Net joint moments and joint powers in horses with superficial digital flexor tendinitis

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Objective—To determine whether analysis of net joint moments and joint powers is a suitable technique for evaluation of mechanics and energetics of lameness in horses and to measure effects of superficial digital flexor tendinitis.

Animals—6 sound horses.

Procedure—Horses were evaluated before (sound evaluation) and after (lame evaluation) induction of superficial digital flexor tendinitis in 1 forelimb by injection of collagenase. Recordings were made with an optoelectronic system and a force plate as horses trotted. Net joint moments and joint powers in the sagittal plane at each joint in the forelimbs during the stance phase were determined. Peak values were determined, and mechanical energy absorbed and generated at each joint was calculated. Comparisons were made between contralateral limbs during sound and lame evaluations.

Results—Lame limbs had significant reductions in peak values for net joint moments on the palmar aspect of metacarpophalangeal ( fetlock), carpal, and humeroulnar joints. Total energy absorbed was significantly lower at every joint in lame limbs, compared with compensating limbs.

Conclusions and Clinical Relevance—Horses with superficial digital flexor tendinitis had significant differences between lame and compensating limbs for net joint moments and joint powers at all joints, indicating that the gait of horses with superficial digital flexor tendinitis is energetically inefficient. Assessment of net joint moments and joint powers is a useful tool in evaluating equine lameness. (Am J Vet Res 2000;61:197–201)

Lameness is recognized as an abnormality or asymmetry of movement. The kinematic changes that are assessed visually by the clinician are associated with alterations in kinematics and in ground reaction forces (GRF) that may have the effect of relieving pain in the affected structures. Kinematic and GRF adaptations can be combined with morphometric information through inverse dynamics by use of a link segment model. The resulting information describes net joint moments and joint powers, thus linking biomechanical analysis with energetic changes.

Power measures the rate of doing work, and it is calculated as the product of net joint moment and the joint’s angular velocity. If net joint moment acts in the same direction as joint angular velocity, the power is positive (power generation) and the muscles perform positive (concentric) work in which the muscle shortens during muscular contraction. If net joint moment acts in the opposite direction to joint angular velocity, the power is negative (power absorption), and the muscles perform negative (eccentric) work in which the muscle lengthsens as it generates tension. Power absorption occurs when the muscles control joint motion in opposition to the influence of gravity or some other external force. The net work performed (energy expended) over a period of time by the muscles and tendons that cross a specific joint is calculated by mathematical integration of the power curve with time. This yields the energy absorbed and the energy generated.

In humans, the single most useful variable in describing abnormal gait is joint power. Abnormal gaits are inefficient and are associated with an overall increase in energy expenditure; specific gait abnormalities cause characteristic alterations in the shape of the power profile as well as changes in the amount of energy absorbed and generated at the joints. In diseases such as cerebral palsy, changes in the power profile are used to guide decisions regarding surgical intervention and to monitor effects of treatment. Tendinitis of the superficial digital flexor tendon (SDFT) is a common lameness in athletic horses. Strain on the SDFT during the stance phase depends on limb kinematics, especially the angle of the metacarpophalangeal ( fetlock) joint; strain increases with extension of the fetlock joint. The GRF associated with superficial digital flexor tendinitis have been reported, but we are not aware of published information describing net joint moments and joint powers associated with this type of lameness.

The primary objective of the study reported here was to determine whether analysis of net joint moments and joint powers during the stance phase yields useful information for evaluating equine lameness induced by tendinitis. A secondary objective was to measure effects of superficial digital flexor tendinitis on net joint moments and joint powers.

Materials and Methods

Horses and tendinitis model—Six warmblood horses that were clinically sound and did not have ultrasonographic evidence of damage to the tendinous structures in the pal-

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mar metacarpal region were used. Hooves were trimmed in normal balance, flat steel shoes were applied, and hoof angles were measured with a hoof protractor.

Tendinitis was induced in 1 forelimb (randomly selected) by injection of collagenase into the SDFT, as described. Clinical examinations were performed daily after injection and phenylbutazone was administered as required, in accordance with the experimental protocol that was approved by the Animal Ethics Committee at Utrecht University.

Data collection and reduction—Kinematic data from an optoelectric system and GRF data from a force plate embedded in a rubber-covered runway were synchronized in time and space, as described. Four trials were analyzed for the left and right forelimbs of each horse at each recording session. Data recordings were made 1 to 3 days prior to collagenase injection (sound evaluation) and after collagenase injection when the horses were able to trot comfortably with a mild to moderate lameness (lame evaluation). For lame horses, the forelimb injected with collagenase was referred to as the lame limb, whereas the contralateral (noninjected) forelimb was referred to as the compensating limb.

Calculation of net muscle moments and joint powers—The GRF and kinematic data were combined spatially and temporally to obtain an inverse dynamics solution for the resultant net joint moments for the distal interphalangeal (coffin), fetlock, carpal, humeral (elbow), and scapulohumeral (shoulder) joints of both forelimbs. Joint moments were normalized to body mass. Mass, location of the center of mass, and inertial parameters of hoof, pastern, metacarpal, antebrachial, brachial, and scapular segments were determined from published morphometric data for warmblood horses.

Joint angles were measured on the anatomic flexor side of each joint (the caudal-palmar side for all forelimb joints except the elbow). Joint moments on the extensor aspect were assigned a positive sign, and those on the flexor aspect were assigned a negative sign. Angular velocity was positive when the joint angle was extending and negative when the joint angle was flexing. Joint power was calculated as the product of the joint moment and angular velocity of the joint angle was flexing. Joint power was calculated as the product of the joint moment and angular velocity of the joint. A positive joint power indicates power generation in which the muscle shortens as it generates tension (concentric muscular contraction). A negative joint power indicates power absorption in which the muscle lengthens as it generates tension (eccentric muscular contraction).

Statistical analyses—Mean values for net joint moments and joint powers were calculated for each trial for each horse; data sets were time normalized by cubic spline interpolation. For specific points on the moment and power curves, amplitude was determined for each horse on a stride-by-stride basis. The power curve was integrated to determine the mechanical energy generated and absorbed at each joint.

Total energy generated and total energy absorbed at each joint were determined by summation. Mean values and SD for each variable were computed for the 6 horses. Group means were checked for normality of distribution by plotting the residuals, and paired t-tests (n = 6) were used to detect asymmetries between the 2 forelimbs before and after induction of lameness. Differences were considered significant at $P < 0.05$. Statistical comparisons across days were not made, because trotting speed of lame horses was substantially slower than that of sound horses.

### Results

#### Sound horses

Only 1 of the 47 variables describing net joint moments and joint powers differed significantly between the left and right forelimbs of sound horses; this was considered a spurious result.

#### Lame horses

For lame horses, 26 of the 47 variables differed significantly between lame and compensating limbs (Tables 1–5). Compared with compensating limbs, lame limbs had lower palmar net joint moment and energy generation at the elbow, carpal,
and fetlock joints, whereas total energy absorbed was significantly lower at every joint.

Patterns of net joint moments and joint powers (Fig 1–5) for lame and compensating limbs were similar in most respects. The most obvious differences were that the beginning of the negative peak in net coffin joint moment occurred 10 to 20% later in compensating limbs than in lame limbs, and elbow joints of lame limbs had energy generation on the cranial (flexor) side during the terminal 10% of the stance phase. Although statistical comparisons were not made across days, moment and power curves were evaluated qualitatively to detect obvious dissimilarities in shape. The coffin joint moment in compensating limbs became negative at a later time during the stance phase of lame horses. A small amount of coffin joint power generation is usually detected until 35% of the stance phase, but this

### Table 4—Net joint moments, powers, and energies (mean ± SD) for the humeroulnar (elbow) joint of sound and lame horses

<table>
<thead>
<tr>
<th>Measurement</th>
<th>Sound horses</th>
<th>Compensating limb</th>
<th>Lame limb</th>
</tr>
</thead>
<tbody>
<tr>
<td>First positive moment peak (Nm/kg)</td>
<td>–1.23 (0.14)</td>
<td>–1.24 (0.20)</td>
<td>–0.94 (0.21)*</td>
</tr>
<tr>
<td>Second positive moment peak (Nm/kg)</td>
<td>–1.25 (0.24)</td>
<td>–1.36 (0.17)</td>
<td>–0.92 (0.23)*</td>
</tr>
<tr>
<td>Peak negative power (W/kg)</td>
<td>–4.91 (1.41)</td>
<td>–4.95 (2.31)</td>
<td>–3.64 (2.00)</td>
</tr>
<tr>
<td>Peak positive power (W/kg)</td>
<td>3.73 (1.18)</td>
<td>4.37 (1.02)</td>
<td>2.15 (1.04)*</td>
</tr>
<tr>
<td>Total energy generated (J/kg)</td>
<td>0.02 (0.05)</td>
<td>0.25 (0.04)</td>
<td>0.13 (0.07)*</td>
</tr>
<tr>
<td>Total energy absorbed (J/kg)</td>
<td>–0.19 (0.05)</td>
<td>0.20 (0.07)</td>
<td>0.15 (0.07)</td>
</tr>
<tr>
<td>Total net energy (J/kg)</td>
<td>0.00 (0.04)</td>
<td>0.04 (0.04)</td>
<td>–0.01 (0.02)*</td>
</tr>
</tbody>
</table>

See Table 1 for key.

### Table 5—Net joint moments, powers, and energies (mean ± SD) for the scapulohumeral (shoulder) joint of sound and lame horses

<table>
<thead>
<tr>
<th>Measurement</th>
<th>Sound horses</th>
<th>Compensating limb</th>
<th>Lame limb</th>
</tr>
</thead>
<tbody>
<tr>
<td>First positive moment peak (Nm/kg)</td>
<td>0.60 (0.31)</td>
<td>0.42 (0.24)</td>
<td>0.56 (0.32)</td>
</tr>
<tr>
<td>First negative moment peak (Nm/kg)</td>
<td>–0.91 (0.17)</td>
<td>–0.82 (0.25)</td>
<td>–0.80 (0.26)</td>
</tr>
<tr>
<td>Second positive moment peak (Nm/kg)</td>
<td>1.46 (0.16)</td>
<td>1.39 (0.23)</td>
<td>1.06 (0.19)*</td>
</tr>
<tr>
<td>First positive power peak (W/kg)</td>
<td>3.51 (0.89)</td>
<td>4.93 (2.88)</td>
<td>4.07 (1.46)</td>
</tr>
<tr>
<td>First negative power peak (W/kg)</td>
<td>–3.39 (1.61)</td>
<td>–3.79 (1.02)</td>
<td>–2.23 (1.14)</td>
</tr>
<tr>
<td>Second positive power peak (W/kg)</td>
<td>1.97 (1.71)</td>
<td>1.69 (1.38)</td>
<td>1.07 (0.59)</td>
</tr>
<tr>
<td>Third positive power peak (W/kg)</td>
<td>3.50 (0.70)</td>
<td>3.49 (1.08)</td>
<td>2.44 (0.65)</td>
</tr>
<tr>
<td>Total energy generated (J/kg)</td>
<td>0.36 (0.04)</td>
<td>0.34 (0.05)</td>
<td>0.28 (0.06)</td>
</tr>
<tr>
<td>Total energy absorbed (J/kg)</td>
<td>–0.12 (0.06)</td>
<td>0.16 (0.06)</td>
<td>0.09 (0.02)*</td>
</tr>
<tr>
<td>Total net energy (J/kg)</td>
<td>0.24 (0.06)</td>
<td>0.18 (0.10)</td>
<td>0.19 (0.05)</td>
</tr>
</tbody>
</table>

See Table 1 for key.
was not seen in either forelimb of lame horses; instead, power remained close to 0 until the negative burst began at 30% of the stance phase in lame limbs and at 40% of the stance phase in compensating limbs. At the shoulder joint, both limbs had power absorption on the dorsal side in the terminal 10 to 15% of the stance phase in lame horses, whereas energy generation was maintained at the shoulder joint until lift off in sound horses.

**Discussion**

Reports have described GRF in horses with a variety of forelimb lamenesses, including sole pain in the hoof,10 a full-thickness articular cartilage defect on the radial carpal bone,11 tendinitis of the SDFT,6,7 deep digital flexor tendinitis,6 and suspensory desmitis.6 A consistent finding is that vertical GRF and braking longitudinal GRF are lower in lame limbs and increased in the compensating forelimbs. These changes in force magnitudes allow the GRF vector to maintain its alignment with the long axis of the limb despite changes in limb kinematics used by the horse to manage the lameness.5 There is also a higher propulsive longitudinal GRF in the hind limb that moves synchronously with the lame forelimb.11 Perhaps the higher propulsion provided by the hind limb is a consequence of the greater braking longitudinal GRF during the preceding stance phase; unless the braking force is counteracted by an equal propulsive force, the velocity would decrease with every stride.

When a horse has a forelimb lameness, the increased vertical GRF in the compensating limb could be responsible for high palmar moments at the coffin, fet-
lock, carpal, and elbow joints, with a consequent increase in tension in the supporting structures. However, because of the higher braking longitudinal force in the compensating limb, the GRF vector has a more caudal inclination, which reduces its moment arm at the coffin, fetlock, carpal, and elbow joints. Therefore, an increase in braking longitudinal GRF in the first half of the stance phase mitigates the effect of an increase in vertical GRF in terms of the joint moment and the tension required in the palmar soft tissues.

Proximally, the superficial digital flexor has muscular attachments to the medial epicondyle of the humerus, the proximal portion of the ulna, and a tendinous attachment to the distal portion of the radius. Distally, it attaches to the proximal and middle phalanges. Tension in the SDFT contributes to palmar moments at the elbow, carpal, and fetlock joints. Horses with tendinitis of the superficial digital flexor tendon have reduced net joint moment, power absorption, and power generation on the palmar aspect at all of these joints. Significant differences between lame and compensating limbs were particularly striking at the fetlock and elbow joints, both of which function elastically during the stance phase with periods of energy absorption followed by energy generation as the tissues recoil.4 The power profiles indicated that these elastic functions were retained, but with significant reductions in the storage and release of energy.

Although the SDFT does not cross the coffin joint, changes in the GRF affect the net joint moments and powers at this joint, causing later development of the palmar moment at the coffin joint and an overall reduction in its magnitude. The fact that there was no increase in the net coffin joint moment in either limb suggests that the deep digital flexor tendon was not actively compensating for the reduction in SDFT function. The primary action of the coffin joint as an energy damper was retained, but its effect was greatly reduced in magnitude in the lame limb.

In the lame limb, there was a short burst of power generation associated with flexion at the elbow joint in the terminal 10% of the stance phase. These data suggest that the reduction in carpal moment in the lame limb relieves tension on the palmar support structures at an early stage of the stance phase. Loss of tension in the proximal accessory ligament, which normally restrains forward movement of the distal radius, is sufficiently reduced by 85% of the stance phase so that the radius starts to rotate. Consequently, the carpal and elbow joints flex. The fact that there is power generation on the dorsal side of the elbow joint in the terminal 10% of the stance phase in the lame limb is, perhaps, an indication of the need for active elevation of the radial segment as the limb makes the transition from the stance phase to the swing phase. This would provide a mechanism for lifting the distal portion of the limb clear of the ground in the absence of a suspension phase. The brachialis muscle becomes active at the beginning of the swing phase,12 when it acts to elevate the radial segment and flex the elbow joint. Results of the study reported here suggest that the brachialis may become active during the terminal stance phase in horses with SDF tendinitis.

In evaluating these results, the relationship between mechanical and metabolic energy must be considered. Generation of mechanical power involves concentric muscle contraction, whereas absorption of mechanical energy involves eccentric muscle contraction. Concentric and eccentric muscular contractions use metabolic energy. Because positive joint powers (energy generation) and negative joint powers (energy absorption) involve metabolic energy expenditure, considerably more metabolic energy is used in the compensating limb than in the lame limb.

In horses with SDF tendinitis, the peak value of the net joint moment was lower in the lame limb than the compensating limb at all joints crossed by the SDF muscle and its tendon (the elbow, carpal, and fetlock joints). In the lame limb, total energy absorbed was significantly lower at every joint, and total energy generated was significantly lower at the fetlock, carpal, and elbow joints.

References