Bone and joint motions were determined from kinematic analysis of bone reference markers. Dorsoproximal P1 bone surface strains were determined from strain gauges (Singer et al., 2013). MCPJ angles and bone strains were compared between hoof loading conditions using a mixed model analysis of variance (ANOVA).

2.2. Limb preparation

Five forelimbs (4 left and 1 right) were collected from five mature Thoroughbred or Thoroughbred cross horses (mixed age and sex) euthanized for reasons unrelated to forelimb pathology. Limbs were used fresh or were thawed for 24 h after storage at −20 °C. Limbs were transected mid-radius and the proximal end was potted in a cylinder with polymethylmethacrylate (PMMA, Co Tray Plastics, GC America Inc., Alsip, IL, USA) while the limb was loaded in a standing position (Singer et al., 2013; Whitlock et al., 2012). Bone reference markers were placed in MC3 and P1 (Fig. 1). Radiographs acquired to document bone reference marker position also confirmed the absence of osseous pathology in the distal limb bones. Two video cameras (Fastcam PCI, Photron, San Diego, CA, USA), dorsomedial and dorsolateral to the limb, recorded marker motion. Cameras fields of view were calibrated using a 10 in. cubic reference frame (Motion Analysis Calibration Cube, CF-20, Santa Rosa, California).

A rosette (rectangular, 45°, three element, planar) and a uniaxial strain gauge (C2A-06-031WW-350, CEA-06-062UW-350, Vishay Micromeasurements, Malvern, PA) were applied to the dorsoproximal surface of P1 and zeroed with the limb hanging, as previously reported (Singer et al., 2013) (Fig. 1).

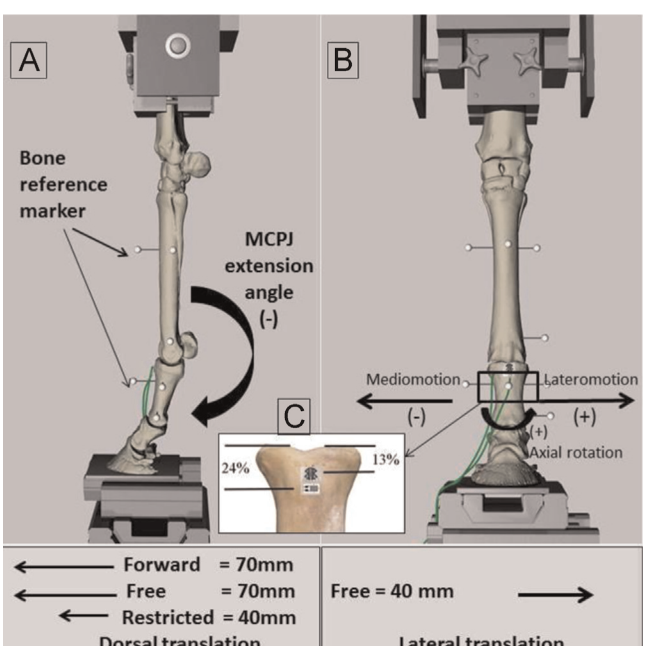

Fig. 1. Lateral (A) and dorsal (B) views illustrate bone instrumentation and hoof translations for foot conditions within the materials testing machine. The inset (C) illustrates the location (percentage length of P1) of the rosette and uniaxial strain gauges on the dorsoproximal aspect of P1. Adapted from Singer et al. (2013).

2.3. Mechanical testing setup

Mechanical loading was performed in a servohydraulic material testing system (Model 809; MTS Systems Corp., Minneapolis, MN) equipped with an axial–torsional load transducer [Model 662.10A-08, MTS Systems Corporation, Eden Prairie, MN]. Two orthogonal translation (405 mm × 400 mm × 40 mm) on a linear bearing system [Super Pillow Block (SPB 32 OPN), Thomson Industries Inc., Port Washington, NY, USA] allowed the hoof to translate in the horizontal plane, in dorsopalmar and lateromedial directions, depending on desired hoof position during limb loading (Brama et al., 2001; Le Jeune et al., 2003; Whitlock et al., 2012).

Three foot conditions were studied by allowing or restricting motion of the translation. In the forward condition, the hoof was permitted to move 70 mm dorsally during loading. In the restricted condition, the hoof was permitted to move only 40 mm dorsally. In the free condition, the hoof was permitted to move 70 mm dorsally and 40 mm laterally. Each limb was loaded in the forward, restricted and free positions with, and without, a compliant mat centered under the hoof. Mat compliance was 6.46×10^{-5} mm/N. The conditions were tested in a randomised block design, with the mat and no mat conditions tested as a group to minimize foot repositioning between tests.

2.4. Data collection

The foot was secured to the translation table with the radius and metacarpal bones aligned parallel to the axis of loading with a physiologic (mean ∼210°) palmar fetlock angle (Weller et al., 2006), at a load of ∼700 N. The limb was preconditioned by loading for 30 sinusoidal cycles from 700 N to 1800 N, the equivalent to stance (Brama et al., 2001), under displacement control at 0.25 Hz. The limb was then loaded from 1800 N to 10,500 N for 4 sinusoidal cycles using displacement control at 0.25 Hz (approximately 5100 N/s) while simultaneous video images (Photron Fastcam Viewer Photron, San Diego, CA, USA) and bone strain data (SCXI 1520, National Instruments Corp., Austin, TX) were recorded at 60 Hz. Load, strain, and MCPJ angle data were recorded at the same frequency to facilitate data synchronization and analysis for the different variables. The load range was selected to capture known peak vertical forces reported for stance (1800 N), walk (3600 N), trot (5400 N) and gallop (10,500 N) (Setterbo et al., 2009; Chateau et al., 2009; McGuigan and Wilson, 2003; Brama et al., 2001; Schryver et al., 1978; Kingsbury et al., 1978).

2.5. Data reduction

Bone reference marker positions were transposed to bone anatomic axes using radiographs of marker instrumented bones. MCPJ collateromotion, axial rotation, and extension angles were calculated in kinematic analysis software (Motus 9.0, VICON, Centennial, CO) (Singer et al., 2013). Collateromotion was positive for lateral, and negative for medial movement of P1 relative to MC3 (Denoix, 1999). Axial rotation was positive for external rotation and negative for internal rotation of P1 relative to MC3. Extension angle was measured on the palmar aspect of the MCPJ, with the magnitude of the angle increasing with extension (Fig. 1). Collateromotion and axial rotation were reported relative to bone positions at 1800 N limb load.

Transverse and axial bone strains were recorded with the uniaxial strain gauge and the middle arm (pd) of the rosette strain gauge, respectively. Rosette strain data were reduced to principal and shear strain magnitudes and directions (Fig. 2) with a custom program (Matlab R2010a, The Mathworks, Natick, MA, USA), using calculations defined in Schajer (1990).

2.6. Statistical analysis

The effects of hoof position (forward, free, and restricted) and load (1800, 3600, 5400, and 10,000 N) on P1 bone strains and fetlock angles (collateromotion, axial rotation, extension) at stance (1800 N), walk (3600 N), trot (5400 N), and gallop (10,000 N) loads were assessed using a mixed model ANOVA that included the load*foot condition interaction and accounted for repeated measures within horse cadaveric limb (SAS, version 9.2, Cary, North Carolina, USA). Horse limb was treated as a random effect, with load and foot condition as fixed effects. The mat effect and mat interactions were excluded due to lack of statistical significance. When appropriate, post-hoc pairwise comparisons were performed between hoof conditions. Least square means and standard errors, adjusted for other factors in the statistical model, are reported. A p-value of ≤ 0.05 was used for statistical significance for all comparisons.

3. Results

For each mechanical test for the different foot conditions, the translation reached the maximum permitted dorsal translation. For the free condition, maximum lateral translation of the limb occurred