A MODEL OF THE HORSE DIGIT — RELIABILITY AND COMPARISON WITH IN-VIVO EXPERIMENTS

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INTRODUCTION: The horse toe consists of metacarpus/tarsus, 3 phalanges, 3 sesamoids (2 proximal and 1 distal), 3 major joints, namely the hoof joint, pastern joint and fetlock joint, and 3 tendons on the flexor side: deep and superficial flexor, and interosseous. The deep flexor consists of a tendinous head (deep check ligament) and a muscular head. This flexor balances the external moments in only one joint, namely the hoof joint. All 3 tendons on the flexor side balance the external moments in the fetlock joint. Especially in sports horses, the toe is affected by various pathologies including tendopathies, joint diseases, and bone fractures. Most injuries are attributed to acute or chronic overloading of the tendons, causing overstrain of the tissue, which results in inflammation or even rupture.
For any results based on a model it is favorable to compare these with experimental in-vivo results. Jansen et al. (1993) studied the tendon forces of the equine toe by means of implanted liquid-metal strain gauges in 5 ponies. As such methods are not suited for routine diagnostics, a mathematical model is necessary, so far as modeling provides results comparable to experimental studies.
The aim of this study was to develop a model for calculation of the moments, muscle and tendon forces, and joint forces of the 3 major joints as well as the proximal and distal sesamoid joints of the digit and to compare the muscle/tendon forces with the results of in-vivo experiments by Jansen et al. (1993).

METHODS: The 2D model is based on inverse-dynamic quasi-static calculation of the above mechanical parameters (software HORSE-FOOT 1.0). Basic input data are: 1) dynamic data — ground reaction forces during walking (amount, direction, and position), 2) kinematic data — joint angles during motion (gait cycle), 3) morphological data — attachments of tendons and ligaments, geometry of tendon deviations and joint surfaces, rotation centers, lever arms, hoof shape, cross sectional areas of tendons and ligaments, 4) material properties — Young's modulus of collagenous tissue (tendons). 1), 2), and 4) were taken from the literature (Becker, 1996), 3) from own investigations (dissections, marking of ligaments and tendons with wires, radiographs).

ANALYSIS: The model consisted of six basic free body diagrams. FBD1: hoof + hoof bone + navicular bone, FBD2: navicular bone, FBD3: hoof + hoof bone, FBD4: FBD1 + coronal bone, FBD5: FBD4 + fetlock bone, FBD6: both proximal sesamoids. External joint moments were calculated from dynamic and kinematic data. Two types of "muscles" are found in horse limbs: 1) typical muscles consisting of muscular tissue and a tendon, 2) tendinous "muscles" without muscular tissue. The former can contract actively and serve for balancing the external moments, the latter act as passive stabilizers which produce a force on elongation. The distance change between proximal and distal attachments of the tendinous muscles (interosseous, including its dorsal branch, and deep check ligament) and elastic ligaments (sesamoid collaterals) was calculated according to morphological and kinematic data. Based on this distance change, the rest length was determined at that time (in % of gait cycle) when the tendon produces a force (according to the results of Jansen et al., 1993). The rest length then allowed the calculation of the length change and the strain (ε). For the calculation of the produced force (F), the Young's modulus (E) and the cross sectional area (A) were necessary.

$$F = \varepsilon E A \quad (1)$$

The cross sectional area of fresh cadaveric tendons was calculated from its length (l), mass (m), and density (ρ):

$$A = m / (l\rho) \quad (2)$$

The density of tendons is 1120 kg/m^3 (Ker, 1981), the Young's modulus of the deep flexor tendon is 800-1000 MPa (Becker, 1996). The factor EA of equation (1) was considered a constant, although E increases with elongation speed and initially with strain, and A decreases with strain. The factor EA of the deep flexor tendon, for example, amounts to about 100000 Pa m^2. The moment equilibrium allowed the calculation of the muscle forces from tendon moments and external moments. The force equilibrium allowed the calculation of joint forces from muscle, tendon, and external forces. Joint force distribution and joint stress was calculated according to Fuss and Fuss (1998).

RESULTS AND DISCUSSION: The load distribution in the different tendons during walking is practically the same in in-vivo experiments (Figure 1) and in the simulation model (Figure 2). The slight differences between the interosseous and deep check ligament curves might be due to the following facts: The forces of both structures depend on the kinematics, i.e., the joint angles with respect to the gait cycle. Kinematics are closely related to the magnitude of the ground reaction forces as well as to their origin (pressure center on the hoof). Jansen et al. used ponies for their experiments. They did not indicate the breed, however. The withers height was about 1.2 m, the body mass between 165 and 240 kg. In contrast to Jansen et al., I used the data of riding horses. The ponies were operated in order to implant the strain gauges. Such a procedure must cause slight gait changes, as the animals either suffer from pain or from paraesthesias due to anaesthetics, or the implant disturbs the tendo-muscular control circuits.
The joint forces calculated from the model simulation are shown in Figure 3. The fetlock joint is the one with the maximal load, which amounted to up to 2.5 times body weight.

CONCLUSIONS: The comparability and reliability of the model results in comparison with the in-vivo results clearly show that in-vivo experiments are no longer necessary and can be completely replaced by model simulation and calculation. The introduced model can be used for the determination of any muscle, tendon, ligament, and joint force of the horse digit during motion. Furthermore, the effects of morphological variability can be defined biomechanically, and predictions concerning the mechanical purpose of diagnostics and treatment strategies can be made. The knowledge of the loading of each structure is of great importance in view of the etiology, prevention, and treatment of sports injuries.

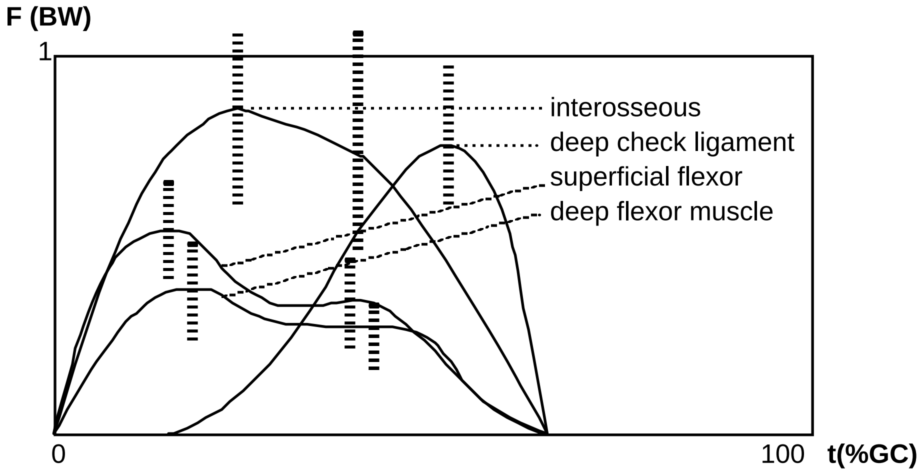

Figure 1 — Results (mean and range) of Jansen et al. (1993). Force (F) in multiples of body weight (BW), time (t) in percentage of gait cycle (GC)

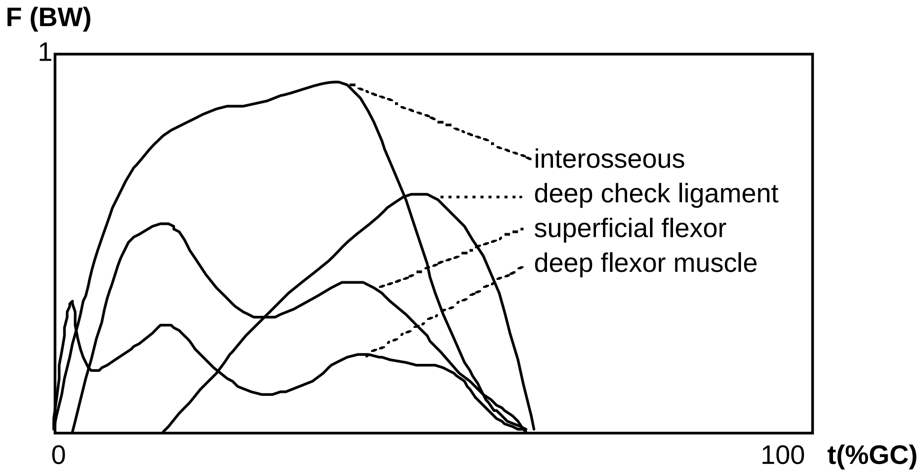

Figure 2 — Muscle and tendon forces, results of the model

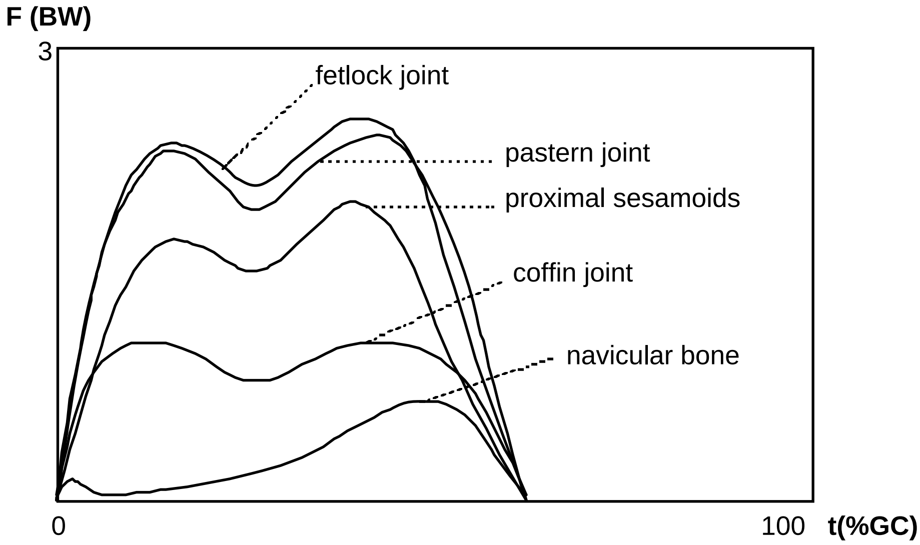

Figure 3 — Joint forces, results of the model

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