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Passive and active mechanical properties of the superficial and deep digital flexor muscles in the forelimbs of anesthetized Thoroughbred horses

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Abstract

The superficial (SDF) and deep digital flexor (DDF) muscles are critical for equine forelimb locomotion. Knowledge of their mechanical properties will enhance our understanding of limb biomechanics. Muscle contractile properties derived from architectural-based algorithms may overestimate real forces and underestimate shortening capacity because of simplistic assumptions regarding muscle architecture. Therefore, passive and active (= total – passive) force–length properties of the SDF and DDF muscles were measured directly in vivo. Muscles from the right forelimbs of four Thoroughbred horses were evaluated during general anesthesia. Limbs were fixed to an external frame with the muscle attached to a linear actuator and load cell. Each muscle was stretched from an unloaded state to a range of prefixed lengths, then stimulated while held at that length. The total force did not exceed 4000 N, the limit for the clamping device. The SDF and DDF muscles produced 716 ± 192 and 1577 ± 203 N maximum active isometric force (F_{max}), had ascending force–length ranges (R_{asc}) of 5.1 ± 0.2 and 9.1 ± 0.4 cm, and had passive stiffnesses of 1186 ± 104 and 1132 ± 51 N/cm, respectively. The values measured for F_{max} were much smaller than predicted based on conservative estimates of muscle specific tension and muscle physiological cross-sectional area. R_{asc} were much larger than predicted based on muscle fiber length estimates. These data suggest that accurate prediction of the active mechanical behavior of architecturally complex muscles such as the equine DDF and SDF requires more sophisticated algorithms.

Keywords: Biomechanics; Contractile properties; Modeling; Isometric

1. Introduction

The superficial digital flexor (SDF) and the deep digital flexor (DDF) muscle–tendon units play major roles in supporting the equine forelimb during the stance phase of gait. Both myotendinous complexes consist of a muscle (≈400 mm long in adult Thoroughbred horses) and an accessory ligament sharing a common, long tendon of insertion (450–550 mm). For equids ranging in size from ponies to adult horses, the SDF is reported to have a single muscle compartment with short, pennate fibers (2–6 mm) and extensive connective tissue, whereas the DDF muscle has multiple compartments of varying fiber lengths (6–62 mm) and connective tissue development (Biewener, 1998; Dimery et al., 1986; Grandage, 1981; Hermanson and Cobb, 1992). The DDF muscle has three heads (ulnar-UH, radial-RH, and humeral-HH), with the considerably larger HH subdivided into long (HH_l), intermediate (HH_i), and short fibered (HH_s) compartments (Wilson et al., 2001). Accessory ligaments and distal tendons provide passive support to metacarpophalangeal structures and contribute to the equine

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forelimb stay apparatus that facilitates forelimb support with minimal muscular effort.

Architectural algorithms based on morphologic information were used to estimate maximum active forces and ranges of active force development for the SDF and DDF muscles. The maximum active isometric force (F_{max}) was estimated as the product of the muscle's physiologic cross-sectional area (PCSA) and its specific tension (Powell et al., 1984). The muscle's range (R_{asc}) for the ascending limb of its force–length (*F–L*) behavior was estimated to be 40% of its fiber length (Gordon et al., 1966). Assuming a specific tension of 30 N/cm^2, an F_{max} of about 5000 N has been estimated for both the SDF and DDF muscles (Wilson et al., 2001). Similarly, based on reported PCSA values in moderate-sized horses (Biewener, 1998), F_{max} was estimated to be 3000 N for the SDF and 420 N (HH_l) and 7800 N ($HH_i + HH_s$) for compartments within the DDF. Assuming muscle length changes are associated with muscle fiber length changes, the fiber lengths of the SDF and DDF suggest R_{asc} of about 1–2 and 2–24 mm, respectively.

There is evidence, however, that some muscles do not behave as estimated using architectural-based algorithms. Muscle function has been related to the ratio of fiber length to overall muscle length (Lieber, 1992; Woittiez et al., 1983). Muscles with very short fibers relative to their overall muscle length (such as the SDF and DDF) exhibit a reduced F_{max}, expanded active ranges, and steep passive *F–L* curves. Complex architectures make estimation of the passive mechanical properties of these muscles difficult. Passive force is generated not only from series and parallel elastic components of muscle fibers, but also from elastic characteristics of the extra-cellular matrix, fascia, and intramuscular aponeurotic tendon. Further, it is difficult to estimate the length at which passive force is developed with respect to the development of active force.

Due to their complex architectures with relatively long muscles comprised of short interconnected fibers, we hypothesized that the SDF and DDF muscles exhibit larger active ranges and smaller active forces than estimated using common architectural-based algorithms. To test this hypothesis, to gain an understanding of their ability to resist stretch passively, and to understand muscle characteristics for modeling forelimb dynamics, we directly measured the active and passive *F–L* properties of the whole SDF and DDF muscles in anesthetized horses.

2. Methods

Active and passive mechanical characteristics of the SDF and DDF muscles from the right forelimbs of four Thoroughbred horses weighing 527 ± 87 (SD) kg (Table 1) were evaluated during general anesthesia after approval by the institutional Animal Care and Use Committee. No abnormalities were observed on clinical and ultrasonographic examinations of the forelimb digital flexor muscle–tendon units of each horse. After pre-medication with xylazine, anesthesia was induced with guaifenesin and ketamine, and maintained with sevoflurane in oxygen using a large animal circuit system (Driessen et al., 2002). Horses were monitored throughout testing, and treated as necessary, to ensure adequate oxygenation, physiologic blood gas and electrolyte levels, and body temperature.

Table 1
Horse signalment

Horse	Body mass (kg)	Age (y)	Sex[a]
1	454	5	G
2	525	3	G
3	650	7	G
4	478	6	F
Mean (SD)	527 (87)	5.3 (1.7)	—

[a] G: gelding (castrated male); F: female.

The limb was prepared for data collection as previously described (Zarucco et al., 2003). Briefly, the median and ulnar nerves were instrumented with cuff electrodes (Micro Probe, Inc., NC452 & NC552) for stimulation to elicit muscle contractions. A wire thread was aligned with each muscle, from proximal to distal muscle–tendon junction (MTJ) (note: the SDF and DDF have virtually no free tendon at their proximal ends), for subsequent measurements of muscle resting length. The right humerus was secured with a metal fixture to an external aluminum frame through which loads could be applied to digital flexor muscles (Fig. 1). In one horse (Horse 4 in Table 1), a slack configuration of the forelimb was determined, with the SDF and DDF muscles (unstimulated) and tendons just taut (accessory ligaments transected), in order to gauge the limb configuration at which passive muscle force began to develop. In preparation for *F–L* measurements, each muscle (SDF followed by DDF) was attached at the distal MTJ by a clamp in series with a load cell (Interface Sealed Super-Mini; #SSM-AF-2000) to a pneumatic linear actuator (Fig. 2). The applied pressure of the clamp onto the tendon at the MTJ was closely monitored to ensure a secure grip without slippage. The actuator was instrumented with a linear potentiometer (250 mm, Midori; #LP-250F-5k) to measure displacement and an adjustable mechanical stop to set the length of stretch. Because there was virtually no free tendon at the proximal end of these muscles and the clamp was connected to the distal end of the muscles, displacement of the actuator represented displacement of the muscle.