The effect of frog pressure and downward vertical load on hoof wall weight-bearing and third phalanx displacement in the horse – an *in vitro* study

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ABSTRACT

A shoe was designed to combine the advantages of a reverse shoe and an adjustable heart bar shoe in the treatment of chronic laminitis. This reverse even frog pressure (REFP) shoe applies pressure uniformly over a large area of the frog solar surface. Pressure is applied vertically upward parallel to the solar surface of the frog and can be increased or decreased as required. Five clinically healthy horses were humanely euthanased and their dismembered forelimbs used in an *in vitro* study. Frog pressure was measured by strain gauges applied to the ground surface of the carrying tab portion of the shoe. A linear variable distance transducer (LVDT) was inserted into a hole drilled in the dorsal hoof wall. The LVDT measured movement of the third phalanx (P3) in a dorsopalmar plane relative to the dorsal hoof wall. The vertical component of hoof wall compression was measured by means of unidirectional strain gauges attached to the toe, quarter and heel of the medial hoof wall of each specimen. The entire limb was mounted vertically in a tensile testing machine and submitted to vertical downward compressive forces of 0 to 2500 N at a rate of 5 cm/minute. The effects of increasing frog pressure on hoof wall weight-bearing and third phalanx movement within the hoof were determined. Each specimen was tested with the shoe under the following conditions: zero frog pressure; frog pressure used to treat clinical cases of chronic laminitis (7 N-cm); frog pressure clinically painful to the horse as determined prior to euthanasia; frog pressure just alleviating this pain. The specimens were also tested after shoe removal. Total weight-bearing on the hoof wall at zero frog pressure was used as the basis for comparison. Pain-causing and pain-alleviating frog pressures decreased total weight-bearing on the hoof wall ($P < 0.05$). Frog pressure of 7 N-cm had no statistically significant effect on hoof wall weight-bearing although there was a trend for it to decrease as load increased. Before loading, the pain-causing and pain-alleviating frog pressures resulted in a palmar movement of P3 relative to the dorsal hoof wall compared to the position of P3 at zero frog pressure ($P < 0.05$). This difference remained statistically significant up to 1300 N load. At higher loads, the position of P3 did not differ significantly for the different frog pressures applied. It is concluded that increased frog pressure using the REFP shoe decreases total hoof wall weight-bearing and causes palmar movement of P3 at low weight-bearing loads. Without a shoe the toe and quarter hoof wall compression remained more constant and less in magnitude, than with a shoe.

Key words: biomechanics, hoof, horse, horseshoe, laminitis, third phalanx.

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INTRODUCTION

Equine laminitis is a serious condition that usually ends the animal's athletic career and often necessitates euthanasia.

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The pathophysiology of equine laminitis has been extensively reported[1,11,17,23–25,30,38,39,51,52], but is still not completely understood.

In a horse with chronic laminitis, P3 may move relative to the hoof wall, either rotating palmarly (capsular or phalangeal rotation) or moving vertically distally (sinker, founder)[19,22]. This movement of P3 may have prognostic significance. The prognosis of return to athletic soundness was reported to be inversely proportional to the degree of palmar rotation of P3[49]. However, the results of another study indicated that a functional athletic outcome of horses did not correlate with the degree of P3 rotation, but that 'clinical assessment (of the horse with chronic laminitis) is a more reliable means of determining the final outcome and should be given precedence over radiographic findings'[26]. There is also a strong association between digital instability and the degree of lameness[22]. Racing performance of horses with radiographic signs of laminitis is poorer than those without[29]. Distal displacement of P3 has a poor prognosis[2,9,26].

In the normal horse, the weight-bearing surface of the hoof wall transfers the forces exerted by the ground through the laminae to P3[15,28]. The sole also contributes to weight-bearing, particularly the sole area dorsal to the apex of the frog[36]. If, during the developmental phase, the shearing forces between the hoof wall and P3 can be minimised, precluding the movement of P3, the dermal laminae and basement membrane may be able to reform, and the P3–hoof wall interface, re-established. If P3 displacement has already occurred, as is the case in many horses with chronic laminitis, one of the main objectives is to redirect the laminar weight-bearing force to prevent further displacement of P3 and further damage to the laminae[15]. Transferring pressure off the wall and sole to the frog may also aid in the treatment of pedal osteitis, subsolar bruising, white line disease and flat soles[31,32,42].

A method used to decrease hoof-wall weight-bearing, is to apply upward vertical pressure to the frog. This pressure is assumed to reduce the weight borne by the hoof wall, thereby decreasing the strain on the laminae–hoof wall interface[15]. From an anatomical point of view, upward force of the ground on the frog is transferred proximally through the digital cushion, the navicular bone, the deep digital flexor tendon, the palmar surface of P3, the second phalanx and up the bony column of the limb[35].

Several methods of applying frog pressure have been described. In the early stages of laminitis, a frog-shaped rubber pad, a roll of bandage or other commercially available frog supports can be taped onto the frog[4,5,12,15,40]. Various shoes have been designed to treat laminitis by increasing frog pressure. The heart bar shoe, first described in 1824 (quoted by Chapman[4]) was reported to not only remove tension from the laminar interface by increased frog pressure[15,16], but also to push P3 dorsally back into position[13,18,46], the shoe may also alleviate compressive forces affecting digital blood supply[4,15,16]. Expansion of the palmar aspect of the hoof is also restricted, thereby providing rigidity and limiting further damage to the submural tissues[10]. This shoe, however, has several disadvantages. It requires regular replacement because continued hoof wall growth decreases the pressure exerted on the frog[15,16,46]; conversely, the frog may be excessively compressed by the continued pressure of the heart bar. The frog pressure required is also a subjective assessment[15]; excessively applied frog pressure may cause lameness[16,46]. The heart bar causes point pressure at its tip and this can result in abscessation[5,46] or pressure necrosis of the frog and underlying structures[15,41,46] .The point of the heart bar on the frog can also cause the development of excess granulation tissue[16].

The adjustable heart bar shoe, which allows adjustment of the heart bar inclination without re-shoeing, was developed to address the problems caused by hoof growth and excessive pressure of the heart bar on the frog. The pressure of the point of the bar against the frog can be adjusted to be comfortable to the patient, as subjectively assessed by the farrier and veterinarian[5,12,15]. This shoe has the disadvantage that the pressure is not distributed uniformly over the entire frog and the pressure exerted on the frog remains subjective[16]. Heart bar shoes do not stabilise or prevent distal phalangeal rotation in all acutely or severely affected horses[33], and may even harm the patient[27].

A shoe applied back to front (reverse shoe) has also been used in the treatment of chronic laminitis[37,53]. The positioning of the toe of the shoe palmar to the heels of the hoof results in a palmar displacement of the horse's centre of gravity, which results in a decrease in dorsal digital load and a decrease in the tensile force exerted on the dorsal P3–hoof interface. Abaxial movement of the palmar aspect of the hoof is also restricted. The open toe eases the breakover at the toe, again decreasing the shearing force at the P3–hoof wall interface. No frog pressure is applied using this shoe. A reverse shoe with a frog-shaped sagittal bar under the frog has been described[3].

The shortcomings of heart bar shoes, particularly the uneven pressure applied to the frog, resulted in the design of a shoe that combined the adjustable heart-bar and reverse shoes. This new shoe was named the reverse even frog pressure (REFP) shoe. The shoe was tested *in vitro* to investigate the following as downward vertical force was applied to the limb:

1) the effect of force applied to the frog to demonstrate that a percentage of the total weight-bearing of the hoof wall is taken up by the frog,
2) the movement of the 3rd phalanx perpendicular to the dorsal hoof wall to obtain an indication of the restriction of movement of P3 when frog pressure was applied,
3) unidirectional compression of the hoof wall as an additional demonstration of the effect of frog pressure on the redistribution of hoof wall weight-bearing.

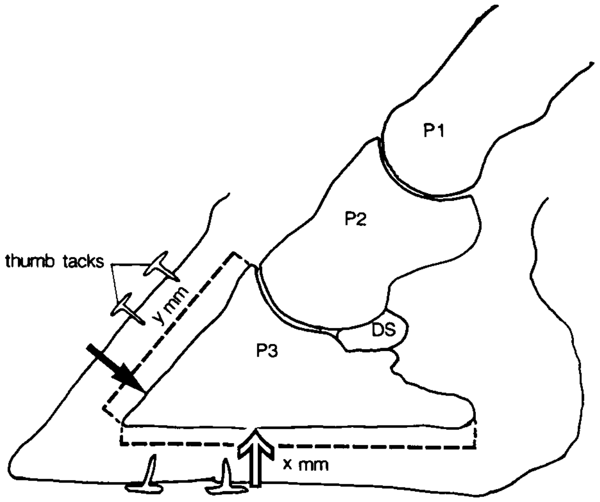


Fig. 1: **Schematic diagram of a lateromedial radiograph of the digit indicating sites of placement of the linear variable distance transducer** (black arrow) **and dorsal point of frog plate** (open white arrow)**. P1 = first phalanx; P2 = second phalanx; P3 = third phalanx; DS = distal sesamoid bone.**

MATERIALS AND METHODS

Five clinically healthy, adult, Thoroughbred horses, with no history or radiological signs of laminitis and no forelimb lameness were selected. Horses were randomly identified as A, B, C, D and E. All horses had been donated to the Equine Clinic at the Department of Companion Animal Clinical Studies, Faculty of Veterinary Science, University of Pretoria.

Both front hooves of each horse were geometrically balanced by a farrier and abnormalities in the hoof conformation were noted. Radiographs of the distal digit were taken. True lateromedial and dorsal 45° proximal-palmarodistal oblique radiographs of the distal interphalangeal joint and P3 were taken[40]. The length of the solar and dorsal surfaces of P3 were measured and corrected for magnification.

A point 4/5ths of the dorsal length of P3 distal to the distal interphalangeal joint was calculated and marked with a notch in the dorsal hoof wall, using thumb tacks as markers. The notch indicated the site for the insertion of the LVDT (200 AG linear variable distance transducer, D P Electronics, South Africa) probe (Fig. 1). Thirty-seven percent of the solar length of P3 palmar to the dorsalmost point of P3 was determined. This point identified the site of placement of the dorsalmost point of frog pressure as described by Platt quoted by Butler[4] (Fig. 1).

REFP shoes were nailed to both front hooves of all horses. The shoe is a mild (low carbon) steel horseshoe that is fitted in reverse to the hoof (Fig. 2). A mild steel (low carbon) 'carrying tab' (20 × 8 mm flat bar) welded to the inner curvature of the toe of the shoe had two 8 mm holes drilled into the tab approximately 2 cm apart which were tapped to accommodate Allen screws.

A 1–mm thick frog-shaped mild steel 'frog plate' was made, with 2 depressions partially drilled through the carrying tab surface corresponding to the holes in the carrying tab. Two 8 mm diameter Allen screws fitted into these depressions when screwed through the holes drilled through the carrying tab. These screws moved the frog plate vertically, parallel to the solar surface of the frog (Fig. 3). Once engaged between the frog and screws the frog plate could not move laterally. The frog plate, with the apex pointing dorsally was slipped into position between the frog and the carrying tab and the Allen screws adjusted to three torque settings for each respective frog pressure test. A set torque (TS) of 7 Newton-centimeter (N–cm) was applied to the frog plate through the Allen screws to all the limbs. This torque was sufficient to press the frog plate firmly against the frog in all the

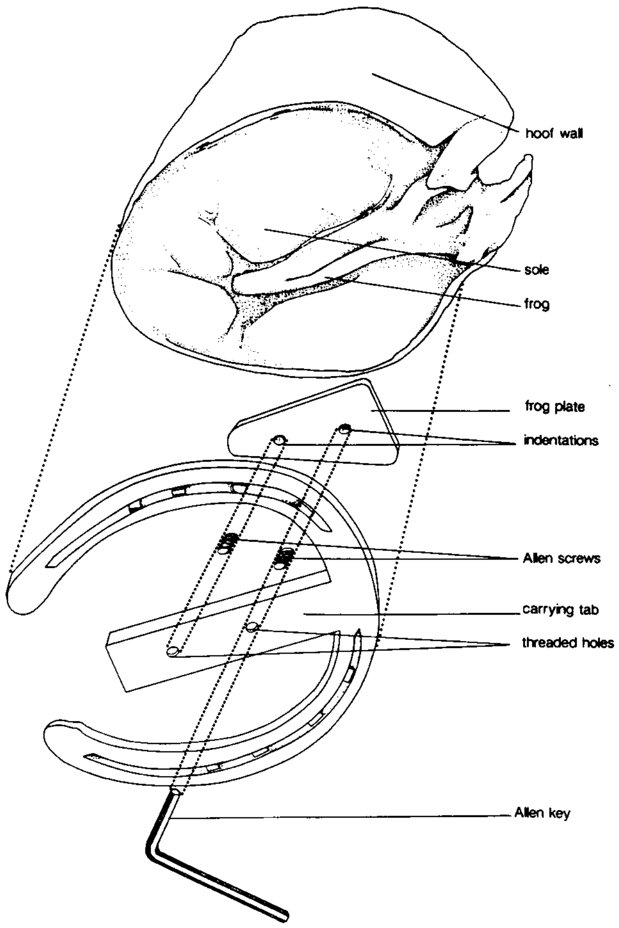


Fig. 2: **Schematic diagram of the reverse even frog pressure shoe.**

horses, when hand-tightened using a 4 mm Allen key.

Approximately 7 N–cm was the torque used to treat clinical cases of chronic laminitis at this clinic. A torque-limiting screwdriver (Torqueleader, Quikset 0–35 N–cm torque limiting screwdriver. M H H Engineering, Bramley, Guildford, England) was used.

The torque of the palmar Allen screw was increased to cause a grade 2 lameness at the trot as defined by Stashak[47]. This torque setting (T1) was noted for both forelimbs of each horse. The dorsal Allen screw was adjusted to position the frog plate and carrying tab parallel to each other. The torque was then decreased in both the palmar and dorsal Allen screws until the lameness was alleviated. The palmar screw torque (T2) at this point was noted. Again the frog plate was adjusted to parallel the carrying tab.

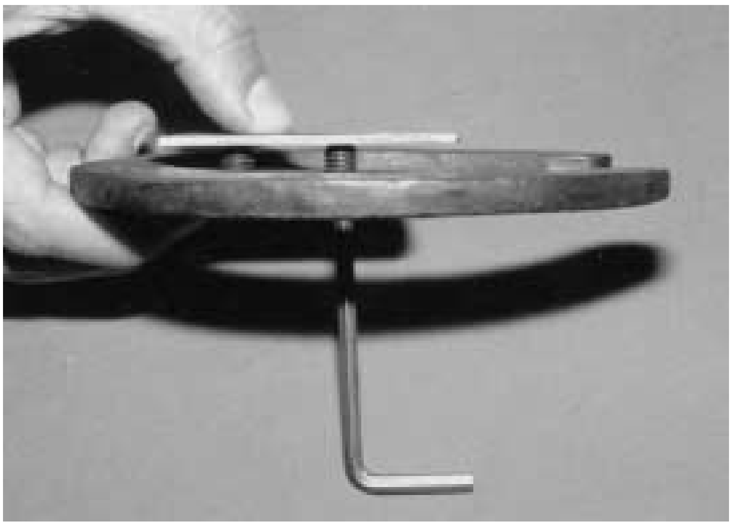


Fig. 3: **Frog plate and reverse even frog pressure shoe** (lateral view).

Each horse was pre-medicated with 0.03 mg/kg acetylpromazine and general anaesthesia induced with 100 mg/kg of a 10 % glycerol-guiacolate-ether solution (G G E Powder, Centaur) and 20 mg/kg sodium-pentothal (Intraval sodium, Maybaker A H) intravenously. The horse was intubated and maintained at surgical plain anaesthesia using halothane (Halothane. ICI South Africa Pharmaceuticals, Johannesburg, South Africa) as required.

Two LY113/120 strain gauges (Hottinger Baldwin Messtechnik) were attached to the ground surface of the carrying tab on the ground surface, 1 near the shoe-carrying tab junction and 1 between the 2 Allen screw holes. The method of strain gauge attachment to the hoof was similar to that described by Colles[6]. The strain gauge wires were soldered onto the soldering tags (Soldering tag LS2. Hottinger Baldwin Messtechnik) using soft solder.

Three LY113/120 strain gauges (Hottinger Baldwin Messtechnik) were glued to the toe, heel and mid-way between the toe and heel (named 'quarter') on the medial hoof wall. Only the medial hoof wall was tested due to financial constraints. The strain gauges were placed parallel to the horn tubules of the hoof for maximal compressive force measurement, approximately 0.4 cm from the distal end of the hoof. In horse C's left leg, the quarter strain gauge was moved 5 mm palmarly due to a superficial crack in the hoof at the calculated site.

The anaesthetised horse was euthanased by severing the carotid artery and exsanguinated. The forelimbs were amputated at the proximal radius, using a saw, cutting perpendicular to the long axis of the bone. The site chosen for amputation was to ensure maximal retention of the normal tensile stresses on the digit by the digital extensors, flexors and the remaining stay apparatus.

A 9 mm diameter hole was drilled in the dorsal hoof wall at the notch site, perpendicular to the dorsal hoof wall until P3 bone was felt. A lateromedial radiograph was taken to ensure that the drill bit point just touched P3. A mild steel cylindrical shoulder, was centred over the hole and attached to the hoof wall, by means of 3 mm self-tapping screws screwed into 2 mm guide holes in the dorsal hoof wall. The LVDT body (P3 displacement probe) fitted snugly into the shoulder after Allen screws holding it into position were tightened (Fig. 4).

Displacement of P3 was measured in mm. Dorsal displacement of P3 (inward displacement of the LVDT) gave a negative reading and palmar displacement, a positive reading.

Fig. 4: **Limb mounted in tensile testing machine.**

The strain gauge wires were soldered with soft solder onto wires connected to a 7–channel measuring amplifier (Hottinger Baldwin Messtechnik, model no. KWS3073). Channels were allocated to each strain guage and adjusted so that compression was measured as a negative reading in microstrain ($\mu\epsilon$) and tension a positive reading.

The tip and base strain gauges measured the magnitude of strain on the carrying tab as vertical force was applied to the limb. After data acquisition the carrying tab of each shoe was subjected to known weights and the corresponding microstrain noted. These data were used to convert carrying tab microstrain into Newton according to bending theory formulae[43]. The 2 carrying tab strain gauges of each foot were wired to 2 mild steel metal plates to form 2 Wheatstone bridges[21]. The 3 hoof strain gauges on 1 hoof formed 3 Wheatstone bridges with the horse's opposite hoof.

A cylindrical pipe fitting with a base was placed over the proximal point of the radius ensuring that no deviation of the limb to the side occurred when vertical pressure was applied. The limb was mounted on a tensile testing machine (J J Tensile testing machine Type T5000, J J Lloyd Scientific Instruments Ltd) in a similar fashion to that described by Crawford *et al.*[8]. The crosshead was set to exert a maximum downward vertical force of 2500 N and to move at a speed of 5 cm/min. A metal chain over the dorsum of the hoof stabilised the distal digit relative to the surface on which the hoof wall and a small portion of the adjoining solar surface rested (Fig. 4). The load cell on the crosshead measured vertical force applied to the limb up to 2500 Newton. Data were acquired as the crossbar applied downward forces from 0 to 2500 Newton to the limb. Total data collection time was 120 seconds.

All channels were connected to a personal computer with an analogue to digital card and zeroed before vertical force was applied to the limb. The LVDT channel was adjusted to register a zero reading when the LVDT was pushed to half-way its maximal excursion point.

Three sets of measurements were made in response to a vertical force applied to each limb: 1) deflection of the carrying tab (indicative of downward force applied to the frog), 2) movement of the 3rd phalanx perpendicular to the dorsal hoof wall, 3) unidirectional compression of the hoof wall. Each limb was tested 5 times under the following conditions: zero frog pressure torque with the frog plate absent (FA); frog pressure of 7 N–cm (TS); pain-causing frog pressure (T1); pain-alleviating frog pressure (T2) and with the shoe absent (SA). In the latter case measurement of the carrying tab deflection was not made since the shoe was absent.

The order of the perturbations (hereafter known as treatments) to the foot were random. Each test was repeated once before the next test was conducted. These repeat tests did not differ from the first and therefore the effect due to order of treatment was not considered to be important. Treatment SA was conducted last, because it was not deemed possible to replace the shoe and achieve the same hoof-shoe fixation as before removal.

The data were grouped into ranges 1–13 of 20 kg applied per range, therefore range 1 = 0 to <20 kg, range 2 = 20 kg to <40 kg, etc. to range 13 = 240 kg to <260 kg. The means of all data for each channel and each treatment in 13 ranges of kg-force applied were determined. The carrying tab tip strain gauge readings for the left leg of horse D and the heel strain gauge readings for the left leg of horse C were discarded for analysis, because of malfunction of the gauges.

Analysis of variance[34,48] was used to analyse all data. A PROC GLM (procedure for general linear models) was run on each range of all the data. The first trial and the repeat trial PROC GLMs were run separately. Pair-wise comparisons were made for each channel between the least square means of FA and the least square means of TS, T1, T2, and SA respectively with the aid of Fisher's LSD[48]. Similar pair-wise comparisons were made for each channel between the least square means of SA and the least square means of TS, T1, T2, and FA respectively.

The percentage of the downward vertical force carried by the hoof wall at each point in time was calculated. The microstrains measured at the base and tip strain gauges attached to the carrying tab were calculated as Force 3 (F3) and Force 4 (F4) respectively. The entire force applied to the carrying tab at a point in time (Fct) was calculated by adding F3 and F4. The vertical kg applied was converted to total force applied (Ftot) by multiplying the vertical force values at each point in time by 9.8 m/s^2 (acceleration due to gravity).

The difference between Ftot and Fct is equal to the amount of force applied to the hoof wall at a point in time. The percentage of hoof wall force (FWP) was calculated as: FWP = (Ftot–Fct)/Ftot ×

Table 1: **Calculated force of hoof wall weight-bearing: log_{10} of least square means in Newton** (standard errors of the means in brackets).

Range	FA	TS	T1	T2
1	2.046 (0.1164)	1.928 (0.1164)	1.681* (0.1164)	1.637* (0.1164)
2	2.037 (0.0888)	1.924 (0.0888)	1.692* (0.0888)	1.665* (0.0888)
3	2.036 (0.0700)	1.936 (0.0700)	1.690* (0.0700)	1.709* (0.0700)
4	2.034 (0.0644)	1.945 (0.0644)	1.709* (0.0644)	1.717* (0.0644)
5	2.033 (0.0538)	1.950 (0.0538)	1.720* (0.0538)	1.747* (0.0538)
6	2.031 (0.0468)	1.952 (0.0468)	1.731* (0.0468)	1.774* (0.0468)
7	2.031 (0.0438)	1.953 (0.0438)	1.760* (0.0482)	1.795* (0.0515)
8	2.030 (0.0370)	1.960 (0.0432)	1.768* (0.0370)	1.800* (0.0370)
9	2.019 (0.0358)	1.954 (0.0358)	1.780* (0.0358)	1.810* (0.0358)
10	0.029 (0.0293)	1.956 (0.0293)	1.790* (0.0293)	1.820* (0.0293)
11	2.028 (0.0273)	1.961 (0.0288)	1.800* (0.0273)	1.826* (0.0273)
12	2.025 (0.0262)	1.958 (0.0243)	1.792* (0.0243)	1.811* (0.0275)

FA = frog plate absent; TS = set torque; T1 = torque applied to frog plate that caused lameness; T2 = torque applied to frog plate that alleviated pain.
*Significantly different from FA ($P < 0.05$).

100. The means of all limbs' FWP for each treatment in 12 ranges of kg-force applied were determined.

Analysis of variance was also used to analyse these data. A PROC GLM was run on the log_{10} of each range of all FWP data. The first trial and the repeat trial PROC GLMs were run separately. Pair-wise comparisons were made between the least square means of FA and the least square means of TS, T1 and T2 respectively with the aid of Fisher's LSD. Pair-wise comparisons were also made between the least square means of the left and the right legs for FA, TS, T1 and T2 respectively with the aid of Fisher's LSD.

The first and repeat trial PROC GLM results of both data sets were found to be so similar that only the results of the first trial were used in the study. Standard errors of the means (SEM) were calculated. For all the statistical interpretations the significance level was kept at $P < 0.05$.

RESULTS

Force on hoof wall as a percentage of downward vertical force applied (Fig. 5, Table 1)

The percentage force carried by the hoof wall with treatment FA was approximately 100 %. This percentage decreased with the increased frog pressure by approximately 20 % at TS. T1 and T2 decreased this percentage even more. Percentage of hoof wall weight-bearing was significantly different between FA and T1 and T2. As load increased for TS, T1 and T2, relatively more weight was carried by the hoof wall.

Third phalanx movement (Fig. 6, Table 2)

P3's starting point was moved palmarly by T1 and T2 frog pressures before load was applied, when compared to the starting points of P3 at the lower frog pressures of FA, TS and SA. The displacement of P3 at T1 and T2 was significantly different to both FA and SA at most of the lower ranges of load applied up to range 7 (1400 N) ($P < 0.05$). As load was increased the difference between T1, T2 and FA, SA decreased and the position of P3 relative to the dorsal hoof wall in all 5 treatments was similar at maximal load.

Carrying tab strain gauge results

Base strain (Fig. 7a, Table 3)

Significant differences were found between FA, and TS, T2 and T1, respectively as frog pressure was increased. The higher the frog pressure, the more the carrying tab was deflected downward as load was applied.

Tip strain (Fig. 7b, Table 4)

The carrying tab tip was deflected downward as vertical force was increased. The downward deflection of the tip of the carrying tab increased as the frog pressure torque was increased. The magnitude of deflection of the carrying tab is smaller further away from the shoe-carrying tab junction as is described by Young's law of elasticity[21].

Hoof wall strain gauge results

Toe strain (Fig. 8a, Table 5)

For all treatments, except SA, hoof wall compression at the toe increased as vertical load increased. Significant differences were seen between the dorsal hoof wall compressions of FA and SA only at the high loads. Differences between FA and T1 were significant at all ranges, with compression of the dorsal hoof wall decreasing as frog pressure increased.

Differences between FA and T2 were significant at particularly the lower ranges. Differences between FA and SA,

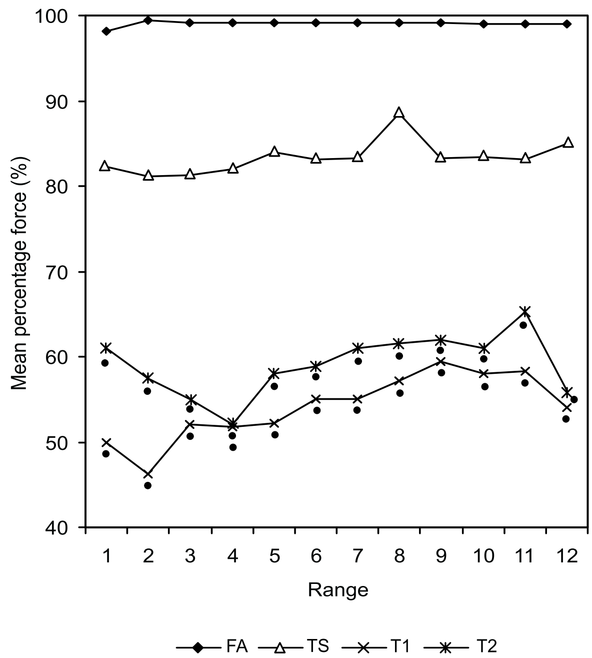


Fig. 5: **Percentage force on the hoof wall. FA = frog plate absent; TS = set torque; T1 = torque applied to the frog plate that caused lameness. T2 = torque applied to the frog plate that alleviated pain. ● Significantly different from FA** ($P < 0.05$).

Table 2: **P3 movement: least square means in mm** (standard errors of the means in brackets)**.**

Range	FA	SA	TS	T1	T2
1	0.092 (0.0857)	0.0001(0.0867)	0.080 (0.0870)	0.454[a] (0.0636)	0.295[c] (0.0968)
2	0.030 (0.0606)	0.047 (0.0571)	0.030 (0.0571)	0.373[a] (0.0571)	0.241[a] (0.0571)
3	0.039 (0.0473)	0.047 (0.0473)	0.038 (0.0473)	0.282[a] (0.0473)	0.205[a] (0.0473)
4	0.037 (0.3890)	0.043 (0.3890)	0.039 (0.3890)	0.217[a] (0.3890)	0.169[a] (0.3890)
5	0.034 (0.0334)	0.038 (0.0334)	0.038(0.0334)	0.179[a] (0.0334)	0.134[b] (0.0334)
6	0.032 (0.0328)	0.031 (0.0328)	0.036 (0.0328)	0.148[a] (0.0328)	0.114 (0.0328)
7	0.030 (0.0276)	0.018 (0.0293)	0.034 (0.0276)	0.190[a] (0.0341)	0.102[c] (0.0276)
8	0.019 (0.0386)	0.014 (0.0343)	0.032 (0.0343)	0.102 (0.0343)	0.087 (0.0343)
9	0.024 (0.0348)	0.006 (0.0348)	0.016 (0.0369)	0.084 (0.0348)	0.075 (0.0369)
10	0.021 (0.0352)	–0.001 (0.0352)	0.029 (0.0352)	0.069 (0.0352)	0.065 (0.0352)
11	0.020 (0.3824)	–0.008 (0.0361)	0.027 (0.0361)	0.056 (0.0361)	0.056 (0.0361)
12	0.017 (0.0389)	–0.014 (0.0366)	0.026 (0.0366)	0.050 (0.0389)	0.048 (0.0366)
13	–0.003 (0.0562)	–0.027 (0.0562)	0.028 (0.0449)	0.020 (0.0533)	0.031 (0.0533)

P3 = third phalanx; FA = frog plate absent; SA = shoe absent; TS = set torque; T1 = torque applied to frog plate that caused lameness; T2 = torque applied to frog plate that alleviated pain.
[a]Significantly different from FA and SA ($P < 0.05$).
[b]Significantly different from SA ($P < 0.05$).
[c]Significantly different from FA ($P < 0.05$).

and T1, T2 were significant at particularly the lower ranges.

Quarter strain (Fig. 8b, Table 6)

No significant differences in the medial quarter compression were found due to treatment. There was, however, a visible trend that hoof wall compression increased as a function of downward vertical force in all treatments except SA.

Heel strain (Fig. 8c, Table 7)

In T1 and T2 heel strain appeared to remain relatively constant, but increased in FA, SA and TS as vertical force increased. Differences between FA and TS were only significant at the high loads. Differences between FA, and T2 and T1, respectively were significant at all loads, with compression of the heel hoof wall decreasing as frog pressure increased. Differences between SA, and T2 and T1, respectively were only not significant at the lower loads.

Difference between left and right legs' measurements

No significant difference between left and right legs for each horse were found for all measurements of FA, TS, T1, T2 at ranges 1–13, for $P < 0.05$.

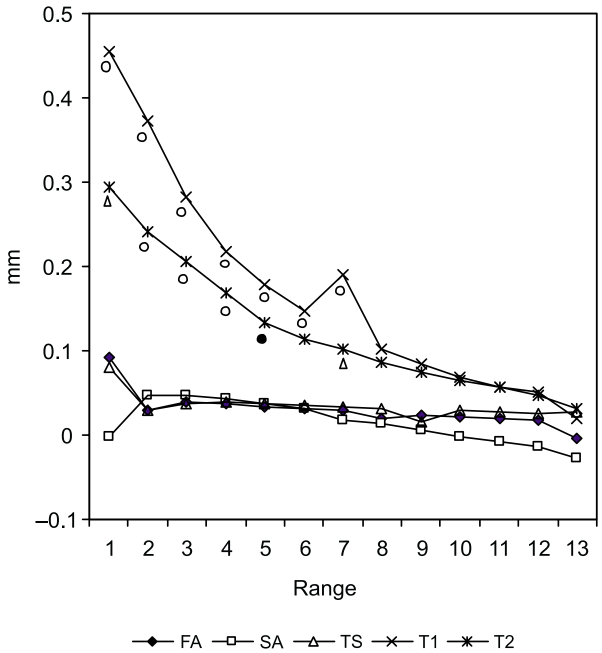


Fig. 6: **P3 movement** (least square means)**. P3 = third phalanx; FA = frog plate absent; SA = shoe absent; TS = set torque; T1 = torque applied to the frog plate that caused lameness; T2 = torque applied to the frog plate that alleviated pain. ❍ Significantly different from FA and SA** ($P < 0.05$); **● significantly different from FA** ($P < 0.05$)**; Δ significantly different from SA** ($P < 0.05$)**.**

DISCUSSION

Although performing this study in the live horse, with presence of the normal physiological responses of the limb to perturbations would have been ideal, this study was done *in vitro* for humane reasons. Horses were anaesthetised during the placement of strain gauges to minimise *post mortem* changes that could occur if strain gauges were placed after euthanasia. Normal horses' feet were studied to acquire normal data to compare with data in future studies on chronic laminitic feet. Forelimbs were used in this study, since laminitis is most often manifested in the forelimbs[47].

The 7 N-cm torque setting (TS) was decided upon by the 1st author and the farrier after 16 clinical cases of chronic laminitis had been treated with the REFP shoe at a similar magnitude of torque, with fair to good results. It is acknowledged that, owing to different physical attributes of the horse's frog, the amount of load-bearing of the frog would differ among individual horses. The pain-causing torque (T1) provided a high frog pressure reading to compare to TS on all the channels measured. The T1 torque has the disadvantage of being a subjective observation. Torques differed among horses due to differences in pain tolerance and frog hardness and compliance. These torques ranged from 30 N-cm to greater than 35 N-cm. Readings above 35 N-cm were not possible with the torque screwdriver used. The pain-relieving torque (T2) was used for the same reasons as T1, with similar disadvantages. These torques ranged from 20 to greater than 35 N-cm.

Table 3: **Carrying tab base strain: least square means in microstrain** (standard errors of the means in brackets)**.**

Range	FA	TS	T1	T2
1	–107.034 (21.4852)	–133.301 (24.8090)	–368.501* (21.4850)	–282.159* (21.4850)
2	–106.902 (23.6547)	–153.132 (23.6547)	–403.958* (23.6547)	–314.022* (23.6547)
3	–107.141 (27.2300)	–173.770 (27.2300)	–458.117* (27.2300)	–360.290* (27.2300)
4	–107.717 (30.2630)	–191.592 (30.2630)	–506.594* (30.2630)	–402.974* (30.2630)
5	–108.214 (33.8226)	–207.741* (33.8226)	–551.032* (33.8226)	–446.514* (33.8226)
6	–108.614 (37.2630)	–223.832* (37.2630)	–595.640* (37.2630)	–487.088* (37.2630)
7	–108.966 (39.6604)	–238.757* (39.6604)	–633.537* (39.6604)	–521.338* (39.6604)
8	–109.227 (43.2960)	–253.178* (43.2960)	–666.330* (43.2960)	–552.076* (43.2960)
9	–109.412 (44.4603)	–257.836* (47.2417)	–693.438* (44.4603)	–575.637* (44.4603)
10	–108.911 (50.9470)	–273.686* (50.9918)	–721.475* (50.9918)	–603.627* (47.8793)
11	–109.968 (47.6047)	–287.669* (47.6047)	–744.763* (47.6047)	–622.045* (50.5828)
12	–103.267 (46.3727)	–298.614* (46.3951)	–800.341* (46.3727)	–649.226* (46.3951)
13	–86.689 (63.5873)	–314.481* (50.8001)	–819.744* (60.3693)	–737.359* (60.3693)

FA = frog plate absent; TS = set torque; T1 = torque applied to the frog plate that caused lameness; T2 = torque applied to the frog plate that alleviated pain.
*Significantly different from FA (*P* < 0.05).

Table 4: **Carrying tab tip strain: least square means in microstrain** (standard errors of the means in brackets)**.**

Range	FA	TS	T1	T2
1	–126.224 (7.9505)	–132.856 (11.8224)	–176.303* (10.3871)	–155.116* (10.0853)
2	–123.458 (6.7430)	–132.428 (7.1316)	–181.588* (6.7430)	–158.752* (6.7430)
3	–123.465 (7.4100)	–135.119 (7.4100)	–190.367* (7.4100)	–166.449* (7.4100)
4	–123.672 (8.3546)	–138.522 (8.3546)	–199.626* (8.3546)	–175.177* (8.3546)
5	–124.403 (9.0434)	–142.016 (9.0434)	–206.517* (9.0434)	–180.894* (9.0434)
6	–124.595 (9.4730)	–144.721 (9.4730)	–213.221* (9.4730)	–185.899* (9.4730)
7	–124.738 (9.9365)	–147.600 (9.9365)	–219.321* (10.6580)	–192.279* (9.9365)
8	–124.584 (11.0289)	–150.118 (10.4192)	–222.749* (10.4192)	–191.019* (12.1391)
9	–124.929 (10.4260)	–50.078 (11.1832)	–226.976* (10.4260)	–197.072* (10.4260)
10	–127.251 (11.3466)	–152.367 (10.5784)	–229.728* (10.5784)	–201.264* (10.5784)
11	–125.571 (10.4009)	–154.326 (10.4009)	–231.764* (10.4009)	–204.296* (10.4009)
12	–125.334 (10.7545)	–154.395 (10.1762)	–238.938* (10.7545)	–210.206* (10.7545)
13	–123.115 (11.3628)	–155.642*(8.9066)	–228.132* (10.6423)	–218.207* (10.6423)

FA = frog plate absent; TS = set torque; T1 = torque applied to the frog plate that caused lameness; T2 = torque applied to the frog plate that alleviated pain.
*Significantly different from FA (*P* < 0.05).

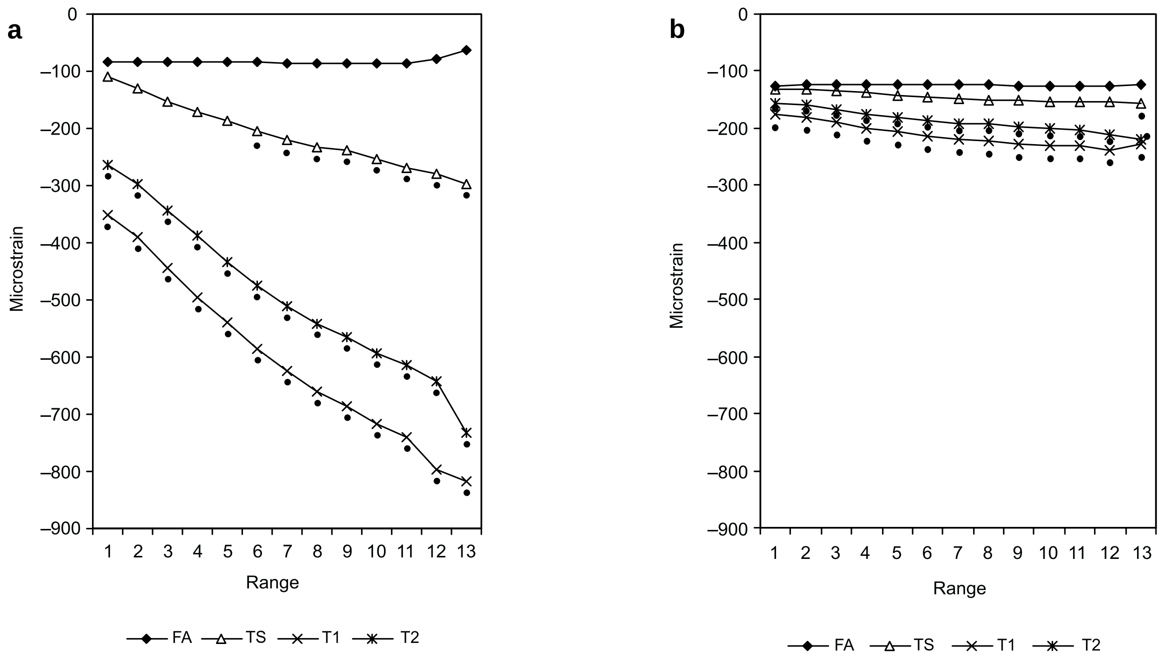
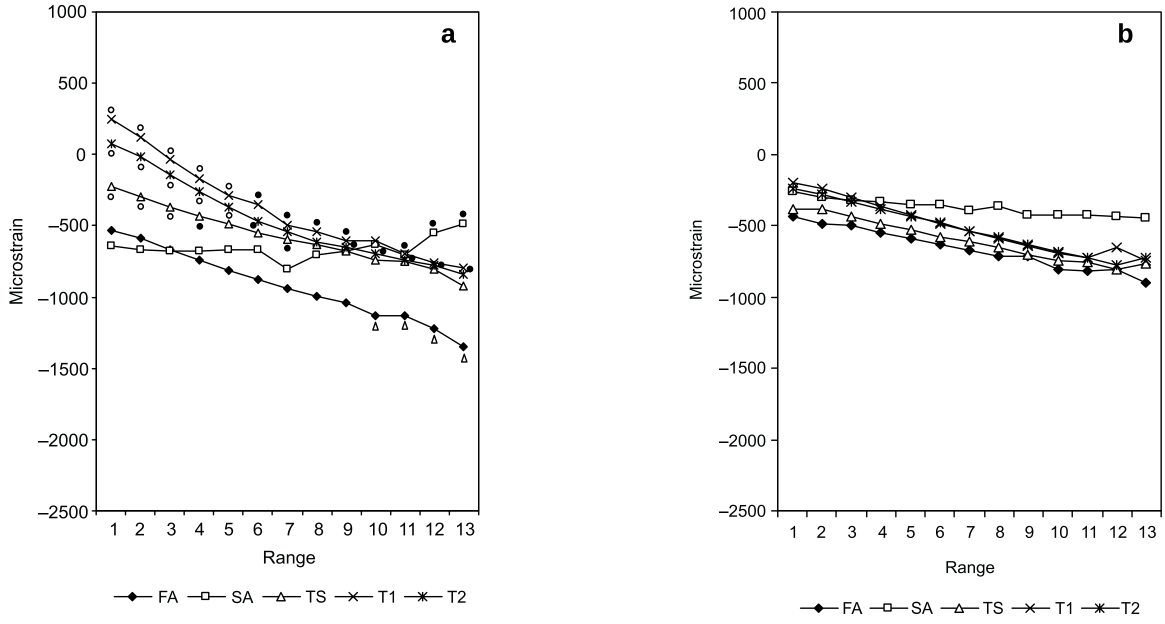


Fig. 7: a, **carrying tab base strain** (least square means); b, **carrying tab tip strain** (least square means). **με = strain; FA = frog plate absent; TS = set torque; T1 = torque applied to the frog plate that caused lameness; T2 = torque applied to the frog plate that alleviated pain. ● Significantly different from FA** (*P* < 0.05)**.**



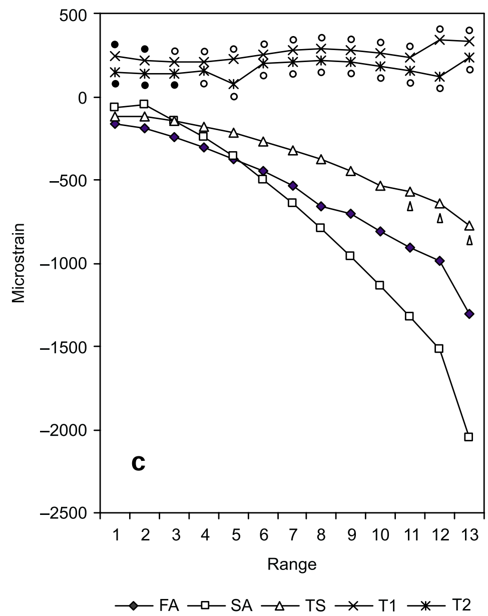


Fig. 8: a, **toe strain** (least square means); b, **quarter strain** (least square means); c, **heel strain** (least square means). **FA = frog plate absent; SA = shoe absent; TS = set torque; T1 = torque applied to the frog plate that caused lameness; T2 = torque applied to the frog plate that alleviated pain. ❍ Significantly different from FA and SA** (P < 0.05)**; ● significantly different from FA** (P < 0.05)**; Δ significantly different from SA** (P < 0.05)**.**

Table 5: **Toe strain: least square means in microstrain** (standard errors of the means in brackets)**.**

Range	FA	SA	TS	T1	T2
1	–532.912 (105.4486)	–639.927 (105.4339)	–224.053[a] (105.4339)	244.359[a] (99.3902)	74.190[a] (99.3902)
2	–588.065 (97.8367)	–664.655 (97.8367)	–293.918[a] (97.8367)	118.714[a] (97.8367)	–17.722[a] (97.8367)
3	–667.324 (102.1594)	–677.316 (102.1594)	–369.495[a] (102.1594)	–33.020[a] (102.1594)	–144.558[a] (102.1594)
4	–744.941 (108.3981)	–674.615 (108.3981)	–433.559[b] (108.3981)	–168.480[a] (108.3981)	–260.499[a] (108.3981)
5	–845.717 (115.1492)	–669.405 (115.1492)	–489.673 (115.1492)	–289.354[a] (115.1492)	–371.746[a] (115.1492)
6	–878.513 (120.7569)	–666.346 (120.7569)	–546.585 (120.7569)	–347.118[b] (120.7569)	–469.458[b] (120.7569)
7	–937.142 (114.5233)	–800.900 (121.5774)	–599.485[b] (114.5233)	–492.590[b] (121.5774)	–544.961[b] (114.5233)
8	–990.765 (130.6500)	–701.789 (130.7022)	–632.069 (130.7022)	–541.608[b] (130.7022)	–616.049 (130.6500)
9	–1038.953 (132.7811)	–677.863 (132.7811)	–678.611 (132.7811)	–604.141[b] (132.7811)	–649.017[b] (132.7811)
10	–1134.097[c] (150.8401)	–635.817[b] (141.9185)	–744.780 (163.6904)	–605.319[b] (150.8401)	–695.090[b] (141.9185)
11	–1127.391[c] (138.0458)	–704.013[b] (146.4200)	–747.925 (138.0458)	–691.634[b] (138.0458)	–738.328 (138.0458)
12	–1224.127[c] (159.5224)	–549.400[b] (150.2667)	–800.232 (150.2667)	–758.544[b] (159.5224)	–775.356[b] (150.2667)
13	–1352.506[c] (225.2533)	–486.598[b] (213.9504)	–924.223 (179.9802)	–792.621[b] (213.9504)	–839.658 (213.9504)

FA = frog plate absent; SA = shoe absent; TS = set torque; T1 = torque applied to the frog plate that caused lameness; T2 = torque applied to the frog plate that alleviated pain.
[a]Significantly different from FA and SA (P < 0.05).
[b]Significantly different from FA (P < 0.05).
[c]Significantly different from SA (P < 0.05).

Table 6: **Quarter strain: least square means in microstrain** (standard errors of the means in brackets)**.**

Range	FA	SA	TS	T1	T2
1	–431.724 (189.0702)	–256.812 (206.5330)	–379.725 (177.8742)	–199.526 (167.5896)	–240.263 (167.5896)
2	–486.094 (170.3502)	–305.397 (160.6077)	–383.774 (160.6077)	–241.076 (160.6077)	–283.590 (160.6077)
3	–496.577 (158.4840)	–319.392 (158.4840)	–438.748 (158.4840)	–300.478 (158.4840)	–331.786 (158.4840)
4	–546.813 (157.0772)	–336.540 (157.0772)	–488.952 (157.0772)	–365.529 (157.0772)	–383.858 (157.0772)
5	–593.922 (158.4460)	–350.683 (158.4460)	–533.023 (158.4460)	–426.320 (158.4460)	–437.469 (158.4460)
6	–636.367 (163.4331)	–355.660 (163.4331)	–575.082 (163.4331)	–482.259 (163.4331)	–473.014 (173.3469)
7	–674.527 (166.5201)	–388.710 (166.5201)	–613.935 (166.5201)	–538.460 (166.5201)	–536.216 (166.5201)
8	–713.518 (173.3322)	–359.681 (183.8465)	–651.589 (173.3322)	–592.879 (173.3322)	–582.709 (173.3322)
9	–716.668 (194.2089)	–422.137 (183.0764)	–705.409 (194.2089)	–644.010 (183.0764)	–628.583 (183.0764)
10	–806.309 (202.2547)	–427.280 (190.6276)	–739.920 (202.2547)	–695.428 (190.6276)	–679.921 (190.6276)
11	–814.822 (214.2636)	–428.900 (201.8637)	–757.425 (201.8637)	–728.892 (214.3859)	–726.840 (214.3859)
12	–807.298 (219.3220)	–430.074 (206.5937)	–806.225 (206.5937)	–656.394 (234.4913)	–777.848 (206.5937)
13	–894.740 (287.1867)	–449.865 (272.7761)	–764.610 (229.4657)	–749.237 (272.7761)	–725.478 (272.7761)

FA = frog plate absent; SA = shoe absent; TS = set torque; T1 = torque applied to the frog plate that caused lameness; T2 = torque applied to the frog plate that alleviated pain.

Table 7: **Heel strain: least square means in microstrain** (standard errors of the means in brackets)**.**

Range	FA	SA	TS	T1	T2
1	–163.175 (106.3780)	–64.894 (120.5604)	–118.316 (116.5825)	243.413[b] (106.3780)	149.130[b] (106.3780)
2	–192.927 (105.5576)	–44.961 (105.5576)	–120.892 (105.5576)	218.198[b] (105.5576)	138.735[b] (105.5576)
3	–243.054 (107.9907)	–144.390 (107.9907)	–145.458 (107.9907)	204.063[a] (107.9907)	139.419[b] (107.9907)
4	–305.191 (114.5356)	–244.296 (114.5356)	–180.527 (114.5356)	211.637[a] (114.5356)	156.801[a] (114.5356)
5	–375.928 (127.0143)	–362.458 (127.0143)	–220.406 (127.0143)	226.269[a] (127.0143)	76.903[a] (127.0143)
6	–450.877 (142.7520)	–498.788 (142.7520)	–266.349 (142.7520)	254.209[a] (142.7520)	195.885[a] (142.7520)
7	–536.614 (159.8678)	–641.682 (159.8678)	–320.573 (159.8678)	278.055[a] (159.8678)	211.508[a] (159.8678)
8	–657.665 (191.9827)	–794.180 (181.4147)	–378.547 (181.4147)	285.929[a] (181.4147)	217.061[a] (181.4147)
9	–707.612 (201.5675)	–961.238 (201.5675)	–445.355 (201.5675)	277.698[a] (201.5675)	203.932[a] (201.5675)
10	–810.633 (228.0565)	–1137.743 (228.0565)	–538.467 (249.8689)	257.772[a] (228.0565)	178.256[a] (228.0565)
11	–908.391 (247.9794)	–1320.326 (247.9794)	–571.871[c] (247.9794)	232.207[a] (247.9794)	154.967[a] (247.9794)
12	–989.174 (321.2893)	–1516.938 (275.3338)	–645.662[c] (275.3338)	336.470[a] (291.1850)	120.251[a] (275.3338)
13	–1303.519 (342.7814)	–2050.326 (342.7814)	–773.409[c] (342.7814)	331.730[a] (342.7814)	237.958[a] (342.7814)

FA = frog plate absent; SA = shoe absent; TS = set torque; T1 = torque applied to the frog plate that caused lameness; T2 = torque applied to the frog plate that alleviated pain.
[a]Significantly different from FA and SA ($P < 0.05$).
[b]Significantly different from FA ($P < 0.05$).
[c]Significantly different from SA ($P < 0.05$).

The dorsalmost point of the frog plate position was chosen using the method described by Platt and quoted by Butler[4]. It is a more objective method than that described by Chapman[5]. The LVDT placement site was arbitrarily selected at a point far enough from the distal interphalangeal joint to register a displacement and where the probe would not slip off the distal tip of P3 when weight was borne on the digit.

A standing horse bears approximately 60 % of its body mass on the forelimbs[35]. At a walk the maximum vertical force of the hoof on the ground is about 0.6 times body mass[45] and at a trot this force is approximately 0.9 times body mass[45]. The masses of the horses in this study ranged from 391 to 517 kg. For the heavier horses the maximum force applied would be below the force calculated for the walk. The relatively slow (5 cm/min) vertical movement of the cross bar would be more comparable to the slow movement seen in a horse with chronic laminitis.

In this study, total hoof wall compression and therefore hoof wall weight-bearing was decreased as frog pressure was increased (the carrying tab was deflected downwards by the frog and overlying tissues as load was increased). In a previous study, a block placed under the frog resulted in a decrease in strain in some horses but an increase in others[7]. It was also evident that, as load increased for TS, T1 and T2, relatively more weight was carried by the hoof wall.

In this study, it was not possible to tell whether the distal portion of P3 (tip) was rotating palmarly (capsular or phalangeal) or moving palmarly in a parallel fashion from the dorsal hoof wall, although the former is usually the case in horses with P3 rotation. The latter could be described as a translation movement, *i.e.* a movement without rotation. It may have been useful to have had two LVDTs: one at the site described here and another more proximally. Similar LVDT results would have indicated a parallel movement of P3.

Movements within human carpal bones were investigated using digitised analysis of radiographs taken in multiple directions simultaneously[44]. A study of P3 movement using this technique would probably yield more meaningful results as to the movement of P3 within the hoof wall as load was applied to the limb.

Fischerleitner[14], using similar downward pressures as used in the present study, reported that P3 rotates palmarly and 'sinks simultaneously' as the foot is loaded in the unshod foot. The tip of P3 was therefore probably undergoing palmar rotation in this study, at least at low frog pressures.

When frog pressure increased up to T1 and T2 before load was applied, the tip of P3 initially moved palmarly (approximately 0.45 and 0.3 mm respectively). This may be due to the most dorsal tip of the frog plate being palmar to the pivot point on the solar surface of P3. As frog pressures increased, the tip of P3 rotated palmarly round this fulcrum. For the treatment of clinical cases of laminitis the dorsal tip of the frog plate (or heart bar) may have to be moved further dorsally in order to prevent this palmar movement.

There is a larger displacement of the tip of P3 when T1 and T2 frog pressures are applied at the lower load ranges and less displacement at the higher load ranges. P3 cannot, therefore, move much with simultaneous high frog and vertical load pressures, probably because the entire distal phalanx is compressed between the frog plate and sole and the dorsal hoof wall during the high load applied.

Further studies are required to investigate the correct position of the tip of the frog plate (or heart bar). The effect that different positions of the frog plate (or heart bar) may have on the movement of P3, the blood supply to the pedal bone and on pressure necrosis of the frog or sole also need to be determined.

The maximum distance moved by P3 from zero load was approximately 0.45 mm in this study. In the horse with chronic laminitis and P3 rotation this distance could be much greater.

Based on the results of this study, the application of the REFP shoe to decrease P3 movement, is not indicated at high frog pressures. The position of P3 remained similar with 7 N-cm frog pressure and with no frog pressure.

This study indicates that the common belief that increased frog pressure 'pushes ' P3 dorsally, does not appear to be correct at high frog pressures in the normal horse. At more clinical frog pressures (TS), P3 remained relatively non-displaced as load was increased.

The results of the measurements of strain gauges attached to the hoof wall must be interpreted with care, since unidirectional strain gauges only measure compression or tension in the direction of the applied gauge. The hoof wall under load not only undergoes compressive or tensile forces, but complex bending and inward and outward movements. The results of the hoof wall strain gauges in this study, however, are supportive of the results that increased frog pressure decreases hoof wall weight-bearing.

Before loading, hoof wall compression at the toe was significantly less at TS, T1, T2 from both SA and FA. Hoof wall compression at the toe increased in all treatments with a shoe as load increased. These results are similar to those of Thomason where increased toe compression was seen until break-over at the trot[50]. Without the shoe (SA) the toe strain was relatively constant, implying that if vertical load is increased, a constant toe pressure is maintained. This information may be helpful in the treatment of chronic laminitic horses, where further laminar damage at the toe may be decreased if weight bearing at the toe can be kept constant. Even with an open toe as in the reverse shoe, there is more of an increase in hoof wall compression at the toe as vertical load is increased as compared to the absence of a shoe.

In the quarter strain measurements the trend (not significant) was increased compression of the hoof wall when the shoe was present. The magnitude of compression was, however, slightly less than toe strain measurements, especially in FA. This implies less weight-bearing by the medial quarter than at the toe as load is increased. There was a trend to a more constant compression by the medial quarter when the shoe was absent (SA) as load was increased. When hoof wall strains were measured using rosette gauges, which measure strain in multiple planes, biaxial strains in the quarter of the hoof were reported[50]. Flaring of the quarters to the side as load was increased has been described[20]. The fact that the quarter strain gauge of horse C's left limb was placed 5 mm palmarly to where it should have been, appeared to have no effect on the results.

The high frog pressure treatments (T1 and T2) maintained constant compression on the heels as load increased. In SA, FA and TS the tendency to increased heel compression is clearly seen, but is least in TS. In laminitis the heel laminae do not appear to be as prone to damage as further dorsally. In fact, treatment is usually aimed at increasing weight-bearing at the heel to take weight off the toe. The proximal dorsal hoof wall moves palmarly as load is applied, supporting the finding of palmar movement of weight-bearing to the heels[20] as increased vertical force is applied.

Since shoes that increase frog pressure have been described to successfully treat chronic laminitic horses[46], decreased hoof wall weight-bearing, as seen in this study, may be one of the mechanisms of action. The fact that the REFP shoe caused P3 rotation, although minimally, at excessively high frog pressures, indicates that excessive frog pressure is contra-indicated in the treatment of chronic laminitis although the location of the dorsalmost tip of frog pressure may influence this movement. The clinically useful frog pressure (TS) did not reveal significant differences to the reverse shoe. It must be emphasised that normal feet were used in this study. Different results might be obtained if feet with chronic laminitis are used.

CONCLUSION

In this study, it was found that total hoof wall weight-bearing decreased as frog pressure increased. This may have clinical application in horses with developmental or chronic laminitis. Minimal palmar rotation of P3 occurred with high applied frog pressures in this study. This rotation may be influenced by the position of the dorsalmost point of the frog plate.

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