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Stance phase kinematics and kinetics of horses trotting over poles

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Summary

Reason for performing study: Trotting over poles is frequently used therapeutically to restore swing phase ranges of joint motion. It is not known whether ground reaction forces (GRFs) increase as the swing phase limbs are lifted higher to clear the poles. Higher GRFs might be painful or jeopardise healing of musculoskeletal injuries.
Objectives: To measure stance phase kinematics and GRFs in the forelimbs and hindlimbs of horses trotting on level ground, over low poles and over high poles, and to test the hypothesis that trotting over poles is associated with increases in peak GRFs and impulses in the supporting hindlimb and forelimb compared with trotting over level ground.
Study design: Repeated measures experimental study on horses with normal gait.
Methods: Kinematic and GRF data were collected from 8 horses trotting on level ground under 3 conditions performed in random order: no poles, low (11 cm) poles and high (20 cm) poles spaced 1.05 ± 0.05 m apart. Spatiotemporal and angular kinematic variables and GRFs were measured during stance. Comparisons among conditions were made using repeated measures ANOVA ($P<0.05$) with Bonferroni correction for *post hoc* testing.
Results: The only GRF component that increased when trotting over poles was peak forelimb braking GRF. Forelimb vertical and braking impulses increased and the transverse impulse changed from medially to laterally directed. Extension of the metatarsophalangeal and metacarpophalangeal joints did not change.
Conclusions: The fact that peak vertical forces and extension of the metatarsophalangeal and metacarpophalangeal joints did not increase when trotting over poles suggests that loading of the musculoskeletal tissues is comparable with that associated with trotting on level ground in horses with symmetrical movement at trot. The findings support the use of trot poles during rehabilitation from lameness in horses that move symmetrically. The generation of laterally directed forelimb transverse forces suggests that trotting over poles may recruit the forelimb adductor musculature.

Keywords: horse; trot poles; ground reaction force; physical therapy; rehabilitation

Introduction

Stepping over an obstacle is a complex motor skill. It requires visual perception of the position and size of the obstacle, an intact neuromotor control system to make decisions and relay commands to the peripheral nervous system, and an appropriate muscular response to ensure obstacle clearance by the limbs during their swing phase. At the same time the stance limbs are responsible for maintaining balance and stability in an energy efficient manner during the perturbation caused by stepping over the obstacle. Forelimb and hindlimb ground reaction forces (GRFs) must be coordinated to ensure a stable platform of support, maintain balance and control the body's angular momentum [1]. Poles placed on the ground or raised above the ground are used in equine training, conditioning and rehabilitation programmes. In the context of rehabilitation, poles are thought to be beneficial for training proprioceptive skills [2], improving or restoring ranges of joint motion [3], and strengthening the propulsive muscles [3,4].

Stance phase kinematic and kinetic variables have been studied quite extensively in horses trotting over level ground at constant speed [5–8] but do not appear to have been reported in horses trotting over a series of poles. The aim of this study was to measure stance phase kinematics and GRFs of horses trotting over no poles or a series of poles of 2 different heights. The objectives were to describe how the diagonal limb pair supports the bodyweight and facilitates swing limb clearance of the poles. This information is important in predicting the benefits and assessing the potential risks of using poles therapeutically to strengthen the locomotor musculature during rehabilitation from lameness. Since the forces that may reinjure damaged tissues are much larger during the stance phase than in the swing phase, it is important to assess the risk of overloading musculoskeletal structures in the supporting limbs. Peak vertical force has the highest sensitivity and specificity for lameness detection [9] and is the variable that is managed in lame horses [10–12]. During rehabilitation peak vertical force should be controlled to avoid causing pain in or damage to tissues that may not have recovered their full strength. The purpose of this study was to evaluate whether the GRFs associated with lifting the swing phase limbs clear of the poles were associated with increases in GRFs or impulses. The experimental hypothesis was that peak forces and impulses in the forelimbs and hindlimbs increase when trotting over low or high poles compared with trotting over level ground without poles.

Materials and methods

The horses and methodology have been described previously [13].

Horses

Eight horses (mean ± s.d. age: 15 ± 5.2 years; weight: 444.3 ± 51.5 kg; height: 142.3 ± 5.0 cm) assessed as having lameness *grade <1* on a 5 point grading scale when trotting in a straight line were trained to trot over poles on the ground and raised poles with a consistent rhythm and speed. They were prepared for gait analysis by attaching of 41 reflective markers over anatomical landmarks on the head, neck, trunk and limbs [13]. Lateral view radiographs taken with the hoof markers in place were used to determine the angle of the third phalanx and the location of the distal interphalangeal joint centre of rotation from the external markers.

Obstacles

Five wooden poles (1.2 m long, 10 cm cross-section) were placed at 1.05 ± 0.05 m intervals with small adjustments to accommodate the individual horses' stride lengths. They were oriented perpendicular to the long axes of a series of 4 force plates, with the first pole preceding the first force plate. A 1 cm spacer (low poles) or a 10 cm block (high poles) was placed under each end of the poles. Horses were evaluated at trot under 3 conditions performed in random order: no poles, low (11 cm) poles and high (20 cm) poles.

Data collection

Kinematic (120 Hz) and GRF (960 Hz) data were collected synchronously. A 10 camera (Eagle cameras)[a] motion analysis system[a] collected kinematic data from a calibrated volume measuring 5 × 3 × 1.5 m (linear measurement error: 0.54 mm/500 mm). GRF data were collected using 4 force plates in series, the first and last plates (FP60120 Force Plate)[b] measuring 60 × 120 cm and the middle 2 plates (FP6090 Force Plate)[b]

TABLE 1: Ground reaction forces (GRFs), impulses and time of peak GRFs for horse trotting over no poles, low poles and high poles. Values are mean (s.d.)

	Forelimb			Hindlimb		
Variable	No poles	Low poles	High poles	No poles	Low poles	High poles
Vertical GRF						
Peak vertical GRF (N/kg)	1.05 (0.07)	1.05 (0.06)	1.06 (0.08)	0.90 (0.08)	0.92 (0.07)	0.93 (0.07)
Time of peak vertical GRF (% stance)	47.14^{a} (2.18)	49.56^{b} (3.40)	51.92^{c} (5.22)	48.11 (2.20)	49.39 (1.83)	48.56 (3.01)
Vertical impulse (N·s)	62.55^{a} (3.15)	65.85^{b} (3.24)	68.08^{c} (4.36)	52.32 (5.54)	54.51 (4.77)	55.56 (4.93)
Longitudinal GRF						
Peak braking GRF (N/kg)	-0.10^{a} (0.02)	-0.12^{b} (0.02)	-0.12^{b} (0.02)	-0.06 (0.01)	-0.06 (0.02)	-0.06 (0.02)
Time of minimal braking GRF (% stance)	25.61^{a} (4.54)	28.75^{b} (3.75)	27.72^{b} (5.36)	24.17 (1.50)	25.78 (1.70)	25.33 (1.85)
Braking impulse (N·s)	-3.69^{a} (0.67)	-4.35^{b} (1.06)	-4.38^{b} (1.15)	-1.81^{a} (0.48)	-1.52^{b} (0.56)	-1.35^{b} (0.53)
Peak propulsive GRF (N/kg)	0.08 (0.01)	0.08 (0.02)	0.08 (0.02)	0.11 (0.02)	0.10 (0.02)	0.11 (0.01)
Time of peak propulsive GRF (% stance)	75.33^{a} (2.69)	79.42^{b} (3.15)	80.67^{c} (2.55)	70.53 (2.53)	71.44 (1.68)	71.47 (3.13)
Propulsive impulse (N·s)	2.27 (0.38)	2.13 (0.60)	2.13 (0.57)	3.32 (0.59)	3.48 (0.56)	3.74 (0.73)
Total longitudinal Impulse (N·s)	-1.42^{a} (0.97)	-2.22^{b} (1.61)	-2.26^{b} (1.68)	1.51^{a} (0.74)	1.96^{a} (0.95)	2.39^{b} (1.04)
Transverse GRF						
Peak medial GRF (N/kg)	-0.017^{a} (0.009)	-0.009^{b} (0.007)	-0.009^{b} (0.008)	-0.020 (0.010)	-0.019 (0.013)	-0.024 (0.014)
Time of peak medial GRF (% stance)	31.00 (19.99)	35.92 (21.93)	43.33 (25.49)	28.36 (21.10)	38.94 (25.55)	32.31 (21.47)
Medial impulse (N·s)	-0.58^{a} (0.37)	-0.25^{b} (0.25)	-0.29^{b} (0.34)	-0.62 (0.50)	-0.61 (0.58)	-0.88 (0.75)
Peak lateral GRF (N/kg)	0.013^{a} (0.005)	0.017^{a} (0.012)	0.024^{b} (0.014)	0.018 (0.013)	0.021 (0.014)	0.020 (0.014)
Time of peak lateral GRF (% stance)	25.28 (19.46)	29.03 (12.17)	33.22 (26.30)	42.11 (18.79)	34.75 (16.47)	37.39 (20.52)
Lateral impulse (N·s)	0.27^{a} (0.27)	0.67^{b} (0.76)	1.04^{c} (0.98)	0.53 (0.52)	0.81 (0.66)	0.84 (0.91)
Total transverse impulse (N·s)	-0.31^{a} (0.56)	0.42^{b} (0.93)	0.75^{b} (1.18)	-0.10 (0.94)	0.19 (1.11)	-0.042 (1.58)

Different superscripts indicate significant differences between conditions ($P<0.05$).

measuring 60 × 90 cm. Each force plate had a 16-bit digital internal amplifier (AM6800 Amplifier)[b] with embedded calibration information to reduce cross-talk between channels. Force data were transmitted via an analogue amplifier into a DAQ board (SCB-100)[c].

Trials were retained when the horse approached and moved through the data collection volume at a consistent speed and rhythm and stepped cleanly over the poles when they were present. For each condition (no poles, low poles, high poles), 6 trotting trials were saved.

Data analysis

For each condition, the first 3 trials that met the criteria of consistent speed, clean force plate contacts and with the line of motion along the longitudinal force plate axis were analysed further. Force data were filtered using a lowpass Butterworth filter with 40 Hz cutoff frequency. One full stride per trial was analysed, starting with the step in which one diagonal pair of hooves contacted the first and second force plates as the swing phase forelimb stepped over the second and third poles and the swing phase hindlimb stepped over the first and second poles in the series.

Ground reaction force data were resolved into vertical, longitudinal (braking, propulsive) and transverse (medial, lateral) components. For each component, peak values and impulses were determined. Vertical force ≥50 N was used to determine stance duration, and data for each stance phase were time normalised to 101 points. Stance phase kinematic data were filtered using a fourth-order, lowpass Butterworth filter with 12 Hz cutoff frequency and analysed using proprietary (Cortex 1.1.4.368 software)[a] and custom (Matlab)[d] software. Values were averaged over the left and right limbs or left and right diagonals.

Correction algorithms for skin displacement [14] were applied to markers overlying the femur, scapula and humerus. The marker on T6 was used to calculate average trotting speed during the trial. Limb joint angles were measured on the anatomical flexor aspect.

Vertical excursions of the markers on T6 (withers) and S2 (croup) during the stance phase were measured. Distances along lines drawn from the T6 and S2 markers to the respective distal hoof markers represented limb length; stance phase shortening of the limbs was calculated as the difference in limb length from contact to its shortest length during stance.

Descriptive statistics (mean, s.d.) were calculated and the Shapiro-Wilk test showed that all variables were normally distributed. A repeated measures ANOVA was performed to investigate the effect of the 3 trotting conditions on measured parameters. In case of significance, pairwise tests with Bonferroni correction for multiple testing were performed.

Results

Ground reaction forces

In the hindlimbs neither peak vertical GRF nor vertical impulse changed significantly when trotting over poles (Table 1, Fig 1). In the forelimbs, although peak vertical GRF did not change, the force peak occurred significantly later in stance (no poles: 47.14 ± 2.18%; low poles: 49.56 ± 3.40%; high poles: 51.92 ± 5.22%) and vertical impulse increased significantly (Table 1), which appeared to be a consequence of maintaining a higher vertical force during the second half of stance (Fig 1).

With regard to the longitudinal GRF variables, the braking (negative) impulse decreased significantly in the hindlimbs and increased significantly in the forelimbs when trotting over poles (Table 1, Fig 1). In the forelimbs, this was associated with a significant increase in peak braking force, a significant delay in time of occurrence of the longitudinal (braking and propulsive) force peaks, and a significantly later transition from braking to propulsion when trotting over poles (Table 1, Fig 1).

The transverse GRF variables did not change significantly in the hindlimbs but showed consistent changes in the forelimbs. After a laterally directed impact spike, the forelimb transverse force was directed medially through most of stance when trotting on level ground, but when trotting over poles it was laterally directed throughout stance. Total forelimb transverse impulse changed from being medially directed on level ground to being laterally directed when trotting over poles (Table 1, Fig 1).

Kinematics

Forelimb stance duration did not change, but hindlimb stance was significantly shorter when trotting over poles, with a delay in hind hoof contact that resulted in a large and significant increase in front-first diagonal dissociation (Table 2). Neither vertical excursion range of the

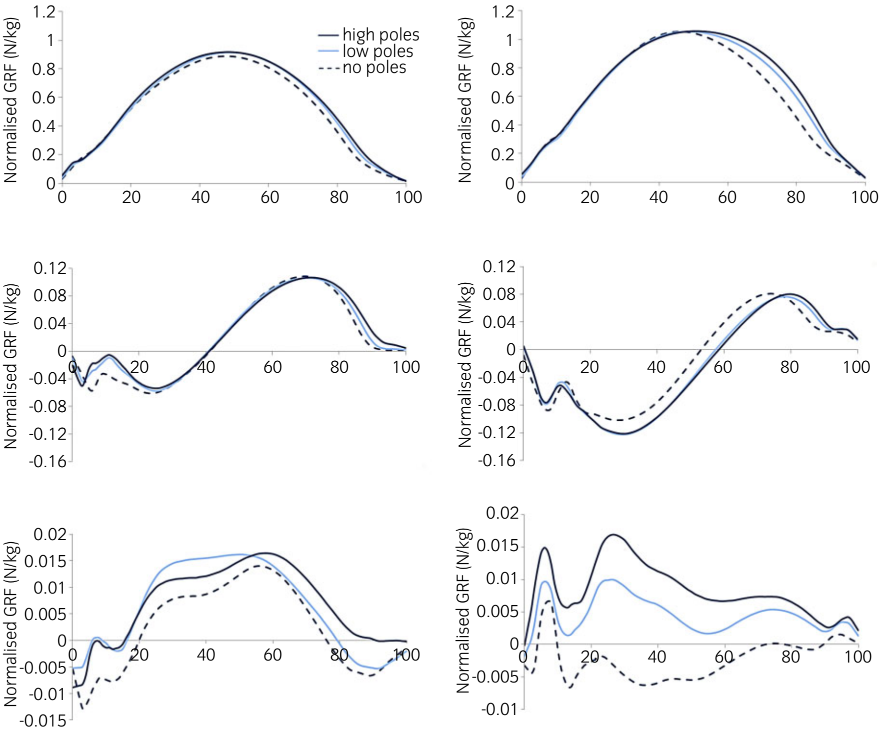

Fig 1: Average ground reaction forces (GRFs) for the hindlimbs (left panel) and the forelimbs (right panel) of horses (n = 8) trotting on level ground over no poles (dark dashed lines), low poles (light continuous lines) and high poles (dark continuous lines).

withers nor stance phase shortening of the forelimb changed when trotting over poles (Table 2). Vertical excursion of the croup increased significantly when trotting over poles as a consequence of greater shortening of the hindlimb in midstance. This was associated with increased flexion of the stifle and tarsal joints (Table 3, Fig 2) and it imparted a bouncing motion to the hind quarters. Notably, peak extension of the metatarsophalangeal (MTP) and metacarpophalangeal (MCP) joints did not increase when trotting over poles.

Discussion

With regard to peak GRF values, the experimental hypotheses were not supported, although there was a delay in time of the peak vertical GRF in the forelimbs. Braking impulse decreased in the hindlimbs and in the forelimbs there were increases in the vertical, braking and lateral impulses, which partially supported the experimental hypotheses. The increase in forelimb vertical impulse was associated with the delay in reaching the vertical GRF peak. The prolongation of the high vertical force acted to maintain the withers in a higher position, stabilise lateral movements of the trunk in the face of perturbations due to stepping over the poles, and counteract the effect of the increase in forelimb braking longitudinal impulse, which tends to increase nose-down torque around the horse's centre of mass [1]. Thus, the delay in peak forelimb vertical GRF when trotting over poles may represent a mechanism similar to that used by dogs, in which vertical forces exerted by the forelimb and hindlimb resist pitching moments created by the longitudinal accelerating/decelerating forces [15].

Stepping over an obstacle is a complex motor task requiring finely tuned coordination between the limbs even in bipeds [16]. In quadrupeds, interlimb coordination is considerably more challenging. The basic locomotor rhythm and coordination are mediated at spinal level by central pattern generators; these coupled neural oscillators control the rhythmic joint flexions and extensions without the need for proprioceptive

TABLE 2: Mean (s.d.) for spatiotemporal gait variable for horses trotting in hand over no poles, low poles and high poles

Variable	No poles	Low poles	High poles
Trotting speed (m/s)	3.03^{a} (0.20)	2.91^{b} (0.17)	2.87^{c} (0.22)
Forelimb stance duration (s)	0.32 (0.02)	0.32 (0.03)	0.32 (0.03)
Hindlimb stance duration (s)	0.28^{a} (0.03)	0.27^{b} (0.03)	0.26^{b} (0.03)
Diagonal dissociation (s)	-0.01^{a} (0.01)	-0.02^{b} (0.01)	-0.02^{b} (0.01)
Stance phase shortening of forelimb (cm)	5.00 (0.49)	5.29 (0.56)	5.61 (1.12)
Stance phase shortening of hindlimb (cm)	5.08^{a} (0.70)	6.52^{b} (0.70)	6.65^{b} (1.18)
Stance phase excursion of withers (cm)	5.36 (0.61)	5.33 (0.79)	5.66 (1.72)
Stance phase excursion of croup (cm)	5.89^{a} (0.82)	7.28^{b} (0.86)	7.40^{b} (1.40)

Different superscripts indicate significant differences between conditions (P<0.05).

TABLE 3: Peak joint angles measured on the anatomical flexor aspect of the joints during the stance phase in horses trotting in hand over no poles, low poles and high poles. Values are mean (s.d.)

Stance phase variables (°)	No poles	Low poles	High poles
Hindlimb			
Minimal hip angle	90.39^{a} (4.46)	92.15^{b} (4.34)	92.04^{b} (4.04)
Minimal stifle angle	150.65^{a} (6.29)	148.70 (6.41)	147.09^{b} (5.20)
Minimal tarsal angle	148.86^{a} (3.92)	148.22 (4.51)	147.35^{b} (5.18)
Maximal MTP angle	235.87 (8.06)	237.34 (7.91)	236.43 (7.88)
Minimal hind DIP angle	147.91 (11.93)	148.38 (12.11)	148.39 (12.92)
Forelimb			
Minimal shoulder angle	111.16 (4.86)	110.96 (4.17)	110.55 (5.14)
Minimal elbow angle	126.96 (4.94)	127.57 (3.88)	127.90 (3.59)
Maximal carpal angle	185.89 (2.37)	186.08 (2.74)	185.73 (2.64)
Maximal MCP angle	237.73 (10.72)	237.71 (11.48)	238.04 (10.63)
Minimal fore DIP angle	167.93 (39.03)	159.21 (35.81)	157.85 (35.35)

Different superscripts indicate significant differences between conditions (P<0.05). DIP = distal interphalangeal; MCP = metacarpophalangeal; MTP = metatarsophalangeal.

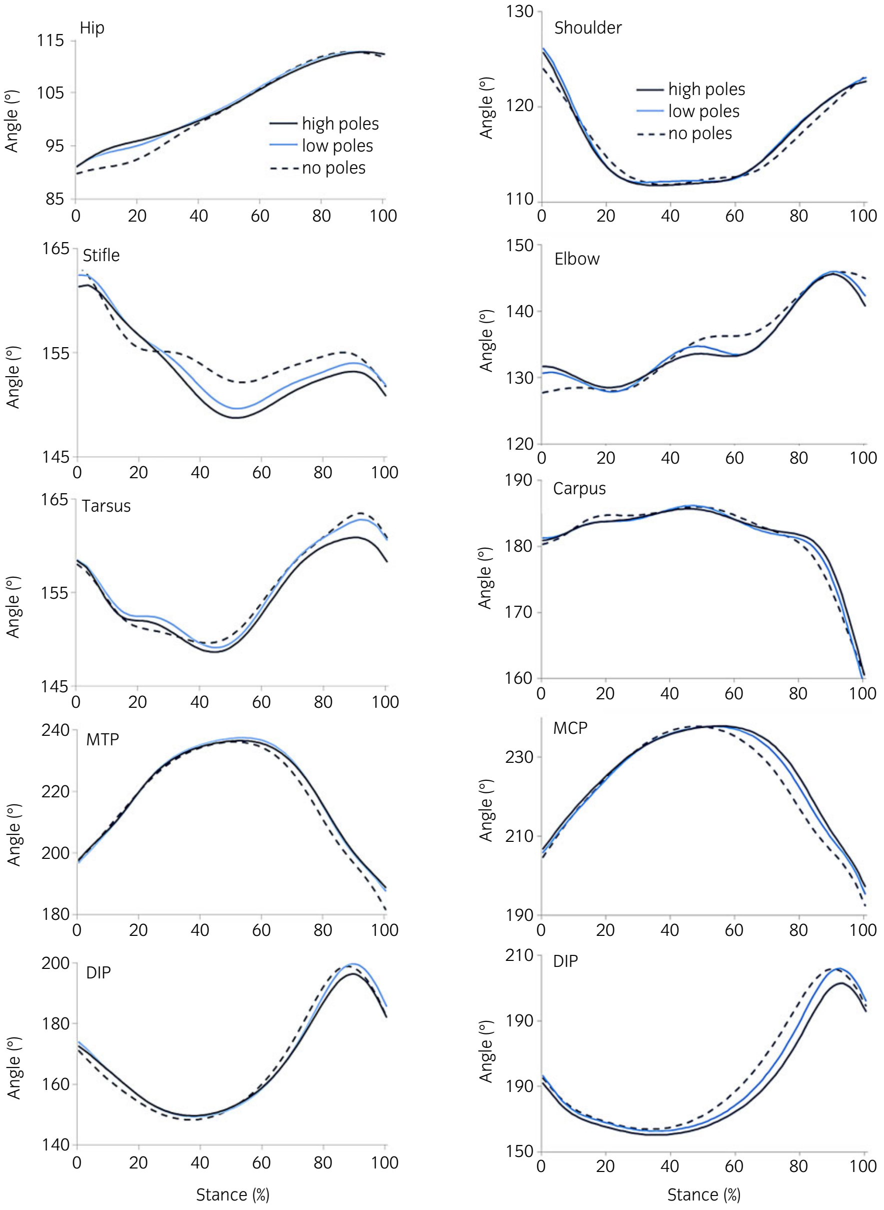

Fig 2: Average joint angle-time curves during the stance phase for the joints of the hindlimbs (left panel; top to bottom: hip, stifle, tarsus, metatarsophalangeal [MTP] and distal interphalangeal [DIP] joints) and the joints of the forelimbs (right panel; top to bottom: shoulder, elbow, carpus, metacarpophalangeal [MCP] and DIP joints) in 8 horses trotting on level ground over no poles (dark dashed lines), low poles (light continuous lines) and high poles (dark continuous lines).

feedback [17]. However, their action can be modified in response to proprioceptive information describing the interaction between the musculoskeletal system and the external environment or visual information that requires a locomotor response. When an obstacle is perceived in the line of travel, the swing phase trajectory of the limbs is modified by changing muscular activity in response to signals from the motor cortex that descend in the corticospinal tracts to the central pattern generators [18]. At the same time, neurons in the brainstem reticular formation ensure that the stance limbs provide an appropriate base of support to maintain balance in the face of perturbations associated with obstacle avoidance, such as the exaggerated movements of the swing limbs as they step over the poles [18]. In addition, the visuomotor system is responsible for placing the feet precisely to avoid stepping on the obstacles. Thus, the therapeutic effects of trotting over poles are likely to include improvements in the horse's balance, stability and precision of movement.

One of the concerns in using trot poles during rehabilitation from musculoskeletal injury is the possibility of overloading compromised tissues during the repair process. Lame horses reduce structural stress in the painful limb by several mechanisms that have the effect of reducing peak vertical force and rate of limb loading [9,11,12]. If a lame horse is forced to maintain trotting speed, stride frequency and relative stance duration increase [19], which spreads the impulse over a longer stance period and allows the necessary impulse to be achieved with a lower peak vertical force. Lame horses also reduce or eliminate the suspension phase that follows lame limb stance; without a suspension phase there is a reduced requirement for upward propulsion, which allows a decrease in vertical force and impulse in this limb [10,19]. As the severity of lameness increases, the functions of load bearing and generation of propulsion are redistributed from the affected limb to the compensating limbs [11,12]. Therefore, lame horses simultaneously reduce peak vertical force in the lame fore- or hindlimb and maintain the total vertical impulse summed over all 4 limbs by redistributing the impulse between limbs, by generating a force of smaller magnitude during a longer period of time and by reducing the suspension phase [10,11,19]. The fact that peak vertical force did not increase in any limb suggests that trotting over poles at the height and speed used in this study is unlikely to overload the musculoskeletal tissues in the limbs compared with trotting on the level over the same surface. It should be noted that trotting speed was slower for pole conditions as a consequence of the extra time required to raise the limbs clear of the poles. In man, stride duration increases linearly with obstacle height [20].

It is not recommended that trot poles be introduced into a lameness rehabilitation programme until the horse appears to move symmetrically on level ground, since an existing asymmetry in load distribution may be exaggerated by the use of trot poles. Furthermore, the fact that extension of the MTP and MCP joints did not change when trotting over poles is in accordance with the fact that peak vertical GRF did not change [21] and suggests that trotting over poles is unlikely to cause excessive strain of the soft tissues that support the distal limb. By comparison, faster trotting speeds are associated with an increase in peak vertical force in the forelimbs [7] with a consequent increase in MCP extension [21], suggesting that faster trotting speeds are not appropriate in rehabilitating distal forelimb injuries. When trotting on an uphill gradient there is an increase in peak vertical force in the hindlimbs [7] together with an increase in maximal extension of the MTP joint [22]. Therefore, the use of uphill gradients is contraindicated for rehabilitation of distal hindlimb injuries.

The transverse GRF vector at trot is normally small in magnitude and, when trotting over level ground, is directed laterally in the hindlimbs and medially in the forelimbs through most of stance. This means that the hoof pushes against the ground with a medially directed force vector and the GRF, which acts in the opposite direction, points somewhat laterally. When the limbs develop forces orthogonal to the direction of motion, gait stabilisation is enhanced in the face of potential locomotor perturbations [23]. Thus, the fact that forelimb transverse GRF and impulse change from being medially directed to being laterally directed when trotting over poles may be a mechanism for increasing lateral stability when the gait is perturbed by the increased elevation of the swing limbs. A laterally directed reaction force would be developed by tension in the adductor muscles, such as the pectoral muscles. Therefore, we speculate that trotting over poles is likely to recruit the forelimb adductor musculature.

Elastic energy storage and release has a large effect on locomotor economy, with the hindlimb contributing about two-thirds and the forelimb contributing about one-third to overall elastic energy storage during trotting [24]. The hindlimb's greater capacity for storage and release of elastic energy may explain the increased vertical excursions of the croup and the associated increases in flexion of the stifle and tarsal joints during stance when trotting over poles.

In conclusion, the fact that peak GRF values do not increase when horses trot over poles supports their use as a safe method for restoring range of motion and muscular strength during rehabilitation in horses with a symmetrical gait at trot. The incorporation of trot poles in a rehabilitation programme is expected to increase ranges of motion of all joints of the forelimbs and hindlimbs in the swing phase [13]. The current study indicates that trot poles also have value for strengthening the musculature that supports the joints during stance, especially the forelimb extensor (propulsive) muscles and the forelimb adductors that maintain elevation of the withers when trotting over poles.

Authors' declaration of interests

None of the authors of this paper has a financial or personal relationship with other people or organisations that could inappropriately influence or bias the content of this paper.

Ethical animal research

The study was performed with approval from the institutional animal care and use committee under protocol number 02/08–020-00.

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Authorship

All authors have contributed to study design, study execution, data analysis/interpretation and preparation of the manuscript.

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[c]National Instruments Corporation, Austin, Texas, USA.
[d]MathWorks, Natick, Massachusetts, USA.

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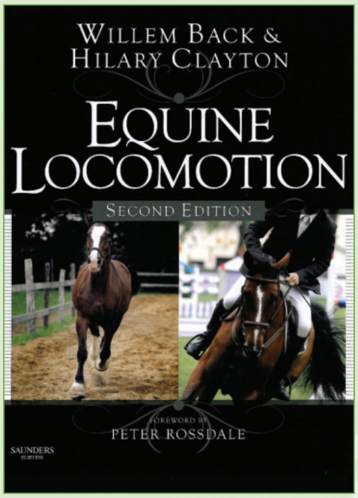

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