Calculated forelimb flexor tendon forces in horses with experimentally induced superficial digital flexor tendinitis and the effects of application of heel wedges

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Objective—To calculate forces in the flexor tendons and the influence of heel wedges in affected and contralateral (compensating) forelimbs of horses with experimentally induced unilateral tendinitis of the superficial digital flexor (SDF) tendon.

Animals—5 Warmblood horses.

Procedure—Ground reaction force and kinematic data were obtained during a previous study while horses were trotting before and after induction of tendinitis in 1 forelimb SDF and after application of 6° heel wedges to both forehooves. Forces in the SDF, deep digital flexor (DDF), and the suspensory ligament (SL) and strain in the accessory ligament (AL) of the DDF were calculated, using an in vitro model of the distal region of the forelimb.

Results—After induction of tendinitis, trotting speed slowed, and forces decreased in most tendons. In the affected limb, SL force decreased more than SDF and DDF forces. In the compensating limb, SDF force increased, and the other forces decreased. After application of heel wedges, SDF force in both limbs increased but not significantly. Furthermore, there was a decrease in DDF force and AL strain.

Conclusions and Clinical Relevance—The increase in SDF force in the compensating forelimb of horses with unilateral SDF tendinitis may explain the high secondary injury rate in this tendon. The lack of decrease of SDF force in either limb after application of heel wedges suggests that heel wedges are not beneficial in horses with SDF tendinitis. Instead, heel wedges may exacerbate the existing lesion. (Am J Vet Res 2002;63:432–437)

The superficial digital flexor (SDF) tendon is 1 of the most important flexor tendons in the forelimb of horses. It is heavily loaded not only during demanding activities such as jump landings but also during nondemanding activities such as trotting. Not surprisingly, SDF tendinitis is an important cause of lameness in Thoroughbred and Standardbred racehorses as well as in other athletic horses. The forelimb SDF tendon is more frequently affected than the hind limb tendon, and tendinitis is often bilateral. The resulting lameness is a source of discomfort to affected horses and results in large economic losses in the racing and other equine athletic industries.

Lame horses try to limit discomfort by reducing the load (force) on the affected structure. Load reduction can be achieved by reducing speed of movement or by shifting the load to other compensating structures. Loads can be shifted either to structures within the affected (lame) limb (intralimb compensation) or to other limbs (interlimb compensation). Intralimb compensation may occur in lame horses, but it cannot be easily evaluated, because doing so requires quantification of internal loads. Interlimb compensation, however, has been documented in lame horses. The associated changes in kinematics are, in fact, an important indication of lameness. The additional loading of the compensating limb may be the key factor in the development of secondary lameness in that limb. However, although interlimb compensation is a recognized phenomenon, it is not known how it affects the loading of individual structures within the compensating limb, because evaluation of this would also require quantification of internal loads.

Orthopedic shoeing is a technique for the treatment of lame horses that aims at load reduction of the affected structure. An example of such shoeing is the application of heel wedges. Results of several studies indicate that application of heel wedges reduces loading of the deep digital flexor (DDF) tendon and its accessory ligament (AL, or distal check ligament). However, results of studies evaluating SDF loading on ponies that are not lame have been contradictory. Also, results of such studies probably cannot be extrapolated to horses with SDF tendinitis, because the response to heel wedges is influenced by tendinitis.

In 2 studies of SDF tendinitis and the influence of heel wedges, net joint moments were calculated, but loading of individual tendons could not be separately determined. Furthermore, direct invasive determination of tendon loading in horses with tendinitis may not be possible, because induction of tendinitis will interfere with such measurements. However, we
recently described a method to calculate flexor tendon forces from joint angles and joint moments, using an in vitro model of the distal region of the limb. This model can be applied to available data regarding kinematics and ground reaction forces of horses with SDF tendinitis to quantify individual tendon loads in both lame and compensating limbs with and without heel wedges. The purpose of the study reported here was to determine the influence of SDF tendinitis on flexor tendon loading and load distribution in lame and compensating equine forelimbs and the effect of application of heel wedges on flexor tendon loading in horses with SDF tendinitis. We calculated flexor tendon forces, using data published by Clayton et al13,14 and our in vitro model.15

Materials and Methods
Collection of in vivo data—In previous studies, Clayton et al13,14 collected kinematic and net joint moment data from trotting horses before and after induction of SDF tendinitis and after application of heel wedges. These data were used in the present study. In vivo data collection and analysis procedures have been described in detail elsewhere. Briefly, tendinitis was induced in 5 Warmblood horses (body weight, 473 to 500 kg) by injection of collagenase in the SDF tendon of 1 forelimb. For each horse, data were collected during the 5 following sessions: before lameness induction (sound), after development of mild but consistent lameness (lame 1), 1 hour after application of 6° heel wedges to both forehooves (wedge 1), 5 days after application of heel wedges (wedge 2), and 1 hour after removal of heel wedges (lame 2). The experimental protocol was approved by the Animal Ethics Committee at Utrecht University.

During each data collection session, horses were trotted at a comfortable speed. Ground reaction forces and kinematics were measured in both forelimbs. Markers were attached to the hoof and the joint centers of rotation of each forelimb. Positions of the distal interphalangeal (coffin) and metacarpophalangeal (fetlock) joints with respect to the markers were determined from radiographs. Net joint moments were calculated, using standard inverse dynamic methods. Data were normalized to stance phase, and for each session, values from 4 trials for each forelimb of each horse were averaged.

In vitro model and force calculations—Tendon forces were calculated from the net joint moments and joint angles, using an in vitro model of the distal region of the limb described in detail elsewhere. Briefly, this in vitro model describes the line of action of the tendons and the mechanical properties of the suspensory ligament (SL). The lines of action are determined from longitudinal limb sections and are described by use of a pulley model. Suspensory ligament properties were determined during in vitro limb and tendon loading experiments and are described by the relationships between fetlock joint angle and SL strain and between SL strain and SL force. Force calculations were performed in several steps. First, the instantaneous moment arms of the tendons with respect to the coffin and fetlock joints were calculated from the measured joint angles, using the pulley model. Subsequently, DDF force (ie, the force in the distal part of the tendon, which represents a combination of AL and muscle forces) was calculated by dividing the net distal interphalangeal joint moment by the DDF moment arm. Suspensory ligament force was calculated using the fetlock joint angle, using joint-angle-strain and strain-force relationships determined in vitro. The SL strain was assumed to be zero at a fetlock joint angle equal to the joint angle at ground contact in the sound condition. Finally, SDF force was calculated from the difference between the fetlock joint moment determined by use of inverse dynamic analysis and the moments generated by the DDF and SL. In addition, the total length of the AL and distal part of the DDF tendon (LAL+DIST) was used as a measure of AL strain. This length was calculated from the joint angles, using the in vitro model. These force calculations were made assuming that there are no forces in the extensors of the coffin and fetlock joints and ignoring the contribution of the navicular ligaments to the flexor moment at the distal interphalangeal joint. Furthermore, for the study reported here, we assumed that this in vitro model was valid for use with data collected from horses with experimentally induced SDF tendinitis.

Statistical analyses—Peak forces in the SL, DDF, and SDF were calculated for both forelimbs of each horse during each session. Differences between peak forces determined during the lame sessions (ie, lame and wedge) and peak forces during the sound session were calculated and used for statistical analyses. Absolute differences were used, because relative differences are more sensitive to errors in the model and are variable between subjects. Because results did not significantly differ between either lame session or either wedge session, values obtained during each lame or wedge session were averaged. The influence of lameness and heel wedges on force distribution in both limbs was determined by use of a repeated measures 3-factor ANOVA. The 3 factors were tendon (SL, DDF, or DDF), limb (lame, compensating), and session (lame, wedge). The influence of lameness and wedges on AL strain (ie, peak LAL+DIST) was determined by use of a repeated measures 2-factor ANOVA. The 2 factors were session (sound, lame, wedge) and limb (lame, compensating). Significance was set at P ≤ 0.05 for both tests. If significant effects were found, selected differences were compared by use of posthoc Bonferroni tests. Significance was set at a corrected P ≤ 0.05. Six horses were included in the original study. However, because data for the fetlock joint angle at ground contact were missing in the sound condition for 1 limb of 1 horse, we only analyzed the complete data sets from the 5 remaining horses in the present study.

Results
During each data collection session, horses were allowed to trot at a comfortable speed; speed was not controlled. Induction of SDF tendinitis caused a significant reduction of this speed. Mean ± SD trotting speed was 3.31 ± 0.23 m/s during the sound session, 3.00 ± 0.26 m/s during the lame session, and 2.99 ± 0.22 m/s during the lame and compensating limbs. Differences in speed were not significant between lame and wedge sessions.

Both induction of SDF tendinitis in sound horses and application of heel wedges to both forehooves of lame horses influenced the amplitude of tendon forces but, in general, did not influence the shape of the force or strain patterns. The timing of peak values followed that determined during the sound session in lame and compensating limbs; peak SDF force occurred at approximately 40% of the stance phase, peak SL force at approximately midstance (50%), peak DDF force at approximately 65% of the stance phase, and peak AL strain at approximately 80% of the stance phase (Fig 1 and 2). However, the pattern of DDF force in the lame limb was influenced by tendinitis. During the lame session, DDF force in the lame limb was similar to that determined during the sound session over the first 40% of the stance phase but was reduced over the remaining stance phase. In the compensating limb, however,
DDF force was decreased during the entire stance phase. Therefore, during the early stance phase in the lame session, DDF force in the lame limb exceeded DDF force in the compensating limb.

Although the shape of the force patterns did not change after induction of tendinitis, trotting speed and amplitude of most of the force peaks decreased. Furthermore, peak forces were less in the lame limb, compared with the compensating limb (Fig 1, Table 1). However, the decrease in force differed among tendons (Table 2). In the lame limb, SL force decreased more than SDF and DDF forces, whereas in the compensating limb, SDF force increased, and SL and DDF forces tended to decrease. Accessory ligament strain was not significantly affected by induction of tendinitis, nor was AL strain significantly different between lame and compensating limbs.

Changes in calculated tendon forces and strain after bilateral application of heel wedges were similar between lame and compensating limbs but differed among tendons. Although SDF force was greater after application of heel wedges, this difference was not statistically significant (P = 0.061; Fig 3, Table 1). Deep

**Table 1**—Mean calculated peak forces or differences in peak forces determined for the flexor tendons of 5 horses while trotting before (sound) and after induction of unilateral forelimb superficial digital flexor tendinitis (lame) and bilateral application of heel wedges (wedge).

<table>
<thead>
<tr>
<th>Condition</th>
<th>SL</th>
<th>SDF</th>
<th>DDF</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sound</td>
<td>13.07</td>
<td>6.96</td>
<td>5.23</td>
</tr>
<tr>
<td>Lame</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Affected</td>
<td>-3.58</td>
<td>-2.83</td>
<td>-1.11</td>
</tr>
<tr>
<td>Comp</td>
<td>-0.01</td>
<td>1.55</td>
<td>-0.77</td>
</tr>
<tr>
<td>Wedge</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Affected</td>
<td>0.03</td>
<td>0.54</td>
<td>-0.60</td>
</tr>
<tr>
<td>Comp</td>
<td>-0.38</td>
<td>0.39</td>
<td>0.94</td>
</tr>
</tbody>
</table>

*Values for the sound condition represent the mean of values determined for both forelimbs. Values for the lame condition represent the difference between values for the sound condition and values for the lame condition. Values for the wedge condition represent the difference between values for the lame condition and values for the wedge condition.

**Table 2**—Influence of experimentally induced unilateral forelimb superficial digital flexor tendinitis and bilateral application of heel wedges on flexor tendon forces in the forelimbs of 5 horses.

<table>
<thead>
<tr>
<th>Interaction</th>
<th>P value*</th>
</tr>
</thead>
<tbody>
<tr>
<td>Tendon</td>
<td></td>
</tr>
<tr>
<td>Limb</td>
<td>0.012†</td>
</tr>
<tr>
<td>Limb X session</td>
<td>0.011†</td>
</tr>
<tr>
<td>Tendon X session</td>
<td>0.798</td>
</tr>
<tr>
<td>SL (lame vs wedge)</td>
<td>0.99</td>
</tr>
<tr>
<td>SDF (lame vs wedge)</td>
<td>0.061</td>
</tr>
<tr>
<td>DDF (lame vs wedge)</td>
<td>0.002†</td>
</tr>
</tbody>
</table>

*Interaction effects were assessed by use of a repeated measures 3-factor ANOVA. When a significant (P ≤ 0.05) interaction was detected, indicated pairs were compared by use of posthoc Bonferroni tests; indicated values for these comparisons represent P values after correction. †Significant (P ≤ 0.05) interaction or difference.

Although the shape of the force patterns did not change after induction of tendinitis, trotting speed and amplitude of most of the force peaks decreased. Furthermore, peak forces were less in the lame limb, compared with the compensating limb (Fig 1, Table 1). However, the decrease in force differed among tendons (Table 2). In the lame limb, SL force decreased more than SDF and DDF forces, whereas in the compensating limb, SDF force increased, and SL and DDF forces tended to decrease. Accessory ligament strain was not significantly affected by induction of tendinitis, nor was AL strain significantly (P = 0.86) different between lame and compensating limbs.

Changes in calculated tendon forces and strain after bilateral application of heel wedges were similar between lame and compensating limbs but differed among tendons. Although SDF force was greater after application of heel wedges, this difference was not statistically significant (P = 0.061; Fig 3, Table 1). Deep
digital flexor force and AL strain decreased significantly (P = 0.002 and 0.02, respectively; Fig 2), whereas SL force did not change systematically after application of heel wedges.

Discussion

The purpose of the present study was to determine the influence of SDF tendinitis and application of heel wedges on flexor tendon forces in the forelimbs of horses. Forces were calculated by applying an in vitro model of the distal portion of the forelimb to inverse dynamic data obtained in previous studies evaluating horses with experimentally induced unilateral SDF tendinitis. The advantage of this in vitro model is that it does not require the use of invasive techniques to determine forces in individual tendons. The general application of this model, including assumptions made and sensitivity to errors, has been discussed elsewhere. However, application of this model to horses with tendinitis may influence the validity of 2 assumptions on which the calculations are based. Before discussing the results of the present study, we will, therefore, discuss the influence of these assumptions on our results.

First, the use of the in vitro model assumes that there are no forces in the extensor tendons of the coffin and fetlock joints. However, after application of heel wedges, a net extensor distal interphalangeal joint moment was detected in the compensating limb during the early stance phase, indicating that heel wedges resulted in an extensor force. Because generation of muscle force does not stop instantaneously, the extensor force may be evident even immediately after reversal of the net joint moment. Neglecting this force at the distal interphalangeal (coffin) joint causes an underestimation of the DDF force. In fact, calculated DDF forces will be negative during extensor distal interphalangeal joint moments. If the extensor moment is also present at the fetlock joint, neglecting it will cause underestimation of the flexor forces at this joint also. However, underestimation of the DDF force counterbalances most of this latter effect. Therefore, the influence of extensor forces on calculated flexor forces is mainly limited to the DDF force. Furthermore, peak tendon forces do not occur simultaneously with the extensor distal interphalangeal joint moment, so we believe that neglecting the extensor forces did not seriously influence peak forces calculated in the present study.

The second assumption that may influence the results is the assumption that lameness or application of heel wedges does not influence the mechanical properties of tendons as described by the in vitro model. In reality, tendinitis changes the mechanical properties of the affected tendon. Furthermore, changes in tendon loading attributable to changes in movement pattern probably cause long-term adaptation of tendon properties in other tendons. Therefore, the model is, in general, not valid for lame horses. However, tendinitis induced in the present study was limited to the SDF tendon, and most measurements were performed within 1 month of induction. This time frame was probably too brief for serious adaptation of properties of the other tendons. Thus, we made the assumption that only SDF tendon properties changed as a result of induction of tendinitis. Because these properties were not used for any calculation, SDF tendinitis should not influence the validity of our results. Of course, changes in SDF tendon properties as well as changes in coordination will influence loading of the affected SDF in horses with tendinitis. Because SDF force is determined from measured ground reaction forces and kinematic data, these influences can be quantified adequately by the method used in the present study.

Naturally occurring tendinitis is characterized by a large variability of lesions. To obtain a consistent lesion that was similar among horses and to enable measurements prior to onset of lameness, tendinitis was experimentally induced by injection of collagenase into 1 forelimb SDF tendon. Although injection of collagenase does not mimic exactly the etiopathogenesis of naturally occurring SDF tendinitis, it can be used as a model to study the biomechanical consequences of this abnormality. Results of the present study as well as published ground reaction forces and kinematic data revealed a substantial asymmetry between lame and compensating limbs, indicating that the method used to induce tendinitis did indeed induce serious lameness. Horses were allowed to trot at a comfortable speed without controlling speed among horses or data collec-
tion sessions. Not surprisingly, trotting speed was lower during the lame and wedge sessions, compared with the sound session. This difference in speed resembles the reaction of horses with naturally occurring tendinitis and adequately describes the influence of tendinitis on tendon loading. However, the lower speed during the lame sessions may have caused a general decrease of tendon forces. Therefore, decreases in force between sound and lame sessions may have been overestimated, whereas increases were probably underestimated. This is only true for the influence of tendinitis and not for the influence of heel wedges, because mean trotting speeds between lame and wedge sessions were not significantly different.

Results of the present study indicate that there is a decrease in force in the injured SDF after induction of lameness. Remarkably, the decrease in SL force was even larger, suggesting that the SL in the lame limb is not used for intralimb compensation. However, SL force can only be increased by additional hyperextension of the fetlock joint, which also results in an additional loading of the accessory ligament of the SDF (ie, the tendinous connection between the distal portion of the radius and the proximal portion of the tendon, also referred to as the proximal check ligament). Any additional loading of this ligament will increase loading of the SDF tendon. Therefore, it may be impossible to shift a substantial amount of force from the SDF to the SL. The only alternative tendon to which force can be shifted within the lame limb is the DDF. The decrease in peak DDF force after induction of lameness was not significantly different from the decrease in SDF force. However, DDF force in the lame limb over the first 40% of the stance phase after induction of tendinitis was not different from that before induction and exceeded the DDF force in the compensating limb. Because the peak in SDF force normally occurs at approximately 40% of the stance phase, the interlimb difference in DDF loading that we detected may reflect some compensatory loading of the DDF in the lame limb. Because AL strain did not significantly differ between limbs, the difference in DDF force must have been actively generated by the DDF muscle.

The increase in loading of the contralateral SDF after induction of lameness clearly reflects interlimb compensation; it is highly unlikely that this increase was caused by a decrease in trotting speed. Furthermore, the force in the contralateral SL did not significantly change despite the decrease in speed. This probably reflects a lameness-related increase in SL loading that was compensated by a speed-related decrease in loading. These results suggest that the SL also contributes to interlimb compensation, at least if it is assumed that a decrease in speed normally reduces loading of the SL. Finally, DDF force in the compensating limb was decreased during the entire stance phase, and peak DDF force and AL strain were approximately equal in both limbs. This suggests that the contralateral DDF and AL do not contribute substantially to interlimb compensation.

The compensatory increase in tendon force may be an important factor in the development of secondary injuries in lame horses. Because of the decreased trotting speed, forces in the SL and DDF did not exceed forces determined during the sound session (ie, normal forces). However, despite the decrease in speed, SDF force in the contralateral limb was increased above the normal peak force. This finding offers an explanation for the fact that 37 of 55 (67%) horses with SDF tendinitis in 1 forelimb also had lesions in the SDF tendon of the compensating limb.1

In a previous study,7 the influence of heel wedges differed between the 2 forelimbs. However, this difference was limited to the presence of an extending distal interphalangeal joint moment. Thus, application of heel wedges to both lame and compensating limbs affects extensor tendon forces differently. In the present study only flexor tendon forces were calculated, and they were influenced similarly in the 2 limbs. The decrease in DDF force and AL strain that we detected is in agreement with previous results of studies12,13,4 evaluating the effect of heel wedges on sound ponies and horses. Moreover, the decrease in loading of the DDF and the AL can easily be explained by the reduction in passive loading attributable to the increase in flexion of the distal interphalangeal joint. Because the DDF force was already low as a result of the decrease in trotting speed, the further reduction in force after application of heel wedges may not be an important advantage for horses with SDF tendinitis. Although the increase in SDF force after application of wedges was small (±0.5 kN) and not significant (P = 0.061), the present results indicate that heel wedges did not result in a decrease in SDF force in either limb. Instead, heel wedges may cause SDF force to increase. An increase in SDF force would be harmful in both the lame and compensating limb. In the lame limb, an increase in force would result in higher loading of the affected tendon, thus exacerbating the existing lesion. In the compensating limb, it would add to the compensatory increase in force, which would augment the likelihood of secondary injuries. Therefore, application of heel wedges may not be advantageous for horses with SDF tendinitis and may even be harmful.

Horses with unilateral forelimb SDF tendinitis trot at a reduced speed and generate additional force in the SDF of the contralateral limb to unload the affected tendon. Furthermore, there may be a slight compensatory loading of the SL in the contralateral limb and earlier activation of the DDF muscle in the lame limb. The increased loading of the contralateral SDF tendon may help explain the high secondary injury rate in this tendon. On the basis of the present results, application of heel wedges cannot be considered beneficial for horses with SDF tendinitis and may even be harmful. The results of the present study could not be obtained by use of standard inverse dynamic analysis only but resulted from additional calculations made on the basis of an in vitro model of the forelimb. The use of this model can provide specific insight into tendon loading and appears to be a useful addition to standard inverse dynamic analysis.

2Reef VB, Martin BB, Elser A. Types of tendon and ligament injuries...
References