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GENERAL ARTICLE

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# Hoof kinetic patterns differ between sound and laminitic horses

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## Abstract

**Background:** No kinetic data on hoof loading in laminitic horses are available, despite their importance for optimising supportive shoeing therapies.

**Objectives:** To quantify the load distribution pattern in laminitic and sound horses.

**Study design:** Controlled observational study.

**Methods:** Fifty-four sound and laminitic horses were assigned to three groups: control group (sound horses), group 1 (G1) horses with acute laminitis, evaluated immediately after acute clinical signs subsided, and group 2 (G2) horses that had been free of acute laminitis signs for 6-12 weeks. Measurements on both forelimbs in barefoot condition were performed during walk using the Hoof™ System. Kinetic parameters were recorded and compared between hoof regions and groups using covariance analyses and *t* tests ($P < .05$).

**Results:** Peak loading in the toe region occurred during midstance phase in control group, but during break-over in laminitic horses. This is reflected by the time to peak vertical force in the toe, which was significantly shorter in the control group compared to laminitic horses (G1 and G2) (76% ± 6% vs 89% ± 9 [$P = .002$], 86% ± 7 [$P = .001$] of stance duration respectively). The relative vertical force in the toe in the control group (46% ± 7%) was significantly higher compared to laminitic horses (G1: 29% ± 9% [$P = .001$]; G2: 32% ± 10% [$P = .003$]). The main shift of the load occurred between toe and middle hoof regions in laminitic horses as compared with the control group. No significant differences were found between G1 and G2.

**Main limitations:** Measurements were not obtained in horses with acute laminitis on admission, to avoid risk of further damage to the lamellae.

**Conclusions:** Supportive therapy in laminitis should focus on supporting both caudal and middle hoof areas to decrease the peak pressure in these regions, and ease break-over during which the maximal loading of the toe occurs.

KEYWORDS
horse, laminitis, load distribution pattern, Hoof™ System

# 1 | INTRODUCTION

Laminitis-associated lameness in the acute phase is characterised by placement of both the hind- and forefeet forward of their normal positions,[1] a short-stilted gait and in some cases by a reluctance to move.[2-3] The chronic phase is characterised by a decrease in the forelimb load as compared to sound horses.[3]

The principles of the orthopaedic supporting therapy for laminitic horses are to relieve the damaged hoof areas and redistribute the load to the undamaged hoof structures.[4-5] In the acute phase, several therapeutic options are available including heel elevation,[6] frog support pads, and toe bevelling,[7] whereas in the chronic phase, a variety of therapeutic shoes have been reported such as heart-bar shoe,[5] the wooden shoe, wide web aluminium shoe and glue-on shoe.[4]

A detailed knowledge of the load distribution pattern within different hoof regions in horses with laminitis will help the equine practitioners to optimise the supportive therapy. The Hoof™ System has been successfully used to evaluate the load distribution within the hoof in shod and unshod horses, and to study the effect of different horseshoes at different ground properties.[8-10] However, no kinetic measurements have been performed to assess the load distribution in the laminitic hoof so far.

The objective of this study was to describe the load distribution pattern in sound and laminitic horses immediately after resolution of acute clinical signs and 6-12 weeks later. Our hypothesis was that there would be a significant reduction of load in the toe region in horses with laminitis compared to sound horses.

# 2 | MATERIALS AND METHODS

## 2.1 | Horses

The control group comprised horses that were clinically sound, unshod for a period of at least 6 months and their feet had been routinely trimmed every 6-8 weeks.

Horses and ponies admitted to the clinic due to acute laminitis, and those with a history of laminitis presenting to our Farriery Teaching School for hoof trimming and shoeing, were included in the study. The diagnosis of acute laminitis was based on clinical and radiographic examination according to the original obel-system.[2,11] The laminitic horses were assigned to two groups, depending on the duration of time since resolution of clinical symptoms of laminitis. Group 1 (G1) were horses that had previously been confined to a stable due to acute laminitis and they were evaluated immediately after any medications were discontinued and the signs of acute laminitis had subsided. If on admission, the horses were shod, horseshoes were removed. Group 2 (G2) were horses with a recent history of acute laminitis, in which the signs had subsided 6-12 weeks prior to inclusion in the study. In both groups G1 and G2, only horses which were affected by laminitis (initial or recurrence episodes) on both forelimbs were included and horses suffering from laminitis on one forelimb or all limbs and those with uniaxial distal displacement of the distal phalanx were excluded.

## 2.2 | Data collection

Both forelimbs were evaluated once in barefoot condition. The measurements were performed after a standard hoof trim in the control group, but prior to performing any manipulation on the hooves in the laminitic horses, in order to exclude any effect of trimming on load distribution pattern.

The measuring system consisted of a Hoof™ System (TekScan®, Tekscan Hoof System®), with a spatial resolution of 3.9 sensels/cm$^2$, and a pressure range of 0-200 N/cm$^2$. The measurements were performed at sampling frequency of 250 Hz. The horses were equipped with the measuring system on both forelimbs. After application of the measuring system, a calibration protocol was performed according to the manufacturer's instructions. The measurements were carried out at a walk on a 15-m-long track in the stall with a level, concrete surface for 10 seconds, allowing the measurement of 7-11 strides.

## 2.3 | Data processing

To evaluate the kinetic data of the pressure measurement system, the mean from five valid measurements was averaged into one pressure image using the Hoof Software (version 6.68, TekScan®, Tekscan Hoof Software®). Each individual hoof print was divided by two lines into three equal regions: toe middle hoof and heel (Figure 1), and the following variables were determined for each region: peak vertical force, time to peak vertical force, which is the time at which the maximal vertical force occurred, expressed as a percentage of stance duration; vertical impulse, calculated by time integration of the force-time-curves; contact area, defined as the surface area of all loaded sensing elements; peak vertical pressure, defined as the pressure on the single sensing element that received the largest amount of load; contact pressure, defined as the total pressure encountered by the loaded sensing elements. The vertical force of the entire hoof, defined as the force measured by all sensing elements in Newton was calculated, then relative vertical force for every hoof region was expressed as a percentage of the entire vertical force. The initial ground contact and stance duration were documented.

## 2.4 | Data analysis

For each variable, data were first analysed by three-way analysis of covariance (ANCOVA) with repeated measures using the body weight as a covariate and assuming approximately normal distribution of the residuals. The side (left and right forelimb) and hoof regions (toe, middle and heel) were considered as fixed effects of

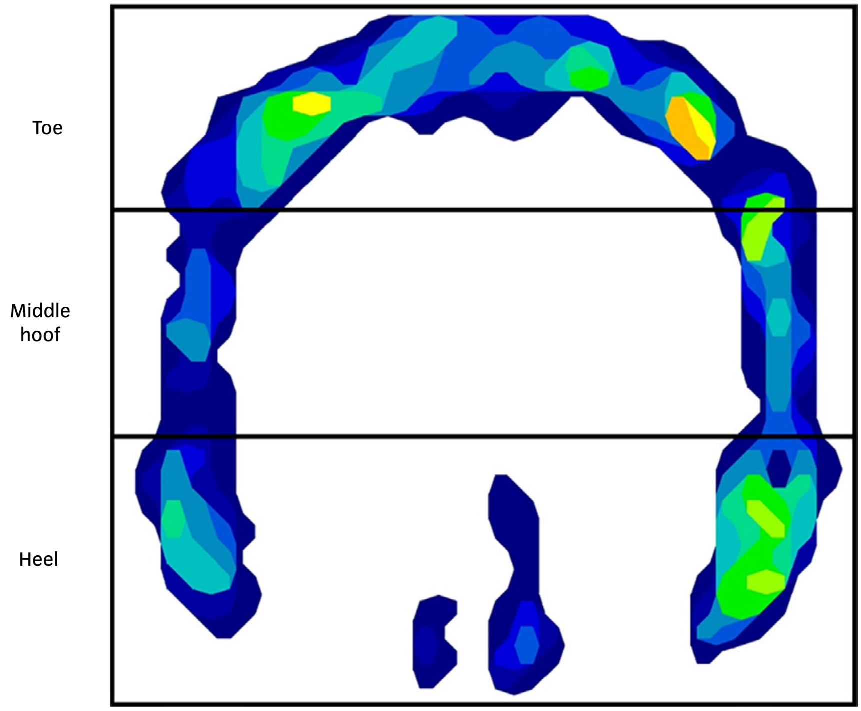


**FIGURE 1** Example of hoof print, divided by two lines into the three regions (toe, middle hoof and heel)

repeated measures. The third fixed factor was the group. Differences were considered as significant at $P < .05$.

There were no significant differences in any of the variables between the left and right forelimbs therefore, the measured variables for both limbs were pooled using the arithmetic mean over both sides. Then, a pairwise mean comparison for adjusted means was performed between the hoof regions within groups using the *t* test for dependent samples, incorporating the mean square error (MSE) of the ANCOVA and controlling the error probability by the method of Bonferroni-Holm. A pairwise group comparison for adjusted means was performed using the *t* test for independent samples with the same technique (MSE coming from ANCOVA, Bonferroni-Holm procedure). All computations used the statistical software package BMDP/Dynamic (BMDP Statistical Software Manual 1992: BMDP Release 8.1. University of California Press).

## 3 | RESULTS

### 3.1 | Horses

The control group included 16 horses (mean ± SD, range) body weight: 561 ± 64, 410-650 kg; age: 14.4 ± 4.8 years, 6-23 years; 11 Warmbloods, 2 Icelandic horses, 1 Irish horse, 1 Haflinger horse and 1 pony.

Group G1 included 17 client-owned horses: body weight: 445 ± 124, 200-600 kg; 14.4 ± 4.8, 6-23 years; 4 Icelandic horses, 3 ponies, 3 Warmbloods, 3 Arabian horses, 1 Quarter horse, 2 Fjord horses and 1 Irish horse. Two horses assigned Obel grade 1, 12 Obel grade 2 and 3 Obel grade 3. Twelve horses were readmitted to our Farriery Teaching School 6 weeks after discharge from the hospital and were then also included in group G2. Group G2 included 21 client-owned horses: body weight 476 ± 153 120-690 kg; age: 11 ± 4.1 5-18 years; 8 Warmbloods, 3 Icelandic horses, 3 ponies, 3 Arabian horses, 3 cold-blooded horses and 1 Haflinger horse. At a walk, 16 were sound and 5 had some degree of stiffness of gait. History, clinical and radiographic findings are listed in Tables S1, S2 and S3.

### 3.2 | Load distribution pattern between hoof regions

Kinetic data are presented in Table 1. In all groups, reflecting the stance phases, the longest time to peak vertical force was observed in the toe region ($P = .003$ for toe region vs middle hoof region and $P < .001$ for toe region vs heel region in all groups), and time to peak vertical force was still longer in the middle hoof region compared to the heel region ($P < .001$ in all groups). Furthermore, the toe region displayed the largest contact area in all groups ($P < .001$ for toe region vs middle hoof region and toe region vs heel region in all groups).The contact pressure was highest in the heel region in all groups.

In the control group, contact pressure in the heel region was higher than in middle hoof region ($P < .001$), but not significantly different from the toe region. The toe region displayed the highest values for relative vertical force (Figure 2, $P < .001$ for toe region vs middle hoof region and $P = .05$ for toe region vs heel region) and vertical impulse ($P = .008$ for toe region vs middle hoof region and toe region vs heel region). The middle hoof region showed the lowest loading in the control group, with the lowest values for relative vertical force, peak vertical force and peak vertical pressure ($P < .001$ for middle hoof region vs toe region and middle hoof region vs heel

**TABLE 1** Hoof™ System measurement data, displayed as adjusted mean ± standard error

| Group | Hoof region | Relative vertical force (%) | Peak vertical force (N) | Time to peak vertical force (% of stance duration) | Vertical impulse (N s) | Contact area ($cm^2$) | Peak vertical pressure ($N/cm^2$) | Contact pressure ($N/cm^2$) | Stance duration (s) |
|---|---|---|---|---|---|---|---|---|---|
| control group (n = 16) | toe region | $46 \pm 0.1^{b}$ | $188 \pm 23^{b}$ | $76 \pm 3^{b,c}$ | $823 \pm 70^{b,c}$ | $24.2 \pm 0.2^{b,c}$ | $209 \pm 17^{b}$ | $90 \pm 10^{b}$ | $0.75 \pm 0.08$ |
| | middle hoof region | $13 \pm 0.1^{a,c}$ | $112 \pm 23^{a,c}$ | $65 \pm 3^{a,c}$ | $198 \pm 70^{a,c}$ | $10 \pm 0.2^{a,c}$ | $117 \pm 17^{a,c}$ | $60 \pm 10^{a,c}$ | |
| | heel region | $41 \pm 0.1^{b}$ | $186 \pm 23^{b}$ | $48 \pm 3^{a,b}$ | $660 \pm 70^{a,b}$ | $18 \pm 0.2^{a,b}$ | $221 \pm 17^{b}$ | $102 \pm 10^{b}$ | |
| G1 (n = 17) | toe region | $29 \pm 0.1^{c,\#}$ | $203 \pm 23^{c}$ | $89 \pm 3^{b,c,\#}$ | $385 \pm 70^{c,\#}$ | $19 \pm 0.2^{b,c}$ | $192 \pm 16^{c}$ | $81 \pm 9^{c}$ | $0.74 \pm 0.12$ |
| | middle hoof region | $31 \pm 0.1^{c,\#}$ | $181 \pm 23^{c}$ | $65 \pm 3^{a,c}$ | $398 \pm 70^{c,\#}$ | $14 \pm 0.2^{a}$ | $194 \pm 16^{c,\#}$ | $86 \pm 9^{c}$ | |
| | heel region | $40 \pm 0.1^{a,b}$ | $252 \pm 23^{a,b}$ | $50 \pm 3^{a,b}$ | $766 \pm 70^{a,b}$ | $13.6 \pm 0.2^{a}$ | $254 \pm 16^{a,b}$ | $112 \pm 9^{a,b}$ | |
| G2 (n = 21) | toe region | $32 \pm 0.1^{\#}$ | $214 \pm 20^{c}$ | $85 \pm 2^{b,c,\#}$ | $331 \pm 61^{b,c,\#}$ | $22.2 \pm 0.1^{b,c}$ | $211 \pm 15^{b}$ | $85 \pm 8^{c}$ | $0.71 \pm 0.12$ |
| | middle hoof region | $29 \pm 0.1^{\#}$ | $204 \pm 20^{c}$ | $61 \pm 2^{a,c}$ | $467 \pm 61^{a,c,\#}$ | $16.7 \pm 0.1^{a}$ | $186 \pm 15^{a,c,\#}$ | $76 \pm 8^{c}$ | |
| | heel region | $39 \pm 0.1$ | $250 \pm 20^{a,b}$ | $48 \pm 2^{a,b}$ | $728 \pm 61^{a,b}$ | $16.2 \pm 0.1^{a}$ | $242 \pm 15^{b}$ | $98 \pm 8^{a,b}$ | |

*Notes*: Letters indicate significant differences between hoof regions within the same group; a indicates a significant difference compared to the toe region; b indicates a significant difference compared to the middle hoof region; c indicates a significant difference compared to the heel region ($P < .05$). Hash marks indicate a significant difference compared to the same hoof region in the control group ($P < .05$).

region, for all parameters) and vertical impulse ($P = .008$ for middle hoof region vs toe region and $P < .001$ for middle hoof region vs heel region) recorded in the middle hoof region.

In the laminitic horses, contact pressure in the heel region was significantly higher compared to both the middle hoof region (G1: $P = .0002$; G2: $P < .001$) and the toe region (G1: $P < .001$; G2: $P = .04$). The heel region had the highest values for relative vertical force (Figure 2, $P = .01$ for heel region vs middle hoof region and heel region vs toe region in G1), peak vertical force ($P < .001$ for heel region vs middle hoof region and heel region vs toe region in G1; $P = .006$ for heel region vs. middle hoof region and heel region vs toe region in G2), vertical impulse ($P < .001$ for heel region vs middle hoof region and heel region vs toe region in G1 and G2) and peak vertical pressure ($P < .001$ for heel region vs middle hoof region and heel region vs toe region in G1; $P = .003$ for heel region vs middle hoof region in G2). The middle hoof region demonstrated the lowest peak vertical force ($P = .05$ for middle hoof region vs toe region and $P < .001$ for middle hoof region vs heel region in G1; $P = .006$ for middle hoof region vs heel region in G2) and peak vertical pressure ($P < .001$ for middle hoof region vs heel region in G1; $P = .02$ for middle hoof region vs toe region and $P = .003$ for middle hoof region vs heel region in G2). Vertical impulse in the middle hoof region was higher than in the toe region ($P = .008$ in G2), while still lower than in the heel region ($P < .001$ in both groups).

## 3.3 | Load distribution in laminitic vs control group

No significant differences were found when comparing the data between G1 and G2, indicating that the load distribution pattern does not change rapidly during early rehabilitation from acute laminitis. However, laminitic horses showed different load distribution patterns as compared to the control group. In the toe region, the relative vertical force and vertical impulse were significantly lower in the laminitis groups than in the control group (G1: $P = .001$ and $P = .002$ respectively; G2: $P = .003$ and $P = .002$ respectively), whereas in the middle hoof region, relative vertical force, vertical impulse and peak vertical pressure were significantly higher in the laminitis groups 1 and 2 than in the control group (G1: $P = .003$, $P = .002$ and $P = .005$ respectively; G2: $P = .005$, $P = .003$ and $P = .0001$ respectively) (Table 1 and Figure 2).

Stance duration was similar in all groups (Table 1). However, laminitic horses showed a different pattern of the load distribution between hoof regions over the time of stance duration (Figure 3). Considering the landing phase, in the control group, 10 of 16 horses showed a flat-foot contact, 3 out of 16 a heel-first, 3 out of 16 lateral-wall-first, whereas in group G1, all horses showed a heel-first contact. Similarly, in group G2, 17 of 21 horses showed a heel-first contact, while 4 of 21 horses showed a lateral-wall-first contact. Furthermore, the peak loading of the toe region occurred during different stance phases in laminitic horses and control group. In the control group, peak loading in the toe region occurred during midstance, but during break-over (from heel-off to toe-off) in laminitic

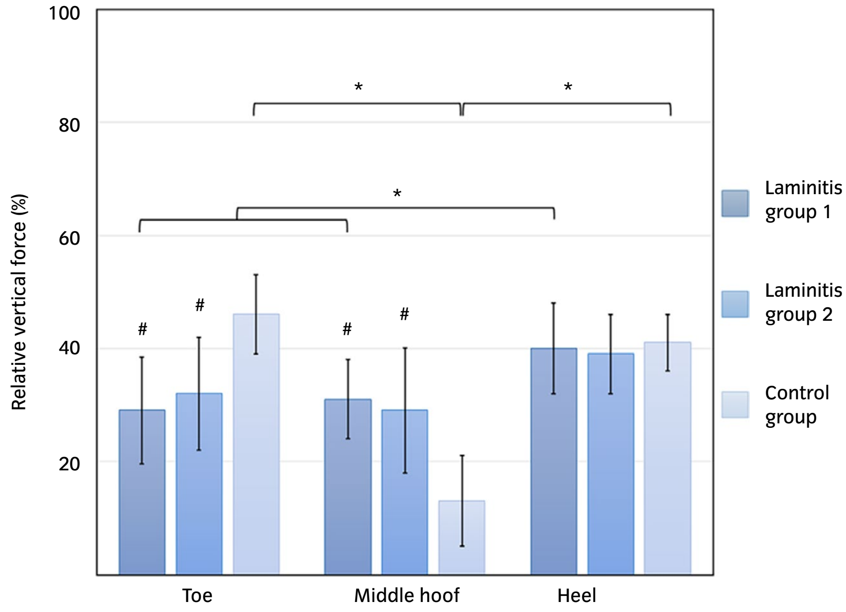


**FIGURE 2** Mean relative vertical force in the different hoof regions in laminitic (groups 1 and 2) and sound horses (control group). Error bars display the SD; stars indicate significant differences between hoof regions within the same group; hash marks indicate significant differences compared the same hoof region in the control group ($P < .05$)

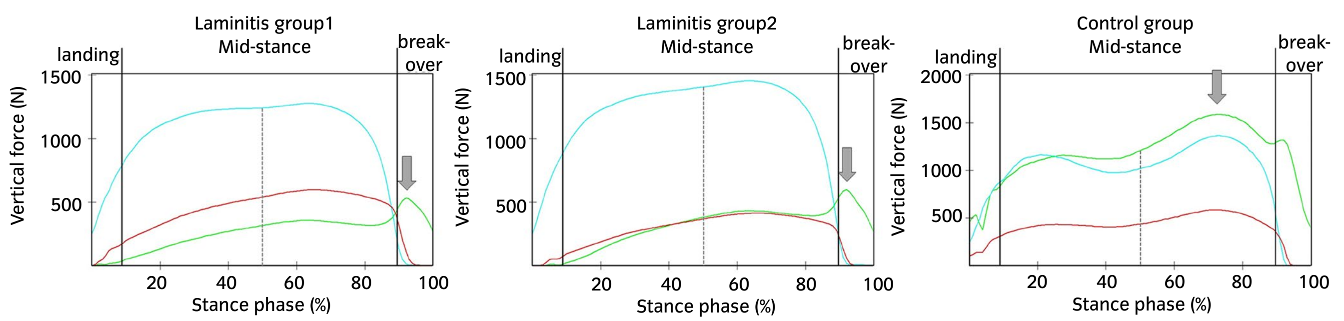


**FIGURE 3** Representative force-time-curves of the three hoof regions in all groups during stance phase. The hoof regions are colour-coded with the toe region in green, the middle hoof region in red and the heel region in sky blue. The arrows indicate peak loading in the toe region

horses in both groups. This is reflected by the time to peak vertical force in the toe region, which was significantly higher in groups G1 and G2 compared with the control group ($P = .002$ and $P < .001$ respectively) (Table 1).

## 4 | DISCUSSION

This study of kinetic measurements of load distribution in laminitic hooves confirmed the long-existing subjective observation that horses suffering from laminitis alter their gait to shift the load from the toe to other hoof regions. However, in contrast to widespread opinion, the current study demonstrated that there is no significant increase in the loading parameters (relative vertical force and vertical impulse) in the heel region in laminitic horses compared to the control group. The shift in the loading parameters occurred mainly between the toe region and the middle hoof region; a significant decrease in relative vertical force and vertical impulse in the toe region with a concurrent increase in relative vertical force and vertical impulse in the middle hoof region in laminitic horses compared to the control group was observed. However, in laminitic horses, relative vertical force and vertical impulse were higher in the heel region than in other regions, while in the control group, relative vertical force and vertical impulse were the highest in the toe region. These results agree with the findings in standing horses with severe laminitis,[8] which showed that the percentage of vertical force under the heel and toe was 61% and 39% respectively. Similarly, in obese ponies, which may be suffering from subclinical stages of laminitis, the load in the heel region was higher than that in the toe region.[13] The toe region is the most painful in horses with laminitis; hence, these horses try to relieve the pain in the toe by shifting the load to the palmar, a less painful area of the foot, explaining the change of load distribution observed in our study. Thus, supporting the middle hoof and heel regions is strongly recommended when considering supportive therapy for laminitic horses.

In the current study, a heel-first contact was observed in most laminitic horses (89%). The time to peak vertical force in the toe region in horses with laminitis was higher than that in the control group (Figure 3). Moreover the maximal loading of the toe region in laminitic horses occurred during the break-over phase. This is a very important result that should be considered when using therapeutic shoes for horses with laminitis. This can be explained by the fact that laminitic horses try to relieve the painful toe region during the whole stance phase but are compelled to load the toe region during break-over, which only occurs in the toe region. Accordingly, procedures to ease break-over are likely to relieve pain and reduce the load on the damaged lamellae in the toe region.

In contrast to the results of the previous study in standing horses[12] demonstrating an even distribution of force between the toe and heel regions in sound unshod horses, we observed a higher load in the toe region compared to other hoof regions. In our study, the measurements were performed at walk, while in the previous study,[12] the measurements were performed under static conditions. This might explain the difference in the distribution pattern of forces in these two studies, as the gait can change the distribution of forces.[14] Our finding is in agreement with two previous studies that indicated greater load in the cranial half of the hoof while walking in unshod horses[8] and higher peak vertical force in the cranial half of the hoof than in the caudal half in sound shod horses.[15]

Although no significant differences were found between the laminitic groups, our data suggested differences associated with recovery. In group 2, in which the horses had been free of acute laminitis symptoms for 6-12 weeks, the time to peak vertical force in the toe region decreased by approximately 4% compared to group 1, and there was an increase of approximately 3% in the relative vertical force in the toe region in group 2 compared to group 1. This supports the hypothesis that as healing progresses, there will be more load in the toe region.

In our study, we divided the hoof prints in three regions. In a previous study,[10] the hoof print was also divided into three regions (toe, quarters and the heel), while in another study,[16] the hoof print was divided into toe and heel regions by a line through the maximal hoof width was performed. The rationale behind the current hoof print division strategy was to get more detailed information about the load distribution within the hoof in horses suffering from laminitis and in sound horses.

The main limitation of this study is that no measurements were performed in horses with acute laminitis on admission. Although data obtained during the acute phase would be valuable, this was not attempted as any exercise that causes loading on the weakened lamella during the acute phase causes further damage and is contraindicated.[17] Another limitation is the variance of weight within and between groups 1 and 2. Thus, direct comparison with absolute values of vertical force between groups was not possible. Laminitis is not a very common disease; hence, we had to enrol horses of different sizes in this study. However, the effect of the different body weight was statistically eliminated by regarding this variable as a covariate in the ANCOVA.

In conclusion, the peak loading in the toe region in laminitic horses occurred during break-over phase. Moreover the main shift of the load within the hooves of laminitic horses occurred between the toe and middle hoof regions, with no significant change of the load in the heel region compared to control group. Based on our results, supportive therapy for laminitic horses should focus on supporting both the middle and caudal hoof areas, including frog and heels, to distribute the load on the middle hoof and heel regions across a larger area, which would decrease the peak pressure acting on these areas. In addition, easing break-over could minimise the load on the damaged lamellae in the toe region.

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## CONFLICT OF INTERESTS

No competing interests have been declared.

## AUTHOR CONTRIBUTIONS

All authors have 1) made substantial contributions to conception and design of, or acquisition of data or analysis and interpretation of data, 2) contributed to drafting the article or revising it critically for important intellectual content, 3) approved of the submitted version of the manuscript.

## ETHICAL ANIMAL RESEARCH

The Ethics Committee of the regional authority in Hesse did not consider the study as an animal experiment (reference number 54 – 19 c 20 15 h 02 GI 18/13 kTV 10/2018).

## OWNER INFORMED CONSENT

Owners gave their informed consent for their horses to be included in the study.

## DATA ACCESSIBILITY STATEMENT

The data that support the findings of this study are available from the corresponding author upon reasonable request.

## PEER REVIEW

The peer review history for this article is available at https://publons.com/publon/10.1111/evj.13311.

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## SUPPORTING INFORMATION

Additional supporting information may be found online in the Supporting Information section.


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