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Evaluation of a subject-specific finite-element model of the equine metacarpophalangeal joint under physiological load

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ABSTRACT

The equine metacarpophalangeal (MCP) joint is frequently injured, especially by racehorses in training. Most injuries result from repetitive loading of the subchondral bone and articular cartilage rather than from acute events. The likelihood of injury is multi-factorial but the magnitude of mechanical loading and the number of loading cycles are believed to play an important role. Therefore, an important step in understanding injury is to determine the distribution of load across the articular surface during normal locomotion. A subject-specific finite-element model of the MCP joint was developed (including deformable cartilage, elastic ligaments, muscle forces and rigid representations of bone), evaluated against measurements obtained from cadaver experiments, and then loaded using data from gait experiments. The sensitivity of the model to force inputs, cartilage stiffness, and cartilage geometry was studied. The FE model predicted MCP joint torque and sesamoid bone flexion angles within 5% of experimental measurements. Muscle–tendon forces, joint loads and cartilage stresses all increased as locomotion speed increased from walking to trotting and finally cantering. Perturbations to muscle–tendon forces resulted in small changes in articular cartilage stresses, whereas variations in joint torque, cartilage geometry and stiffness produced much larger effects. Non-subject-specific cartilage geometry changed the magnitude and distribution of pressure and the von Mises stress markedly. The mean and peak cartilage stresses generally increased with an increase in cartilage stiffness. Areas of peak stress correlated qualitatively with sites of common injury, suggesting that further modelling work may elucidate the types of loading that precede joint injury and may assist in the development of techniques for injury mitigation.

1. Introduction

The metacarpophalangeal (MCP) joint is the site of a large proportion of musculoskeletal injuries in racehorses (Bailey et al., 1999; Parkin et al., 2004). Osteochondral injuries occur predominantly in the palmarodistal aspect of the third metacarpal bone (MC3) and the dorsoproximal articular margin of the proximal phalanx (P1). Subchondral bone damage to the palmar aspect of the MC3 condyle is especially common, resulting in two types of injury: parasagittal fractures of the condyles and palmar osteochondral disease (Barr et al., 2009; Parkin et al., 2006). These injuries are considered fatigue injuries, the result of a high number of stress cycles applied to cartilage and bone, rather than an acute mechanical event (Stepnik et al., 2004; Norrdin and Stover, 2006).

Many factors contribute to fatigue injury, but the magnitude of the stress or strain to which tissues are subjected is critical (Rapillard et al., 2006). The MCP joint experiences the largest loads of the distal limb during locomotion (Merritt et al., 2008; Harrison et al., 2010). MCP joint hyperextension during locomotion results in the storage of elastic strain energy in the long flexor tendons and the suspensory apparatus (Biewener, 1998; Bobbert et al., 2007; Butcher et al., 2009; Harrison et al., 2010; McGuigan and Wilson, 2003; Witte et al., 2004), which is subsequently utilised by the limb to increase the efficiency of locomotion (Butcher et al., 2009; Harrison et al. 2010). However, stretching of the flexor tendons imposes large forces on the MCP joint (Merritt et al., 2008; Harrison et al. 2010). While previous studies have reported on the magnitudes of the resultant forces transmitted by the MCP joint (Merritt et al., 2008; Harrison et al., 2010), the magnitudes and locations of maximum cartilage stresses are unknown.

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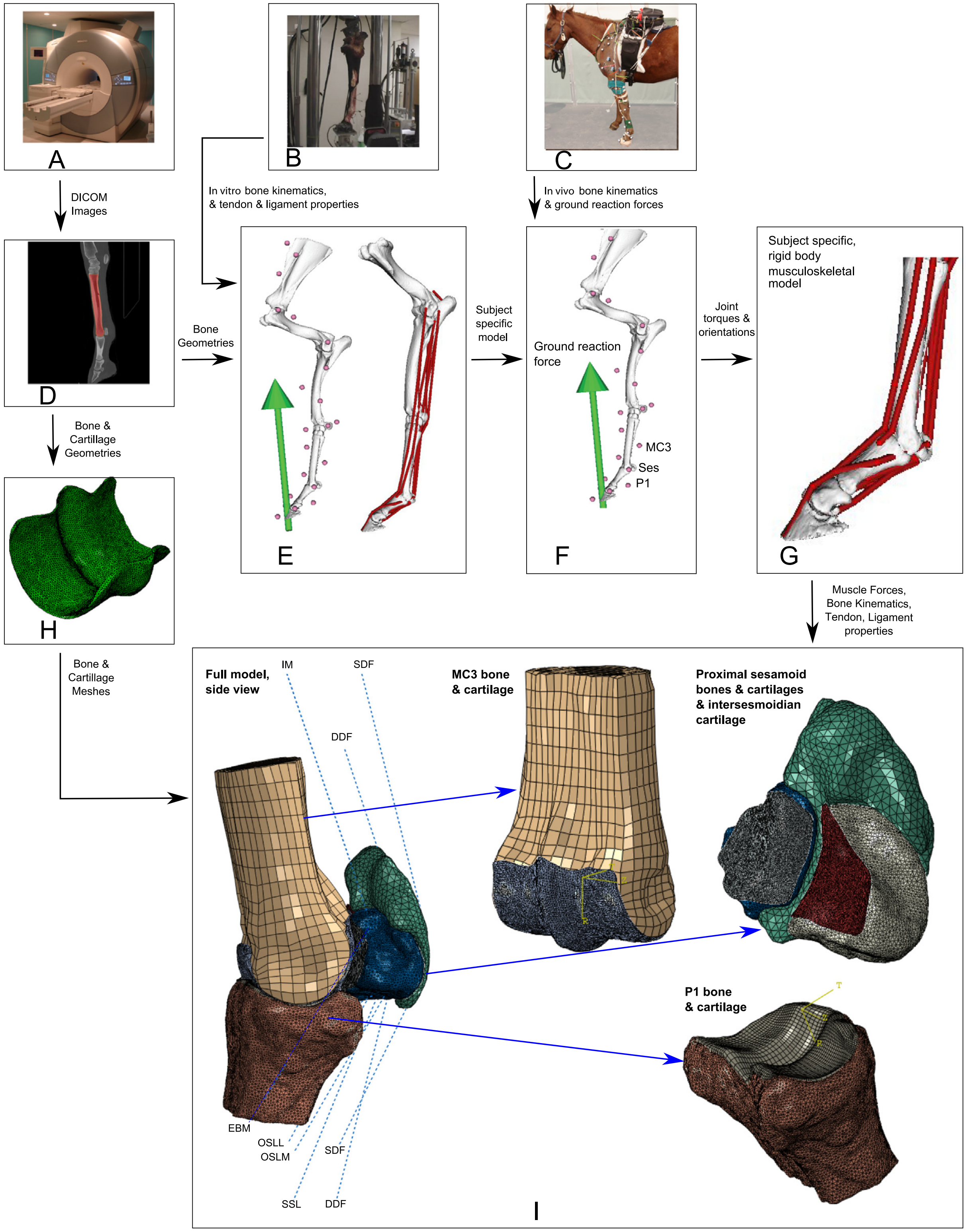

Fig. 1. Development of a subject-specific, rigid-body, musculoskeletal model and a subject-specific, deformable, finite-element joint model. (A) Bone, muscle and cartilage geometries obtained from a cadaveric forelimb were imaged using MRI and CT; (B) tendon and ligament strains, bone kinematics, and hoof forces were determined from *in vitro* mechanical experiments performed on a cadaveric forelimb; (C) gait analysis experiments were performed to measure joint kinematics and hoof loading during walking, trotting and cantering; (D) bone and cartilage geometries and muscle paths were determined using image segmentation; (E) outputs from the mechanical loading experiments, MR imaging, and gait analysis experiments were used to develop a subject-specific rigid-body musculoskeletal model of the distal forelimb; (F) inverse kinematics and inverse dynamics methods were used to determine the joint angles and net moments exerted about the joints in the model; (G) muscle–tendon and ligament forces were calculated based on the subject-specific rigid-body musculoskeletal model; (H) FE meshes were created from bone and cartilage geometries; muscle–tendon and ligament forces obtained from the subject-specific rigid-body musculoskeletal model (G) were input into a subject-specific deformable finite-element (FE) model of the MCP joint; and (I) subject-specific FE model of the MCP joint showing the major tendon/ligament structures and the three bone-cartilage articulations. (a) 3D imaging, (b) cadaver experiments, (c) galt experiments, (d) segmentation, (e) subject specific dynamic musculoskeletal model, (f) inverse dynamics & inverse kinematics, (g) muscle force calculations, (h) mesh creation and (i) FE modelling.