EQUINE VETERINARY JOURNAL
Equine vet. J. (2005) **37** (2) 161-165

Deep digital flexor tendon force and digital mechanics in normal ponies and ponies with rotation of the distal phalanx as a sequel to laminitis

M. P. McGUIGAN[†][#], T. C. WALSH[‡][§], C. H. PARDOE[†], P. S. DAY[‡] and **A. M. WILSON[†]***

*[†]Structure and Motion Laboratory and [‡]Department of Veterinary Clinical Sciences, The Royal Veterinary College, Hawkshead Lane, North Mymms, Hatfield, Hertfordshire AL9 7TA; and *RNOH, UCL, Brockley Hill, Stanmore, Middlesex HA7 4LP, UK.*

Keywords: horse; biomechanics; founder; laminitis; navicular bone

Summary

Reasons for performing study: **Previous studies have implicated tension in the deep digital flexor tendon (DDFT) in the rotation of the distal phalanx (DP) after the breakdown of the dorsal laminae caused by laminitis. Howeveer, once the DP has rotated, the DDFT should become shorter, reducing the force it exerts on the DP.**

Objective: **To compare DDFT force and ground reaction forces (GRFs) in normal ponies and ponies with rotation of the DP as a sequel to laminitis.**

Methods: **Six normal ponies (*Group 1*) and 6 sound ponies with 6–13° of rotation of the DP in relation to the dorsal hoof wall (*Group 2*) were assessed at trot using forceplate and motion analysis. The force in the DDFT was calculated by assuming that the extending moment at the distal interphalangeal (DIP) joint resulting from the GRF was equal to the flexing moment created by the force in the DDFT during the stance phase (inverse dynamics).**

Results: **In early stance, the peak DDFT force (mean ± s.d.) in the normal ponies was 1.92 ± 1.63 N/kg. However, in *Group 2*, the point of zero moment was palmar to the centre of rotation of the DIP joint for the first 40% of stance and hence DDFT force was zero. Force in the DDFT reached a peak of 10.00 ± 3.56 N/kg at 60.7 ± 5.6% of stance in *Group 1* and 6.41 ± 1.37 N/kg at 79.2 ± 9.6% of stance in *Group 2*.**

Conclusions: **DDFT force in *Group 2* laminitic ponies was much reduced until late stance, when it neared normal values.**

Potential relevance: **Further studies of ponies with rotation of the DP as a sequel to laminitis should assist farriery aimed at reducing the force in the DDFT through the breakover phase of stance to protect damaged dorsal laminae.**

Introduction

The cellular pathophysiology of developmental and acute laminitis that gives rise to mechanical weakening of the laminae has been the subject of extensive research (Pollit 1998; Hood 1999). The mechanics of the chronic stages of the condition when laminae detachment has occurred and the foot is mechanically compromised are less well understood, and advice on long-term treatment of the chronic laminitic foot is often contradictory and based on anecdotal experience rather than quantitative evidence. This paper focuses on the mechanical aspects of chronic laminitis, i.e. how rotation of the distal phalanx (DP) affects the force in the deep digital flexor tendon (DDFT) and the mechanics of the digit.

The DP is suspended from the hoof wall via the laminae. These must withstand a large proportion of the horse's limb force; in a single forelimb this is approximately 30% of bodyweight while standing and at least 150% of bodyweight at gallop (McGuigan and Wilson 2003). This force is transferred to the DP by compression through the limb segments and the pull of the DDFT. The laminae are loaded in a combination of shear and tension as the force is transferred from the DP to the hoof. In ponies with laminitis, the laminae are not able to withstand the force imposed upon them and they fail. *In vitro* experiments on sections of the laminar junction showed that the laminae from laminitic ponies on the second day of lameness were able to withstand only 10% of the stress that normal laminae can withstand before failure (Hood 1999). Laminar detachment occurs predominantly in the dorsal region of the foot. This destabilises the DP and results in rotation or sinking, depending on the extent of detachment.

Rotation of the DP occurs when there is weakening of the laminae in the dorsal region but the laminae at the heels remain intact and mechanically competent. The tension in the DDFT and associated dorsal position of the ground reaction force (GRF) vector at the end of stance (Eliashar *et al.* 2002) cause the DP to pivot around the intact laminae and the toe of the bone to move caudally and distally. Distal displacement (sinking) occurs when there is extensive laminar failure throughout the hoof and complete separation of the DP from the hoof wall.

As the deep digital flexor muscle is the only major stance phase muscle that inserts onto the DP, the mechanics of the joint are very simple. During the stance phase the accelerations at the distal interphalangeal (DIP) joint are negligible and therefore moments at the joint must balance (Bartel *et al.* 1978; Willemen *et al.* 1999).

---

*Author to whom correspondence should be addressed. [#]Present address: Concord Field Station, Harvard University, Old Causeway Road, Bedford, Massachusetts 01730, USA.
[§]During the work described in this manuscript, Dr T. C. Walsh sadly passed away.

[Paper received for publication 29.09.03; Accepted 28.09.04]

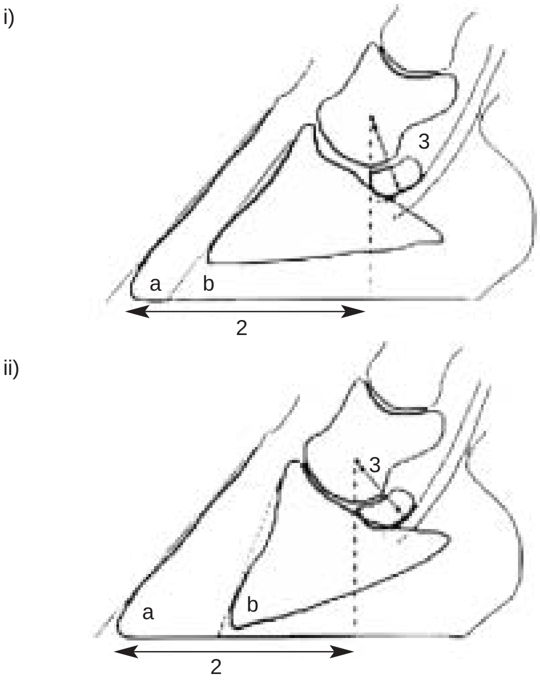

Fig 1: Measurements taken from the radiographs in i) Group 1 controls and ii) Group 2 with rotation of the DP. Rotation of the DP reduces the distance between the origin and insertion of the DDFT, hence reducing the strain and force in the tendon. a = angle of the hoof wall to the ground; b = angle of DP to the ground. a and b were used to calculate the degree of rotation of the DP, i.e. b - a; 2 = the dorsopalmar distance between the centre of the toe and centre of rotation of the DIP joint; 3 = the distance between the centre of rotation of the DIP joint and flexor surface of the navicular bone, i.e. the moment arm of the DDFT.

The point at which the GRF vector intersects with the ground surface of the foot is called the point of zero moment (PZM) or point of force application. The GRF vector orientation is dependent on the relative magnitude of the vertical and horizontal components (or *vice versa*). The position of the GRF vector in relation to the centre of rotation of the DIP joint determines whether the GRF causes an extending or a flexing moment; if the vector is dorsal to the centre of rotation of the DIP joint the GRF results in an extending moment, while if the vector is palmar to the centre of rotation of the DIP joint the GRF results in a flexing moment.

It is possible to measure the position and magnitude of the GRF using a forceplate and motion analysis. Recent studies have shown that, in normal horses, the GRF vector lies approximately 20 mm dorsal to the centre of rotation of the DIP joint for most of stance and then moves dorsally towards the toe as the heels leave the ground at the end of stance (Wilson *et al.* 2001; Eliashar *et al.* 2002). Therefore, the GRF creates an extending moment at the DIP joint throughout the stance phase. As the moments at the joint must balance (or angular acceleration would occur) the flexing moment created by the pull of the deep digital flexor muscle tendon unit (the only structure that flexes the DIP joint) on the palmar surface of the DP must be equal to the GRF extending moment. There have been several studies describing the position of the PZM and the moments and forces acting on the digit, and how these are altered in horses with navicular disease (Willemen *et al.* 1999; Wilson *et al.* 2001) and by the application of shoes (Wilson *et al.* 1998; Eliashar *et al.* 2002).

Due to the accessory ligament of the deep digital flexor muscle tendon unit the DDFT is passively loaded, especially at the end of stance as the limb moves over the hoof, the PZM moves dorsally, the DIP joint extends and the heels leave the ground. When laminae detachment occurs, the pull of the DDFT on the palmar aspect of the DP causes it to rotate (Fig 1). However, as the bone rotates, it should result in shortening of the DDFT and hence a reduction in strain in the tendon (Riemersma *et al.* 1988). The force exerted by the tendon is proportional to its strain (Riemersma and Schamhardt 1985); therefore, rotation of the distal phalanx should result in a reduction in force in the DDFT.

The present study was undertaken to determine the GRF, moment arm of the GRF and force in the DDFT in normal ponies (*Group 1*) and ponies with rotation of the DP as a sequel to laminitis (*Group 2*) to test the hypothesis that the latter have a reduced force in the DDFT compared to *Group 1*.

Materials and methods

Two groups of ponies were compared. *Group 1* consisted of 6 ponies showing no signs of lameness or rotation of the DP and in regular ridden exercise. The ponies were children's riding ponies age >10 years and of mixed breed, including Welsh Section B, New Forest and Connemara. Their height was 127–142 cm and mass 260–420 kg (mean 341 kg).

Group 2 consisted of 6 ponies age 8–18 years with rotation of the DP as a sequel to laminitis. Their mean mass was 405 kg (range 361–450 kg) and height range was 132–148cm. They had all suffered from acute periods of laminitis in the last 3 years and had 6–13° rotation of the DP. Rotation was measured from a radiograph as the difference between the angle made between the dorsal hoof wall and the ground and the dorsal surface of the DP and the ground (Fig 1). The ponies in this group were not overtly lame in a straight line, but all exhibited a stilted gait.

All ponies' feet were trimmed 2 weeks before they were assessed so they were at a similar state of foot growth but any soreness from foot trimming in *Group 2* had subsided. The feet were trimmed in a uniform manner to achieve static mediolateral balance. The toe was shortened to establish a straight line from the coronary band to the distal toe and the heels were trimmed so there was frog pressure with the ground.

The ponies were weighed and mediolateral radiographs taken of all front feet with a 40 mm metal wire placed on the dorsal hoof wall. The following measurements were made from the radiographs (Fig 1): 1) angle of the hoof wall to the ground (a) and of the DP to the ground (b) to quantify the degree of rotation of the DP (b - a); 2) dorsopalmar distance between the centre of rotation of the DIP joint and the centre of the toe, used to calculate the position of the foot marker seen by the motion analysis system in relation to the centre of rotation of the DIP joint (see below for further detail); and 3) the moment arm of the DDFT at the DIP joint, i.e. the distance from the centre of rotation of the DIP joint to the flexor surface of the navicular bone.

Length measurements from the radiographs were corrected for magnification due to beam divergence using the length of the metal wire placed on the midline of the dorsal hoof wall.

Hemispherical markers[1] (22 mm in diameter, constructed of high density polystyrene, covered in retroreflective tape[2]) were applied using hot melt glue and a hot glue gun[3] to the lateral hoof wall of the left forelimb and the medial hoof wall of the right forelimb, approximately over the centre of rotation of the DIP joint. An additional marker was applied to the left side of the thorax for speed determination.

The ponies were trotted at a speed comfortable for the individual along a forceplate runway within a 25 m long polythene tunnel covered in lightproof material. The forceplate (Kistler 9827BA)[4] was set in concrete at the mid-length of a 6 mm thick commercial conveyer belt matting runway. A 900 x 600 x 10 mm aluminium plate covered in the same rubber matting was bolted to the top of the forceplate and lay flush with the surrounding rubber matting. The forceplate signal was amplified by an integral 8 channel charge amplifier, filtered through a low-pass filter (6 dB/octave from 50 Hz) and logged at 500 samples/sec, via a 12 bit AD converter, into a personal computer using software written in LabView 5.0[5]. A 3D motion analysis system (ProReflex 2.5)[6] was used to determine the position of the markers from the horse's left side at a frame rate of 240 Hz. Between 6 and 9 foot strikes were recorded for each forelimb. Data were rejected if the pony was not judged to be moving freely at constant velocity or if the foot was placed outside or on the edge of the forceplate.

Data analysis

Standard formulae were used to calculate the coordinates of the PZM throughout stance relative to the forceplate, and a previously published correction algorithm (Bobbert and Schamhardt 1990) was applied to improve the accuracy of PZM determination. The motion analysis system gave the position of the marker on the foot relative to the forceplate. From this information, it was possible to express the position of the PZM relative to the foot marker. However, in order to relate the position of the GRF vector to the centre of rotation of the DIP joint it was necessary to calculate the positions of the marker and of the joint relative to a common, easily definable point on the exterior of the foot, that could also be recognised on a radiograph, i.e. the centre of the toe. The mediolateral and dorsopalmar position of the foot marker relative to the centre of the toe was measured and used to express the position of the PZM relative to the centre of the toe. This was then corrected for the distance between the toe and the centre of rotation of the DIP joint (measured from the radiographs).

The moment arm of the GRF at the DIP joint is the perpendicular distance between the GRF vector and the centre of rotation of the joint. The GRF vector intersects the ground surface of the hoof at the PZM but the orientation of the GRF vector changes throughout the stance phase, and this must be taken into account when calculating the moment arm. The extending moment at the DIP joint during stance is the product of the GRF and moment arm of the GRF. As stated earlier, the flexing moment at the joint is equal and opposite to the extending moment. The flexing moment is the product of the force in the DDFT and its moment arm, created by the navicular bone. This moment arm was measured from the radiographs of each foot and assumed to be constant during stance. Therefore, it is possible to calculate the force in the DDFT by dividing the extending moment by the moment arm of the DDFT.

The stance phase was defined as the period when the vertical GRF was greater than 50 N and the values of vertical and craniocaudal GRF and position of the PZM relative to the centre of rotation of the DIP joint were reduced to 100 points evenly spaced over stance by linear interpolation (Wilson *et al.* 2001). From these values and the measurements described above, the moment arm of the GRF, DIP extending joint moment and force in the DDFT were calculated for each run. Mediolateral GRF was ignored as it is small and variable. Force data were normalised from body mass.

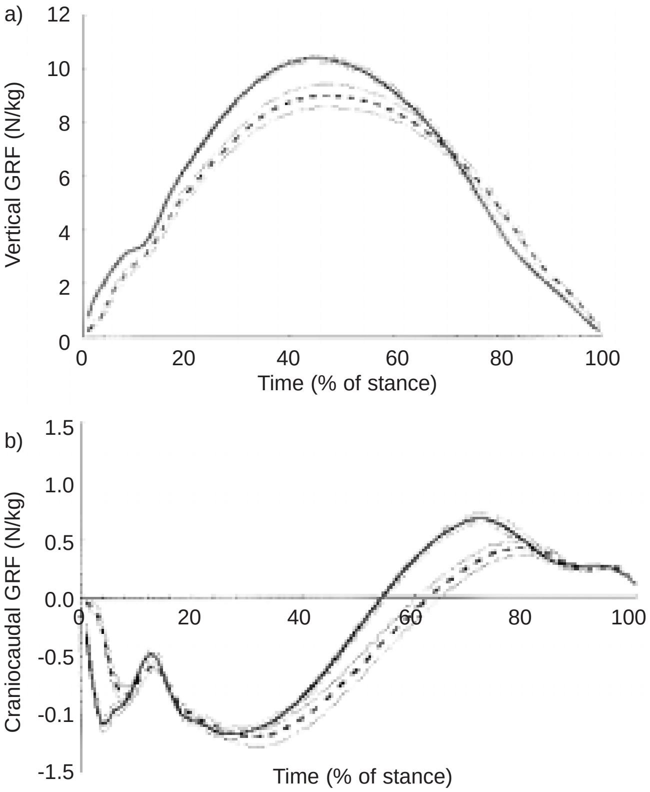

Fig 2: Mean a) vertical and b) craniocaudal ground reaction force (GRF) through the stance phase in Groups 1 *(solid lines) and* 2 *(broken lines). Dotted lines represent ± 1 s.e. of the mean.*

Mean curves were produced for each forelimb and then averaged to produce a mean (± s.e.) plot for each group. As the intra pony (left-right) variability was similar to the interpony variability, left and right limbs were treated as independent samples; therefore, n = 12 in both groups.

Peak vertical and craniocaudal GRFs, the moment arm of the GRF at the DIP joint and the force in the DDFT in the 2 groups were compared using a Student's *t* test, at the beginning of stance (10% of stance) and at the beginning of breakover. This is the time when the heels leave the ground, and corresponds with a peak in DDFT force. The time when the heels left the ground was determined from the plateau at the end of the PZM-time curve for each animal, which occurs at approximately 86% of stance (Eliashar *et al.* 2002). In all statistics, a P value of less than 0.01 (to account for multiple comparisons) indicated a significant difference between *Groups 1* and *2*.

Results

Figures 2a and 2b show the vertical and craniocaudal GRFs, respectively, for the 2 groups of ponies. The peak vertical GRF was significantly lower in *Group 2* (mean ± s.d., 9.04 ± 1.25 N/kg) than *Group 1* (10.41 ± 0.44 N/kg) (P = 0.002). This decrease in vertical GRF was associated with an increase in stance time in *Group 2* (277 ± 24 msecs for *Group 1* and 332 ± 28 msecs for *Group 2*, P<0.001), resulting in a similar vertical impulse in the 2 groups. There was, however, a small difference in

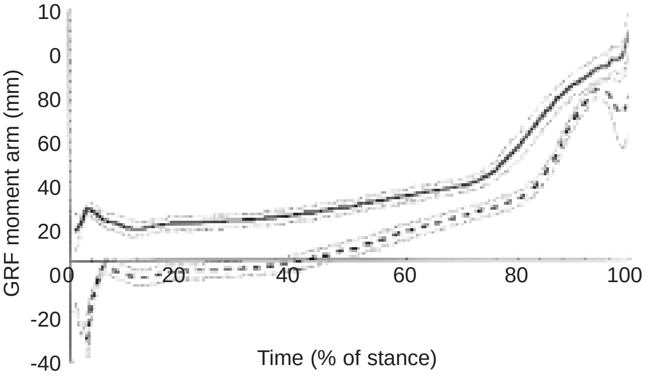

Fig 3: Mean moment arm of the ground reaction force (GRF) at the distal interphalangeal joint during the stance phase in Groups 1 *(solid line) and* 2 *(broken line). Positive values indicate a moment arm dorsal to the DIP joint, which creates an extending moment, and negative values indicate a moment arm palmar to the DIP joint, which creates a flexing moment. Dotted lines represent ±1 s.e. of the mean.*

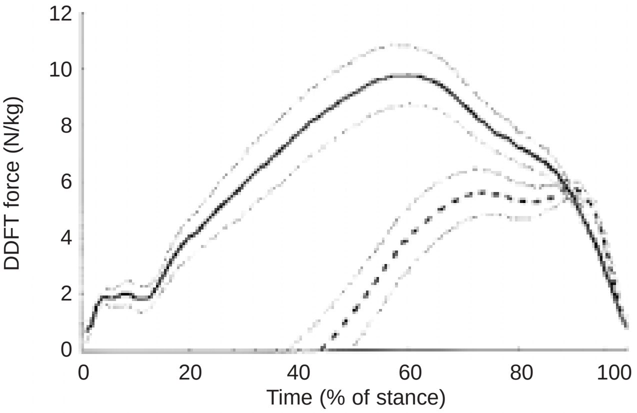

Fig 4: Mean force in the deep digital flexor tendon (N/kg body mass) during the stance phase in Groups 1 *(solid lines) and* 2 *(broken lines). As the moment arm of the GRF is palmar to the DIP joint for the first 40% of stance (Fig 3), there is no force in the DDFT early in the stance phase. Dotted lines represent ±1 s.e. of the mean.*

speed between the 2 groups; mean ± s.d. speed for *Group 1* was 2.9 ± 0.1 m/sec and for *Group 2* 2.7 ± 0.2 m/sec (P = 0.02).

The craniocaudal GRF was also altered in *Group 2* (Fig 2b). The peak accelerative force was significantly lower in *Group 2* (0.46 ± 0.14 N/kg) than *Group 1* (0.69 ± 0.15 N/kg) (P = 0.001). The time of the cross-over between a decelerative and an accelerative force was delayed in *Group 2*, occurring at 63.3 ± 6.5% of stance compared to 54.9 ± 2.5% of stance in *Group 1* (P<0.001).

Figure 3 shows the moment arm of the GRF at the DIP joint in the 2 groups. The moment arm was 14 ± 12 mm in *Group 1* and -5 ± 10 mm in *Group 2* at the beginning of stance (P<0.001), and 59 ± 19 mm in *Group 1* and 35 ± 10 mm in *Group 2* at the beginning of breakover (P = 0.001). The negative values for the moment arm at the beginning of stance in *Group 2* indicate that the GRF vector was located palmar to the centre of rotation of the DIP joint and the ponies were landing heel first.

The force in the DDFT was reduced greatly during early and mid-stance in *Group 2* (Fig 4). At the beginning of stance the DDFT force was 1.92 ± 1.63 N/kg in *Group 1* and zero in *Group 2*, as the GRF vector was behind the DIP joint (P<0.001). The difference between the 2 groups diminished through stance, and by the time the heels left the ground the DDFT force in *Group 2* (6.39 ± 1.88 N/kg) was similar to that in *Group 1* (5.97 ± 0.92 N/kg), although the heels of *Group 2* left the ground later (89.6 ± 2.5 vs. 84.6 ± 3.4% in *Group 1*; P = 0.001). Force in the DDFT reached a peak of 10.00 ± 3.56 N/kg at 60.7 ± 5.6% of stance in *Group 1* and 6.41 ± 1.37 N/kg at 79.2 ± 9.6% in *Group 2*.

Discussion

As hypothesised, the ponies with rotation of the DP (*Group 2*) had a reduced force in the DDFT during early and mid-stance. It is likely that this reduction in force is passive and due to the rotation of the DP in the hoof capsule and resultant shortening of the tendon path for any limb orientation.

The laminitic ponies in this study had 6–13° of rotation of the DP about the centre of rotation of the DIP joint The moment arm of the DDFT at the DIP joint was approximately 20 mm. Theoretically, a 10° rotation of the DP enables a shortening of approximately 4 mm in the DDFT (i.e. the insertion of the DDFT is moved proximally by 4 mm) (Fig 1). The length of the DDFT from the insertion of the accessory ligament to the insertion on the DP is approximately 300 mm; therefore, a 4 mm length change equates to a change in strain of approximately 1.3%. The force in the DDFT is approximately 1800 N per percent strain (Riemersma and Schamhardt 1985). Therefore, a reduction in strain by 1.3% causes a reduction in force in the tendon of 2340 N.

This theoretical value of the reduction in force in the DDFT caused by the rotation of the bone in *Group 2* is similar to the difference in the force in the tendon in the 2 groups in this study. At mid-stance the measured difference was 8 N/kg body mass, i.e. 2400 N in a 300 kg pony. Therefore, the rotation of the DP caused by the failure of the dorsal laminae can alone account for the difference in force in the tendon in the 2 groups. In addition to this, the palmar displacement of the GRF vector reduces the moment arm of the GRF at the metacarpophalangeal joint, further reducing the length and force in the DDFT. Gait changes, not examined in this study, may also contribute to the difference in DDFT force patterns between *Groups 1* and *2*.

The reduced force in the tendon unloads the dorsal laminae and increases the proportion of the load transferred through the less compromised palmar laminae when the foot is flat. Rotation of the DP may therefore be a self-limiting event, the extent of which is dependent on the degree of laminar detachment. If very extensive laminar detachment occurs, then the forces exerted on the remaining laminae will exceed their mechanical capacity and the DP sinks rather than rotates.

The force in the tendon was similar in the 2 groups at the end of stance. As the DDFT is passively loaded via its accessory ligament, the force within it must increase at the end of stance as the limb moves over the foot and DIP joint extends. Tightening of the DDFT through extension of the DIP and MCP joints eventually pulls the heels off the ground. *Group 2* had slacker tendons and hence the heels left the ground later. This is apparent in the graph of the moment arm (Fig 3) which increased later (i.e. the PZM moved forward later) in *Group 2*.

The laminitic ponies may also have been attempting to reduce the peak vertical GRF in the limb. Although the 7% speed difference between the 2 groups (*Group 1* 2.9 ± 0.1 m/sec; *Group 2* 2.7 ± 0.2 m/sec) accounts for some of the 13% reduction in peak vertical GRF in *Group 2* (9.04 ± 1.25 vs. 10.41 ± 0.44 N/kg in *Group 1*), it does not explain all the 20% increase in stance time (332 ± 28 vs. 277 ± 24 msecs in *Group 1*). It appears that the laminitic ponies may be increasing their foot contact time in an attempt to reduce peak forces in the limb.

In conclusion, our findings show that rotation of the DP as a sequel to laminitis results in palmar shift in the PZM and hence a reduced force in the DDFT during the early and middle stance phase. The shortening of the DDFT caused by rotation of the DP can account for the reduced force in the tendon. Further study of ponies with rotation of the DP as a sequel to laminitis should be aimed at investigating the effect of foot trimming and corrective farriery regimes on reducing the force in the DDFT at the end of stance.

Acknowledgements

We would like to acknowledge The Home of Rest for Horses for their financial support, the Enfield Chase Pony Club for supplying *Group 1* and Miss Kate Rogers and Miss Lucy Rowe for their assistance with data collection and analysis.

Manufacturers' addresses

[1]Pinflare Creative Crafts, Hertford, Hertfordshire, UK.
[2]3M, Manchester, UK.
[3]Bostik Ltd., Leicester, Leicestershire, UK
[4]Kistler Instruments Ltd. Alton, Hampshire, UK.
[5]National Instruments, Newbury, Berkshire, UK.
[6]Qualisys AB, Sävedalen, Sweden.

References

Bartel, D.L., Schryver, H.F., Lowe, J.E. and Parker, R.A. (1978) Locomotion in the horse: a procedure for computing the internal forces in the digit. *Am. J. vet. Res.* **39**, 1721-1727.

Bobbert, M.F. and Schamhardt, H.C. (1990) Accuracy of determining the point of force application with piezoelectric force plates. *J. Biomech.* **23**, 705-710.

Eliashar, E., McGuigan, M.P., Rogers, K.A. and Wilson, A.M. (2002) A comparison of three horseshoeing styles on the kinetics of breakover in sound horses. *Equine vet. J.* **34**, 184-190.

Hood, D.M. (1999) The mechanisms and consequences of structural failure of the foot. *Vet. Clin. N. Am.: Equine Pract.* **15**, 437-463.

McGuigan, M.P. and Wilson, A.M. (2003) The effect of gait and digital flexor muscle activation on limb compliance in the forelimb of the horse, *Equus caballus*. *J. expt. Biol.* **206**, 1325-1336.

Pollitt, C.C. (1998) The anatomy and physiology of the hoof wall. *Equine vet. Educ., Manual* **4**, 3-10.

Riemersma, D.J. and Schamhardt, H.C. (1985) *In vitro* mechanical properties of equine tendons in relation to cross-sectional area and collagen content. *Res. vet. Sci.* **39**, 263-270.

Riemersma, D.J., van den Bogert, A.J., Schamhardt, H.C. and Hartman, W. (1988) Kinetics and kinematics of the equine hindlimb: *in vivo* tendon strain and joint kinematics. *Am. J. vet. Res.* **49**, 1353-1350.

Willemen, M.A., Savelberg, H.H. and Barneveld, A. (1999) The effect of orthopaedic shoeing on the force exerted by the deep digital flexor tendon on the navicular bone in horses. *Equine vet. J.* **31**, 25-30.

Wilson, A.M., Seelig, T.J., Shield, R.A. and Silverman, B.W. (1998) The effect of hoof inbalance on point of force application in the horse. *Equine vet. J.* **30**, 540-545.

Wilson, A.M., McGuigan, M.P., Fouracre, L. and MacMahon, L. (2001) The force and contact stress on the navicular bone during trot locomotion in sound horses and horses with navicular disease. *Equine vet. J.* **33**, 159-165.