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How do metacarpophalangeal joint extension, collateromotion and axial rotation influence dorsal surface strains of the equine proximal phalanx at different loads *in vitro*?

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A B S T R A C T

The biomechanical circumstances that promote sagittal fracture of the equine proximal phalanx (P1) are poorly understood. In order to improve our understanding of equine metacarpophalangeal joint (MCPJ) biomechanics and potential aetiologies of sagittal P1 fractures, the study objectives were to quantify P1 bone strains, collateromotion and axial rotation during MCPJ extension under controlled loading circumstances. Unilateral limbs from six cadavers were instrumented with bone reference markers for measurement of P1 movement relative to third metacarpal bone positions during axial limb loading to 10,500 N. Bone reference markers recorded by video were digitized and the movement analyzed during MCPJ extension. Concurrently, dorsoproximal P1 surface strains were measured with one uniaxial and one rosette strain gauge. Strain gauge data was reduced to determine principal and shear strain magnitude and direction. External axial rotation and collateromotion increased with increasing MCPJ extension. Maximum principal strain increased linearly as load increased from 2000 to 10,500 N. Minimum principal and maximum shear strains had curvilinear relationships with limb loading, with negligible strain magnitude until approximately 6000 N load, after which strain increased rapidly. The direction of P1 minimum principal strain shifted approximately 30–40° as load increased from 5400 N to 10,000 N, moving from proximolateral–distomedial to a nearly proximodistal direction. At near maximal MCPJ extension, with concurrent axial rotation and collateromotion, a rapid increase in dorsoproximal P1 bone strain and a change in principal strain direction occurred. The alterations in principal strain magnitude and direction associated with maximal MCPJ extension may support a biomechanical theory for sagittal P1 fracture occurrence in horses.

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1. Introduction

Sagittal fractures of the proximal phalanx (P1) are common in Thoroughbred racehorses in United Kingdom (UK). Solitary P1 fractures constituted 23% of catastrophic distal limb fractures incurred during racing and 40% of fatal distal limb fractures during turf flat racing (Parkin et al., 2004). Sagittal P1 fractures also occur commonly (Ramzen and Palmer, 2011; Verheyen and Wood, 2004) during training.

Most P1 fractures originate from the sagittal groove of the proximal articular surface (Powell, 2012) with a component that propagates toward the lateral diaphyseal cortex (Ellis et al., 1987; Holcombe et al., 1995; Markel and Richardson, 1985). Fractures are thought to result from an acute biomechanical event that induces compressive and torsional forces by articulation of the sagittal ridge of the distal third metacarpal (MC3) bone within the sagittal groove of P1 (Ellis et al., 1987; Holcombe et al., 1995; Markel and Richardson, 1985). The ridge is theorized to act as a chisel, splitting P1 as the metacarpophalangeal joint (MCPJ) moves from extension to flexion during stance (Holcombe et al., 1995). Impingement of the dorsoproximal margin of P1 on MC3 during extreme hyperextension with high speed activity (Brama et al., 2001; Pool, 1996) could also play a role in fracture pathogenesis.

While most MCPJ motions occur with flexion and extension in the sagittal plane, collateromotion and axial rotation also occur (Clayton et al., 2007a, 2007b). Excessive collateromotion and axial rotation may contribute to fracture pathogenesis because the metacarpal sagittal ridge interdigitates with the phalangeal sagittal groove. Interdigitation normally constrains collateromotion and axial rotation of P1 relative to MC3 (Chateau et al., 2001). Increased articular contact between MC3 and P1 and ridge-groove

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interaction during high speed activity (Brama et al., 2001; Easton and Kawcak, 2007) may exacerbate the effects of collateromotion and axial rotation on joint biomechanics. In order to improve our understanding of MCPJ biomechanics and potential aetiologies of sagittal P1 fractures, our objectives were to quantify P1 bone strains, collateromotion and axial rotation during MCPJ hyper-extension under controlled loading circumstances.

2. Materials and methods

2.1. Study design

Six equine cadaveric forelimbs were loaded *in vitro* to simulate walk, trot, and gallop loads. MCPJ motions were determined from implanted bone reference markers. Proximal phalangeal bone surface strains were determined from strain gauges on dorsoproximal P1. MCPJ motions and P1 strains were characterized as a function of MCPJ angle and limb load.

2.2. Anatomic materials

Six forelimbs were collected from mature Thoroughbred or Thoroughbred cross horses (mixed age and sex) euthanized for reasons unrelated to forelimb pathology. Four left and two right forelimbs were used. Limbs were used fresh or were stored at −20 °C until 24 h before use. Limbs were transected in the middle of the radius to maintain the accessory ligaments of the superficial and deep digital flexor tendons and the fetlock stay apparatus (Whitlock et al., 2011). The proximal end of the radius was potted in a cylinder filled with PMMA (PMMA, Co Tray Plastics, GC America Inc, Alsip, IL, USA) while the limb was loaded with a 210–220° palmar MCPJ angle to mimic limb stance at rest.

2.3. Limb instrumentation

2.3.1. Bone reference markers

Spherical markers (3/8″" diameter PTFE balls [McMaster-Carr, Atlanta, GA]) covered by Scotchlite Silver Reflective Tape (3 M, St. Paul, MN, USA) attached to 4.8 mm diameter Steinmann pins were used to track movement of MC3 and P1 (Fig. 1). Pins were inserted perpendicular to the long axis of the limb into predrilled 4 mm diameter holes. Lateromedial and dorsal pins were placed in the proximal aspect, and lateral pins in the distal aspect, of MC3 and P1.

Dorsopalmar and lateromedial radiographs (Digital processor: Mark III, Sound-Eklin DR, Carlsbad, CA; Generator: HF100/30+, MinXray, Inc., Northbrook, IL) were taken (58 kVp, 10.2 mAs, 1 m film-focal distance) of the instrumented limb to allow conversion of marker positions to MC3 and P1 reference frames.

2.3.2. Strain gauge application

Rosette and uniaxial strain gauges were applied to the dorsoproximal surface of P1 (Fig. 1). Soft tissues, including a small section of the common digital extensor tendon and the distal MCPJ capsule were removed from the dorsoproximal aspect of P1 over a 3 × 3 cm area. There was no disruption to the soft tissue structures of the stay apparatus that supports the MCPJ during loading. The bone surface was abraded (360 grit sandpaper), degreased (acetone), and chemically cleaned (M-Prep Conditioner A and M-Prep Neutralizer 5A, Vishay Micro-Measurements, Malvern, PA). Strain gauges (C2A-06-031WW-350, CEA-06-062UW-350, Vishay) were adhered to the bone (M-bond, Vishay), waterproofed with silicone gel (ITW Devcon, Riviera Beach, FL), attached to a signal conditioning and data collection system (SCXI-1520 and PCI-MIO-16E4, National Instruments Corporation, Austin, TX) and zeroed with the limb hanging.

2.3.3. Mechanical testing set-up

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]. A translation table (405 mm × 400 mm × 40 mm) on a linear bearing system [Super Pillow Block (SPB 32 OPN), Thomson Industries Inc., Port Washington, NY, USA] was mounted on the actuator to allow the hoof to move in a dorsal direction to allow the metacarpus to remain approximately vertical during limb loading (Le Jeune et al., 2003; Whitlock et al., 2011; Brama et al., 2001).

2.4. Limb loading and data collection

The radius was secured to the proximal actuator by the PMMA cylinder. 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

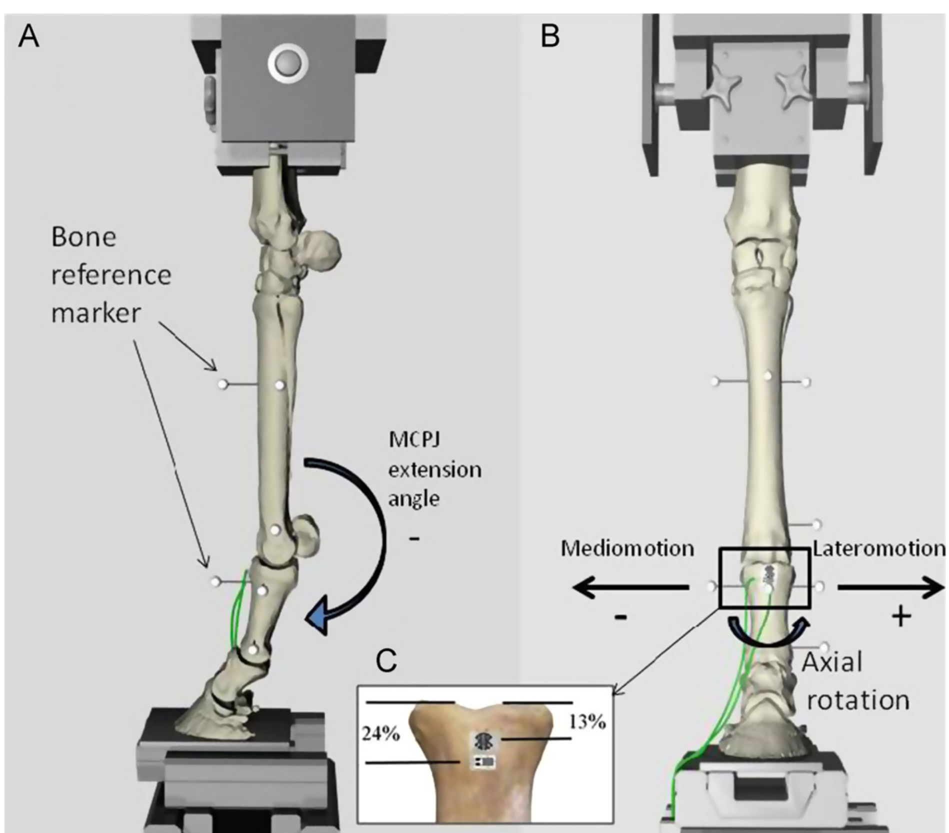

Fig. 1. Fig. 1: Lateral (A) and dorsal (B) views illustrating the instrumentation and orientation of forelimb bones within the materials testing system. Supporting soft tissues were maintained during tests. The inset (C) illustrates the location (percent of P1 length) and orientation of the strain gauges on the dorsoproximal aspect of P1.

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