

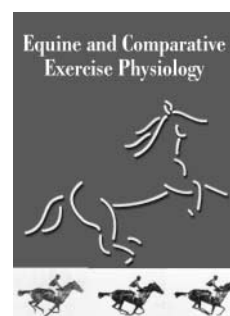
Relationships between exercise capacity and front hoof longitudinal balance in horses

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Abstract

To the authors' knowledge, the effect of hoof balance alteration on exercise capacity or performance has not been investigated. With the aim of evaluating the relationships between longitudinal front hoof balance and exercise capacity (lactate vs. speed relationship, run time and stride characteristics), two experiments were undertaken. In the first test the horses, left unshod, performed an incremental speed test in which parameters chosen to evaluate exercise capacity were related to hoof longitudinal balance. In the second part of the study the same group of horses had the length of the toe altered (decreased and increased) with the application of shoes, while the angle of the foot and the height of the foot from the ground remained the same. The relative change in exercise capacity due to the alteration of longitudinal balance was observed. In the unshod experiment, lactate level at the speed of 10 m s^{-1} ($5.0 \pm 2.0 \text{ mmol l}^{-1}$) was significantly associated with the angles DC° (angle described by the dorsal cortex with respect to the ground; $50.0 \pm 3.2^\circ$) and PC° (angle described by the palmar cortex with respect to the ground; $29.6 \pm 2.9^\circ$), while run time ($14.07 \pm 1.44 \text{ min}$) was associated with breakover indices (Breakover index1 0.33 ± 0.03 ; Breakover index2 0.30 ± 0.04 – all values mean $\pm$ standard deviation (SD)) (breakover indices were created to express the distance between the point of the toe and the point of the third phalanx relative to the length of the palmar cortex or relative to the distance between the point of the third phalanx and the centre of rotation of the distal interphalangeal joint). These associations have to be judged cautiously because the influence of hoof balance on exercise capacity could be biased by other physiological factors and because hoof balance parameters themselves could reflect the conformation of other anatomical structures far from the phalanges. The selective alteration of front hoof balance in the second part of the study produced a significant difference in blood lactate level only at 6 m s^{-1} (mean $\pm$ SD: $\text{La}_{6 \text{ m s}^{-1}}$ $0.32 \pm 0.39 \text{ mmol l}^{-1}$), with this benefit in terms of lactate level being associated with an increase in stride length (mean $\pm$ SD: $\Delta \text{SL}_{6 \text{ m s}^{-1}}$ $0.01 \pm 0.05 \text{ m}$; $\Delta \text{SL}_{10 \text{ m s}^{-1}}$ $0.112 \pm 0.218 \text{ m}$). In conclusion, while higher exercise capacity seemed to be associated with lower DC° , PC° and breakover indices, decreasing the toe length without altering the foot angle was beneficial only in terms of lactate level at the speed of 6 m s^{-1} for horses with DC° greater than 45° ; this benefit was accompanied by a slight lengthening of the stride at both 6 and 10 m s^{-1} .

Keywords: hoof balance; breakover index; exercise capacity; toe length

Introduction

The relationship between hoof balance and catastrophic injury in horses has been investigated¹ in a post-mortem study. Apart from that paper, to the authors' knowledge, the clinical consequences of a 'bad' or 'good' shoeing technique or a balanced or unbalanced hoof were only supposed or inferred

from results obtained in experiments observing 'forces' or 'strains' related to various balance conditions^{2–10}. Mostly these papers dealt with aspects of hoof balance that could interfere with normal gait mechanics or could promote or exacerbate lameness, and did not consider the consequences of hoof balance on performance or exercise capacity. A parameter that can

be used to evaluate exercise capacity alteration is the relationship between blood lactate level and speed. Lactic acid production arises because glycolysis activation is more rapid than the activation of oxidative phosphorylation, while the accumulation of lactate that accompanies an increase in velocity can be attributed to the disparities between lactic acid production and removal¹¹. The relationship between velocity and blood lactate level in horses was demonstrated many years ago¹², so it is convenient to use blood lactate levels at a given velocity as a way to evaluate the change in exercise capacity due to hoof balance alteration in horses. Other parameters that can be used to evaluate advantages in exercise capacity due to hoof balance are heart rate, stride length, stride frequency and, in an incremental speed test, run time.

The aim of the present study was to evaluate the relationships between longitudinal balance in the front hooves and exercise capacity in a group of untrained horses, to test the hypothesis that shortening the toe without altering the hoof angle would be beneficial in terms of exercise capacity. The study was divided into two parts. In the first experiment, exercise capacity was related to hoof balance in a group of unshod horses; then the same subjects were involved in another experiment in which a selected feature of front hoof longitudinal balance was altered to evaluate differences in exercise capacity related to this change.

Materials and methods

Horses

Nine horses aged from 3 to 19 years – four Thoroughbreds, four Standardbreds and one crossbred – were used. Horses were left unshod in a large paddock for at least 2 months before the beginning of the study and forced exercise or trimming of the feet was avoided. Nutrition consisted of free grazing in the paddock and supplementation with hay. None of the horses showed signs of lameness during the period of the study.

Testing protocol

Horses were accustomed to exercising on the treadmill before the beginning of the test. Horses performed three incremental exercise tests at 3-week intervals on a motorized high-speed treadmill (Beltalong; Bonds Bottom, Euroa, VIC, Australia). Each exercise test started with a warm-up period of 3 min at 2 m s^{-1} and 3 min at 4 m s^{-1} . After the warm-up period, the speed was set at 6 m s^{-1} and then increased by 1 m s^{-1} each minute until the horse could not keep pace with the machine. After the maximal speed was achieved the horse trotted at 4 m s^{-1} for 3 min and then walked at 2 m s^{-1} for 12 min for a 15-min cool-down period.

The first test was done with the horses unshod; in the second part of the study hoof balance was changed

on the front feet using shoes. The length of the toe was reduced by rasping the hoof from the point of the toe in a backwards direction or positioning the shoe forward with respect to the point of the toe, so the main angle of the foot was not changed. The selected feature of hoof balance that was changed in this way was the toe length. There was no alteration of either the main angle of the foot or the height of the foot. The radiographic parameter affected was the breakover length (BrOvL). The amount of toe to be cut or the position of the shoe was calculated in such a way that BrOvL could be modified to decrease or increase Breakover index2 by 10% with respect to the unshod value. Breakover index2 was increased by 10% in five horses and decreased by 10% in four horses. The horses were allowed to move freely in the paddock for 3 weeks and then the first test of the second part of the study was performed. After this test, the hoof balance was modified in the following way:

- The five horses that had the index increased then had toe length reduced, to reduce the centre of rotation breakover index by 10% compared with the unshod situation;
- The four horses that started with a decreased toe length were treated in the opposite way.

After 3 weeks the incremental speed test was performed for the third time. When shoes were applied on the front feet, an amount of horn equal to the thickness of the shoe was removed before shoeing.

In summary, the second part of the study consisted of two exercise tests separated by 3 weeks in which the horses ran with two different longitudinal balance conditions, increased and decreased Breakover index2: this was achieved by modifying BrOvL without altering Height or angles (Figs 1 and 2).

Hoof balance assessment

The balance of the front feet was measured, at the end of each exercise test, according to a previously validated radiographic technique¹³, using a special support to hold the feet while performing radiography. Balance was expressed using measurements of structures that were imaged radiographically. These parameters were:

- Breakover index1, $\text{BrOvL}/(\text{BrOvL} + \text{PCL})$: where BrOvL is the distance between the point of the third phalanx (P3) and the point of the toe, and PCL is the distance between the point of P3 and the dorsal border of the surface that articulates with the navicular bone;
- Breakover index2, $\text{BrOvL}/(\text{BrOvL} + \text{RotDist})$: where RotDist is the distance between the centre

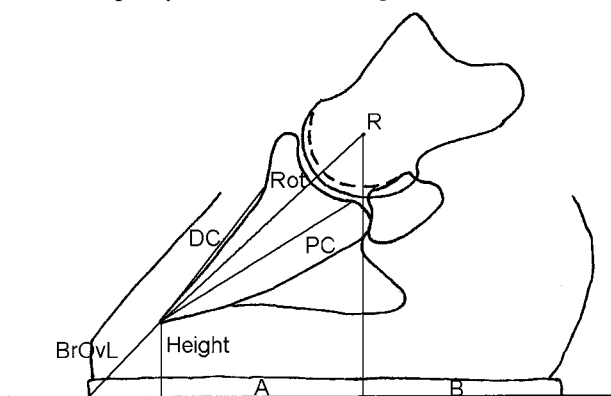


FIG. 1 Drawing of a radiographic image showing the sagittal plane of a front left foot in the decreased Breakover index2 condition, depicting measurements involved in the calculation of balance parameters. R – centre of rotation of the distal interphalangeal joint; Rot – axis from which the distance between R and the point of the third phalanx (P3) and the angle Rot° is measured; DC – axis from which the angle of the dorsal cortex (DC°) is measured; PC – axis from which the radiographic length (PCL) and the angle of the palmar cortex (PC°) is measured; BrOvL – distance between the point of P3 and the point of the toe; A (from the point of the toe to the vertical line that bisects the solar surface) and B (from the heel to the vertical line that bisects the solar surface) – measurements from which the Weight-bearing index ($10 \times [(B - A)/(A + B)]$) is calculated; Height – distance from the point of P3 to the support surface

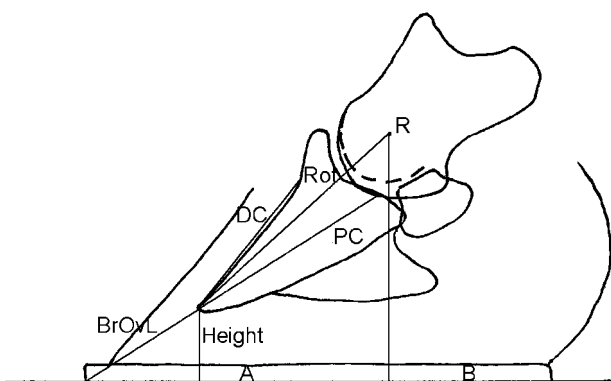


FIG. 2 The same hoof as in Fig. 1 in the increased Breakover index2 condition, depicting measurements involved in the calculation of balance parameters. For legend, please refer to Fig. 1

of rotation of the distal interphalangeal joint (DIJ; the centre of rotation of the coffin joint is outlined with respect to the articular surface of the shorter pastern bone at the level of the sagittal plane) and the point of P3;

- Weight-bearing index, $10 \times [(B - A)/(A + B)]$: on the radiographs a line starting from the centre of rotation of the DIJ and perpendicular to the solar surface was drawn, A is the distance between the intersection of the two lines and the point of the toe and B is the distance between the intersection and the caudal end of the hoof;
- PC°, angle of the palmar cortex: the angle described by the line described by PCL with respect to the support surface;

- DC°, angle of the dorsal cortex: angle described by the main axis of the dorsal cortex with respect to the support surface;
- Rot°, angle described by the axis between the centre of rotation of DIJ and the point of P3 with respect to the support surface;
- Height: the vertical distance between the point of P3 and the support surface.

Another index, calculated from external features of the foot, was used:

- External breakover index, $\text{ExtBrOvL}/(\text{ExtBrOvL} + \text{FrogL})$: where ExtBrOvL is the distance between the apex of the frog and the point of the toe and FrogL is the longitudinal length of the frog.

Each parameter and index was used as the mean of parameters and indices of the right and left front feet. Measurements involved in the calculation of the balance parameters are depicted in Figs 1 and 2.

Parameters recorded during the tests

Parameters related to exercise capacity were recorded during the test. Heart rate was monitored continuously with a portable device (Xtrainer Plus; Polar, Kempele, Finland). Blood samples from the jugular vein were obtained at 6 and 10 m s⁻¹ via an indwelling catheter. Blood was collected during the last 10 s at each particular speed. Blood samples were analysed immediately with a portable lactate analyser (AccuTrend Lactate; Roche Diagnostics GmbH, Mannheim, Germany) and the level of lactate at the velocities of 6 m s⁻¹ (La_{6ms⁻¹}) and 10 m s⁻¹ (La_{10ms⁻¹}) was assessed. Heart rate at 6 m s⁻¹ (HR_{6ms⁻¹}) and 10 m s⁻¹ (HR_{10ms⁻¹}) was used; run time was recorded from the beginning of the warm-up period to the moment when the horse could not keep pace with the treadmill. Seconds in the last step were expressed as decimal of a minute.

Stride length and stride frequency at 6 m s⁻¹ (SL_{6ms⁻¹}, SF_{6ms⁻¹}) and 10 m s⁻¹ (SL_{10ms⁻¹}, SF_{10ms⁻¹}) were recorded using a digital video camera (Sony DCR-TRV 330; Sony Australia Limited, North Ryde, NSW, Australia) with an acquisition rate of 25 frames s⁻¹. Stride length and stride frequency were determined by counting the number of strides (and fractions of strides) for 40 s at each velocity (discarding the first and the last 10 s) and counting the number of strides during the time (seconds as a fraction of a minute) run in the last speed achieved.

Statistical analysis

The relationships between balance-related parameters and exercise capacity-related parameters in the unshod test were tested using linear regressions. Linear regressions were also used to test the associations between different balance parameters. In the

second part of the study, the paired *t*-test was used to test the differences between the increased and decreased toe length conditions. To explain and predict the effect of changes in longitudinal balance produced in the increased or decreased toe length condition on exercise capacity, the differences ($\Delta\text{parameter} = \text{parameter}_{\text{increased}} - \text{parameter}_{\text{decreased}}$) obtained for lactic acid concentration, heart rate, stride length, stride frequency and run time were tested with linear regressions against values for angles (recorded in the increased condition) and against differences obtained for Breakover index2, Breakover index1 and External breakover index. Moreover, differences for lactate blood level, heart rate and run time were tested against differences for stride length and stride frequency to verify if any change in exercise capacity was achieved through changes in stride characteristics. Differences in Breakover index2, Breakover index1 and External breakover index were expressed as percentages. Statistics and graphs were made using the statistical software Sigma Stat® (SPSS Inc., Chicago, IL).

Results

Unshod test

In the first experiment significant linear relationships were found between parameters related to exercise capacity and hoof balance parameters. $\text{La}_{10\text{ms}^{-1}}$ was

significantly associated with the angles PC° ($R^2 = 0.69$; $P < 0.01$) and DC° ($R^2 = 0.82$; $P < 0.001$), and $\text{HR}_{6\text{ms}^{-1}}$ was significantly associated with angle DC° ($R^2 = 0.52$; $P < 0.05$), while there was a significant relationship between $\text{HR}_{10\text{ms}^{-1}}$ and both Height ($R^2 = 0.45$; $P < 0.05$) and DC° ($R^2 = 0.48$; $P < 0.05$). Run time was significantly associated with Breakover index2 ($R^2 = 0.65$; $P < 0.01$), Breakover index1 ($R^2 = 0.69$; $P < 0.01$) and Height ($R^2 = 0.51$; $P < 0.01$). The parameter Height was significantly associated with both $\text{SF}_{10\text{ms}^{-1}}$ ($R^2 = 0.47$; $P < 0.05$) and $\text{SL}_{10\text{ms}^{-1}}$ ($R^2 = 0.47$; $P < 0.05$), while the angle Rot° was significantly associated with $\text{SF}_{6\text{ms}^{-1}}$ ($R^2 = 0.55$; $P < 0.05$). Mean values of parameters recorded during the unshod tests are given in Table 1, while example relationships between the parameters are shown in Figs 3–5.

Correlation between balance parameters

Significant relationships were also found between the different balance-related parameters registered in the unshod condition: Height was associated with Breakover index2 ($R^2 = 0.76$; $P < 0.01$), Breakover index1 ($R^2 = 0.751$; $P < 0.01$) and Weight-bearing index ($R^2 = 0.52$; $P < 0.05$). Associations were even found between angles between Rot° and DC° ($R^2 = 0.56$; $P < 0.05$), Rot° and PC° ($R^2 = 0.87$; $P < 0.001$) and PC° and DC° ($R^2 = 0.74$; $P < 0.01$).

Table 1 Mean values for exercise capacity, economy of locomotion and balance parameters recorded during the three tests (values in parentheses are standard deviation)

Parameter	Unshod test	Test with increased Breakover index2	Test with decreased Breakover index2
$\text{La}_{6\text{ms}^{-1}}$ (mmol l ⁻¹)	2.0 (± 0.6)	1.9 (± 0.4)	1.6 (± 0.4)
$\text{La}_{10\text{ms}^{-1}}$ (mmol l ⁻¹)	5.0 (± 2.0)	4.4 (± 1.5)	4.3 (± 1.4)
$\text{HR}_{6\text{ms}^{-1}}$ (beats min ⁻¹)	153 (± 19)	147.9 (± 14)	149.4 (± 11.6)
$\text{HR}_{10\text{ms}^{-1}}$ (beats min ⁻¹)	190.1 (± 20.9)	186.1 (± 19.3)	189.7 (± 16.9)
Run time (min)	14.07 (± 1.44)	14.11 (± 1.02)	14.31 (± 1.20)
$\text{SL}_{6\text{ms}^{-1}}$ (m)	3.6 (± 0.2)	3.6 (± 0.1)	3.6 (± 0.1)
$\text{SF}_{6\text{ms}^{-1}}$ (strides min ⁻¹)	101.2 (± 5.8)	99.2 (± 3.6)	99.2 (± 3.3)
$\text{SL}_{10\text{ms}^{-1}}$ (m)	5.1 (± 0.3)	5.3 (± 0.2)	5.2 (± 0.2)
$\text{SF}_{10\text{ms}^{-1}}$ (strides min ⁻¹)	118 (± 7.0)	113.6 (± 3.8)	115.6 (± 4.8)
Breakover index2	0.30 (± 0.03)	0.35 (± 0.02)	0.29 (± 0.02)
Breakover index1	0.33 (± 0.04)	0.40 (± 0.02)	0.33 (± 0.02)
Weight-bearing index	- 0.32 (± 0.06)	- 0.44 (± 0.05)	- 0.34 (± 0.06)
External breakover index	0.38 (± 0.03)	0.38 (± 0.04)	0.33 (± 0.02)
PC° (°)	29.6 (± 2.9)	29.4 (± 2.7)	29.9 (± 2.5)
Rot° (°)	40.4 (± 3.0)	40.1 (± 2.5)	39.9 (± 2.5)
DC° (°)	50.0 (± 3.2)	49.1 (± 3.2)	49.4 (± 3.1)

$\text{La}_{6\text{ms}^{-1}}$ – lactate level at the speed of 6 ms⁻¹; $\text{La}_{10\text{ms}^{-1}}$ – lactate level at the speed of 10 ms⁻¹; $\text{HR}_{6\text{ms}^{-1}}$ – heart rate at the speed of 6 ms⁻¹; $\text{HR}_{10\text{ms}^{-1}}$ – heart rate at the speed of 10 ms⁻¹; Run time – the time passed from the beginning of the warm-up period to the moment when the horse could not keep pace with the treadmill; $\text{SL}_{6\text{ms}^{-1}}$ – stride length at the speed of 6 ms⁻¹; $\text{SF}_{6\text{ms}^{-1}}$ – stride frequency at the speed of 6 ms⁻¹; $\text{SL}_{10\text{ms}^{-1}}$ – stride length at the speed of 10 ms⁻¹; $\text{SF}_{10\text{ms}^{-1}}$ – stride frequency at the speed of 10 ms⁻¹; Breakover index1 – $\text{BrOvL}/(\text{BrOvL} + \text{PCL})$, where BrOvL is the distance between the point of the third phalanx (P3) and the point of the toe and PCL is the distance between the point of P3 and the dorsal border of the surface that articulates with the navicular bone; Breakover index2 – $\text{BrOvL}/(\text{BrOvL} + \text{RotDist})$, where RotDist is the distance between the centre of rotation of the distal interphalangeal joint (DIJ) and the point of P3; Weight-bearing index – $10 \times [(B - A)/(A + B)]$, on the radiograph a line from the centre of rotation of the DIJ and perpendicular to the solar surface was drawn, A is the distance between the intersection of the two lines and the point of the toe and B is the distance between the intersection and the caudal end of the hoof; External breakover index – $\text{ExtBrOvL}/(\text{ExtBrOvL} + \text{FrogL})$, where ExtBrOvL is the distance between the apex of the frog and the point of the toe and FrogL is the longitudinal length of the frog; PC° – angle of the palmar cortex; Rot° – angle described by the axis between the centre of rotation of DIJ and the point of P3 with respect to the support surface; DC° – angle of the dorsal cortex.

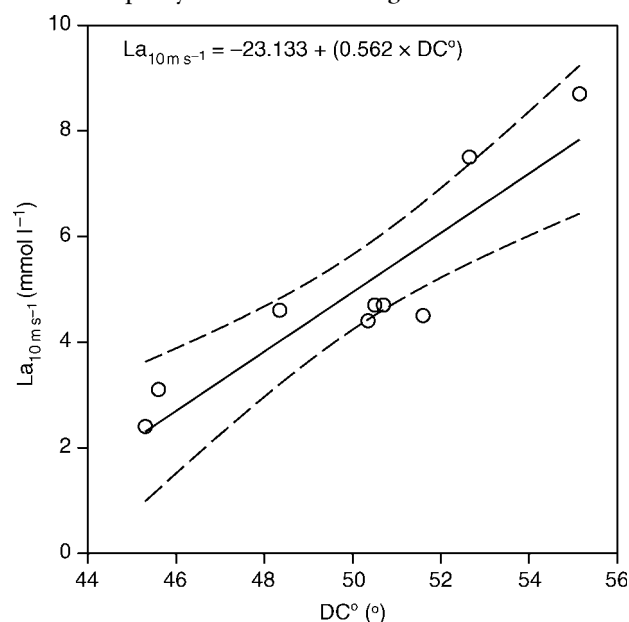


Fig. 3 Relationship between blood lactate level at 10 ms^{-1} ($\text{La}_{10 \text{ ms}^{-1}}$) and angle described by the dorsal cortex with respect to the ground (DC°) in the unshod test: regression line (solid) and 95% confidence intervals (dashed), $R^2 = 0.82$; $P < 0.001$. Horses with steeper DC° are less economical at 10 ms^{-1} (i.e. produce more lactate), while horses with lower DC° are more economical

Increasing and decreasing toe length

In the second part of the study, paired t -tests showed significant differences between the increased and the decreased condition only for $\text{La}_{6 \text{ ms}^{-1}}$ ($P < 0.05$). Paired t -tests confirmed that there was a significant difference in Breakover index2 ($P < 0.001$), Breakover index1 ($P < 0.001$), Weight-bearing index ($P < 0.001$)

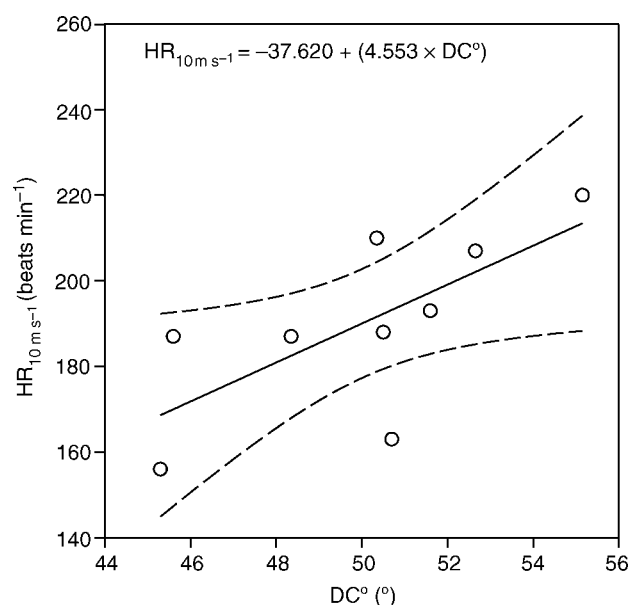


Fig. 4 Relationship between heart rate at 10 ms^{-1} ($\text{HR}_{10 \text{ ms}^{-1}}$) and angle described by the dorsal cortex with respect to the ground (DC°) in the unshod test: regression line (solid) and 95% confidence intervals (dashed), $R^2 = 0.48$; $P < 0.05$. Lower heart rate at 10 ms^{-1} is associated with lower DC° values

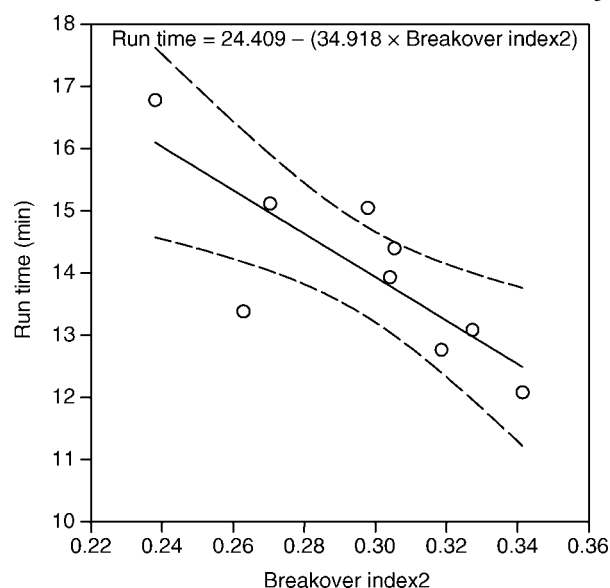


Fig. 5 Relationship between run time (with fraction of the last step expressed as decimal of a minute) and Breakover index2 in the unshod test: regression line (solid) and 95% confidence intervals (dashed), $R^2 = 0.69$; $P < 0.001$. Horses with higher Breakover index2 (i.e. longer toe) run for less time during the incremental treadmill test, attaining slower velocities

and External breakover index ($P < 0.01$) between the two conditions (increased and decreased toe length), and that Height and angles were not changed ($P > 0.05$).

Change in parameters

Linear regressions between change in parameters (Δ) and angles showed significant relationships between $\Delta \text{La}_{6 \text{ ms}^{-1}}$ and DC° ($R^2 = 0.49$; $P < 0.05$) (Fig. 6), $\Delta \text{La}_{6 \text{ ms}^{-1}}$ and $\Delta \text{SL}_{6 \text{ ms}^{-1}}$ ($R^2 = 0.60$; $P < 0.05$) (Fig. 7), $\Delta \text{La}_{6 \text{ ms}^{-1}}$ and $\Delta \text{SF}_{6 \text{ ms}^{-1}}$ ($R^2 = 0.60$; $P < 0.05$), $\Delta \text{La}_{6 \text{ ms}^{-1}}$ and $\Delta \text{SL}_{10 \text{ ms}^{-1}}$ ($R^2 = 0.50$; $P < 0.05$) (Fig. 8), and $\Delta \text{La}_{6 \text{ ms}^{-1}}$ and $\Delta \text{SF}_{10 \text{ ms}^{-1}}$ ($R^2 = 0.47$; $P < 0.05$). These results mean that the change in lactate level at the speed of 6 ms^{-1} between the increased and decreased toe length condition could partly be attributed to the different DC° angles of each horse. Moreover, the same changes in lactate level between the two hoof balance conditions were accompanied by an alteration in stride characteristics at both 6 and 10 ms^{-1} . Table 2 presents the Δ parameters measured for each horse.

Discussion

The first point of discussion must be the testing method: the choice of unshod and untrimmed horses. This condition was not chosen because it is considered ideal for the horses but because the shape of the hoof surely influences its mechanical usage. The unshod condition (for at least 2 months),

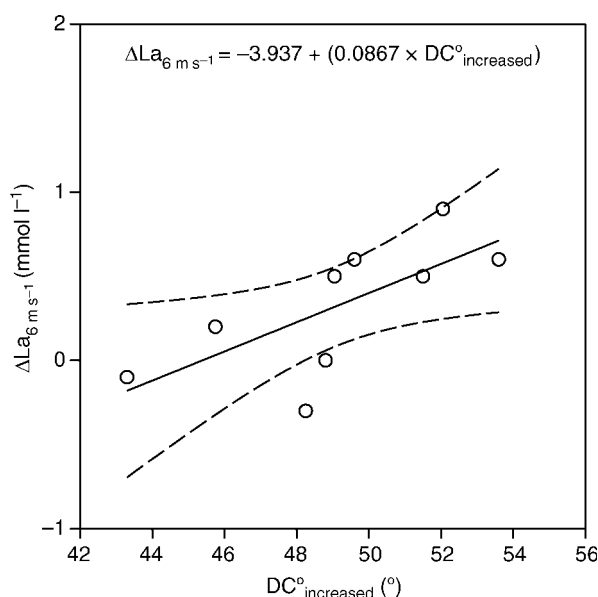


Fig. 6 Relationship between the difference in blood lactate level at 6 ms^{-1} ($\Delta\text{La}_{6 \text{ ms}^{-1}}$; equal to $\text{La}_{6 \text{ ms}^{-1}}$ in the increased condition minus $\text{La}_{6 \text{ ms}^{-1}}$ in the decreased condition) and angle described by the dorsal cortex with respect to the ground (DC°) in the experiment regarding the alteration of Breakover index2: regression line (solid) and 95% confidence intervals (dashed), $R^2 = 0.49$; $P < 0.05$. Horse with higher values of DC° responded to the treatment (i.e. decreased Breakover index2) by increasing economy of locomotion (i.e. lowering $\text{La}_{6 \text{ ms}^{-1}}$ when decreasing Breakover index2)

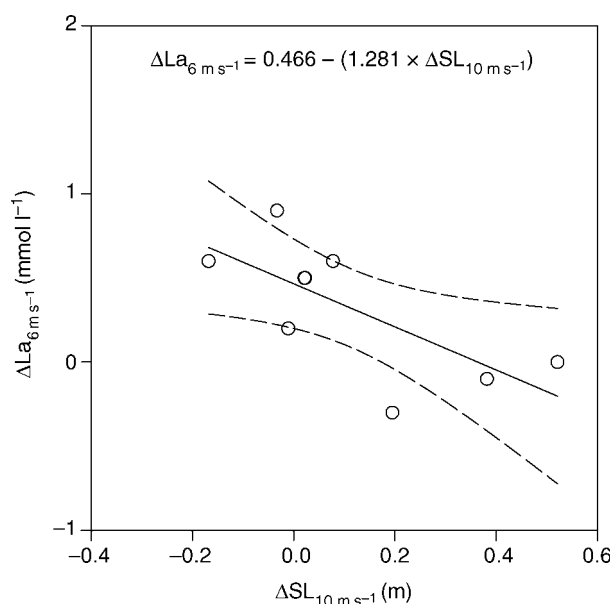


Fig. 8 Relationship between the difference in blood lactate level at 6 ms^{-1} ($\Delta\text{La}_{6 \text{ ms}^{-1}}$; equal to $\text{La}_{6 \text{ ms}^{-1}}$ in the increased condition minus $\text{La}_{6 \text{ ms}^{-1}}$ in the decreased condition) and difference in stride length at 10 ms^{-1} ($\Delta\text{SL}_{10 \text{ ms}^{-1}}$; equal to $\text{SL}_{10 \text{ ms}^{-1}}$ in the increased condition minus $\text{SL}_{10 \text{ ms}^{-1}}$ in the decreased condition) in the experiment regarding the alteration of Breakover index2: regression line (solid) and 95% confidence intervals (dashed), $R^2 = 0.50$; $P < 0.05$. In horses where decreased Breakover index2 produced an increase in economy of locomotion (i.e. lower lactate level) at 6 ms^{-1} , this change was accompanied by longer strides at 10 ms^{-1}

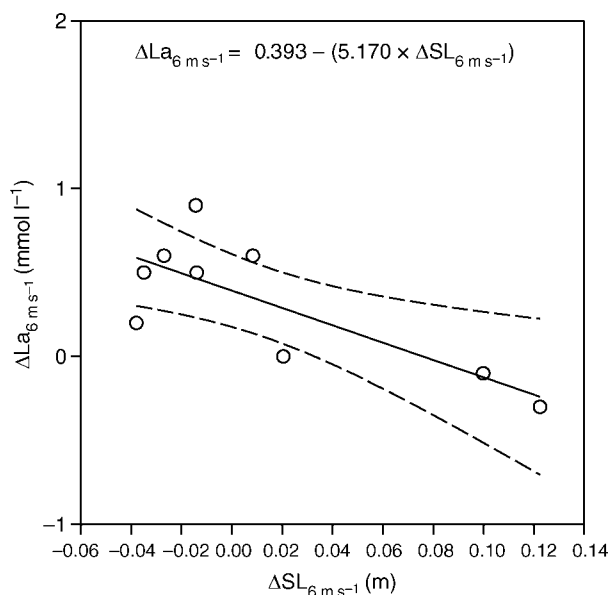


Fig. 7 Relationship between the difference in blood lactate level at 6 ms^{-1} ($\Delta\text{La}_{6 \text{ ms}^{-1}}$; equal to $\text{La}_{6 \text{ ms}^{-1}}$ in the increased condition minus $\text{La}_{6 \text{ ms}^{-1}}$ in the decreased condition) and difference in stride length at 6 ms^{-1} ($\Delta\text{SL}_{6 \text{ ms}^{-1}}$; equal to $\text{SL}_{6 \text{ ms}^{-1}}$ in the increased condition minus $\text{SL}_{6 \text{ ms}^{-1}}$ in the decreased condition) in the experiment regarding the alteration of Breakover index2: regression line (solid) and 95% confidence intervals (dashed), $R^2 = 0.60$; $P < 0.05$. In horses where decreased Breakover index2 produced an increase in economy of locomotion (i.e. lower lactate level) at 6 ms^{-1} , this change was accompanied by longer strides at the same velocity

with all the defects or benefits that could arise from it, was thought to be more representative of the real mechanical characteristics of the foot of each horse. Division of the study into two parts was done to ensure that the results obtained could really represent the relationships between hoof characteristics and exercise capacity. In fact, even though the two experiments seem to lead to similar conclusions, it is possible that some aspects of longitudinal balance - particularly in unshod horses - have some relationships with the morphology of other anatomical structures of the musculoskeletal system that are far from the foot. The actual shape of the front foot in a horse is the result of the action of forces applied to the hoof by muscles that are proximal to the carpus. In other words, it is possible that a particular balance condition proving to be beneficial for performance optimization or injury prevention could solely be the result of an advantage due to the conformation of other structures, for which the shape of the foot is only a secondary effect. Moreover, it has to be borne in mind that it is extremely difficult selectively to change a single parameter in hoof balance and that changing the shape of the hoof mostly produces changes of several mechanical features. Therefore even if, for example, a particular value of an angle is associated with a benefit in exercise capacity, when

Table 2 Change in parameter values ($\Delta\text{parameter} = \text{parameter}_{\text{increased}} - \text{parameter}_{\text{decreased}}$) for exercise capacity and economy of locomotion, for each horse that participated in the study

Parameter	Horse								
	1	2	3	4	5	6	7	8	9
$\Delta\text{La}_{6\text{ms}^{-1}}$ (mmol l ⁻¹)	0.5	0	-0.1	0.9	0.6	-0.3	0.2	0.5	0.6
$\Delta\text{La}_{10\text{ms}^{-1}}$ (mmol l ⁻¹)	0.7	-1.0	-0.2	2.0	0.8	0.9	-0.5	-0.6	-1.2
$\Delta\text{HR}_{6\text{ms}^{-1}}$ (beats min ⁻¹)	-6	-2	-3	0	-15	-5	-1	15	3
$\Delta\text{HR}_{10\text{ms}^{-1}}$ (beats min ⁻¹)	-5	-4	2	1	-10	-22	-5	8	3
$\Delta\text{Run time}$ (min)	-1.48	0.30	-0.28	-0.23	-0.55	-0.03	-0.25	0.65	0.07
$\Delta\text{SL}_{6\text{ms}^{-1}}$ (m)	-0.01	0.02	0.10	-0.01	-0.03	0.12	-0.04	-0.03	0.01
$\Delta\text{SF}_{6\text{ms}^{-1}}$ (strides min ⁻¹)	0.40	-0.59	-2.63	0.34	0.81	-3.21	0.99	1.00	-0.23
$\Delta\text{SL}_{10\text{ms}^{-1}}$ (m)	0.02	0.52	0.38	-0.03	0.08	0.19	-0.01	0.02	-0.17
$\Delta\text{SF}_{10\text{ms}^{-1}}$ (strides min ⁻¹)	-0.46	-12.48	-7.68	0.68	-1.83	-4.15	0.23	-0.46	3.81

$\text{La}_{6\text{ms}^{-1}}$ – lactate level at the speed of 6 m s⁻¹; $\text{La}_{10\text{ms}^{-1}}$ – lactate level at the speed of 10 m s⁻¹; $\text{HR}_{6\text{ms}^{-1}}$ – heart rate at the speed of 6 m s⁻¹; $\text{HR}_{10\text{ms}^{-1}}$ – heart rate at the speed of 10 m s⁻¹; Run time – the time passed from the beginning of the warm-up period to the moment when the horse could not keep pace with the treadmill; $\text{SL}_{6\text{ms}^{-1}}$ – stride length at the speed of 6 m s⁻¹; $\text{SF}_{6\text{ms}^{-1}}$ – stride frequency at the speed of 6 m s⁻¹; $\text{SL}_{10\text{ms}^{-1}}$ – stride length at the speed of 10 m s⁻¹; $\text{SF}_{10\text{ms}^{-1}}$ – stride frequency at the speed of 10 m s⁻¹.

this value is reached in a horse through trimming by the farrier, the same trimming will probably modify other parameters that could interfere positively or negatively with the intended alteration. From these two considerations it has to be concluded that the benefit arising from a particular condition perhaps might not emerge when produced artificially in a horse. If the horse does not show the benefit, it could be because (1) the alteration has changed other parameters and/or (2) the benefit does not lie in the hoof itself but in other structures far from it. So, the aim of the double approach of this study was to understand properly whether the association found between hoof balance parameters and exercise capacity could be maintained when balance was intentionally altered. It was also decided to use unfit horses to avoid the interference of training effects on the experiment. For the same reason, the toe length alteration was not produced at the same time in the same direction in all the horses.

It should be noted that, in the unshod condition, no relationships were found between indices related to the length of the toe and angles. Instead, significant relationships were found between Breakover index2, Breakover index1, Weight-bearing index and Height. This can be attributed to the geometry of the hoof, in which an increase in height from the ground moves the centre of rotation of the DIJ backwards with respect to the solar surface of the hoof and increases the distance between the point of the toe and P3. As there were no associations found between angles and breakover indices, it could be considered that what is popularly known as the long toe-low heel syndrome may not develop in horses that are left unshod. Actually, lower angles were observed to be associated with lower blood lactate level at 10 m s⁻¹ (PC° and DC° with $\text{La}_{10\text{ms}^{-1}}$) and lower heart rate at 6 and 10 m s⁻¹ (DC° with $\text{HR}_{6\text{ms}^{-1}}$ and $\text{HR}_{10\text{ms}^{-1}}$). So a low angle would not be detrimental

by itself if the toe was left to wear normally, as happened in the unshod horses. It should be noted that the association between DC° and $\text{La}_{10\text{ms}^{-1}}$ was very strong ($R^2 = 0.82$; $P < 0.001$) and that a marginally non-significant association was found between $\text{La}_{6\text{ms}^{-1}}$ and DC° ($R^2 = 0.41$; $P = 0.06$). Despite this, higher values for Breakover index2, Breakover index1 and Height were associated with a lower run time. Thus the long toe condition, even if not associated with a low heel or a low toe angle, could have a detrimental effect on exercise capacity as assessed in the type of exercise test performed in this study.

In the unshod exercise test, Height partially accounted for heart rate, stride length and stride frequency such that horses whose feet had a higher vertical distance between the point of P3 and the ground had a higher heart rate at 10 m s⁻¹, a lower run time and shorter and more frequent strides at 10 m s⁻¹. This seems to indicate that lower exercise capacity related to hoof balance condition is associated with shortening of the stride, which is less economical. An association was found between $\text{SF}_{6\text{ms}^{-1}}$ and Rot°, showing that lower Rot° produced less frequent strides at 6 m s⁻¹ (lower DC° was associated with lower values of $\text{La}_{10\text{ms}^{-1}}$, $\text{HR}_{6\text{ms}^{-1}}$ and $\text{HR}_{10\text{ms}^{-1}}$). This is an example of a balance condition that was more economical, being associated with longer strides.

External breakover index was not associated with any parameter of exercise capacity. So, external dimensions such as frog length or distance between the frog and the toe in the front feet do not seem suited to guide trimming or shoeing if the goal of the farrier is to alter stride characteristics or exercise capacity. Finally, the relationships between angles in the unshod test seem to indicate that the angle of the foot can be measured equally well by any of the three angles.

However, it must be remembered that the results of the unshod exercise suffer from the limitations

expressed above and will need to be confirmed in further investigations.

The second part of the study was conducted to produce a selective change in longitudinal balance in the front hooves and to observe differences in exercise capacity resulting from this change. The aim of this experiment was to confirm that reducing the break-over indices could increase exercise capacity, as the first experiment suggested.

Paired *t*-tests confirmed that the only parameters altered were Breakover index2, Breakover index1, Weight-bearing index and External breakover index, while Height and angles remained constant. The only parameter related to exercise capacity that was significantly changed was $La_{6ms^{-1}}$. In humans it has been shown that running economy is dependent on the speed at which it is measured: human athletes are more economical at velocities close to their usual race pace¹⁴. It is possible that the effect of Breakover index2 on exercise capacity was seen at only $6ms^{-1}$ because this slow speed (the slowest tested during the exercise test) was the closest to that which the horses, not forced to exercise, were experiencing in the paddock during the 3-week interval (slow trot at $\sim 4ms^{-1}$). The reasons for the lack of significant change in other parameters influenced by the balance alteration are not completely clear from the results presented here. While factors not measured in this study (such as anaerobic capacity and lactate buffering capacity of the muscles) could have contributed to run time together with the effect of hoof balance alterations, it is not possible to raise arguments for the lack of significant changes in heart rate at both 6 and $10ms^{-1}$ with different balance conditions. Changes in stride were so slight (as can be seen in Table 2) that the paired *t*-test found them not significant even though the significant alteration in lactate level at $6ms^{-1}$ was accompanied by changes in stride characteristics at both 6 and $10ms^{-1}$.

Blood lactate level at $6ms^{-1}$ was not always lower in the decreased condition, as some of the horses produced less lactate in the increased condition. This result did not confirm our initial hypothesis or the result of the unshod experiment, for which lower breakover indices were associated with better results in the exercise test. As mentioned above, the changes in $La_{6ms^{-1}}$ between the two hoof balance conditions were explained by the angle DC° . The significant relationship between $\Delta La_{6ms^{-1}}$ and DC° showed that, for the lowest DC° values, a lower lactate level has to be expected from an increased Breakover index2 (with Height and angle fixed) while decreasing toe length is beneficial in terms of $La_{6ms^{-1}}$ only for horses with higher DC° values (Fig. 6). Eliashar *et al.*¹⁰ found that a shoeing technique which resembled the balance modification done in this

study reduced the moment arm of the ground reaction force during breakover, but the dorsal hoof wall angle (which can be compared with our DC°) was very similar within the group of horses used (between 51 and 52°). Decreasing the toe length will probably always decrease the moment arm of the ground reaction force by the straightforward mechanical effect of the length of the lever. This effect must still be present in the results presented here, but clearly is of less mechanical significance than some other mechanism in horses with more extreme conformations. A better understanding of the mechanisms that led to changes in exercise capacity seems to come from the relationships between $\Delta La_{6ms^{-1}}$ and stride characteristics both at 6 and at $10ms^{-1}$. These relationships showed that a kind of locomotion that produced less lactate was achieved in association with a lengthening of the stride and consequently a reduction in stride frequency (Figs 7 and 8).

A possible explanation for the difference in economy of locomotion and exercise capacity due to longitudinal hoof balance registered in this study could come from a study on running turkeys. Roberts *et al.*¹⁵ showed in their work that a strategy for muscles to save energy when running on level ground is to operate 'active muscle fibers isometrically while the stretch and recoil of tendon springs provide the work of the bouncing body'. This effect would increase with increasing body mass and is likely to be a significant factor in exercising horses. When turkeys run on uphill slopes, more muscle fibres have to be recruited in order to achieve the same force produced on level ground¹⁶. The reason for this is that 'almost all the increase in muscle work occurred as a result of increased muscle shortening'¹⁵. So, an increase of muscle shortening (i.e. an increase in mechanical work performed actively by the muscle at a given velocity) produces a force-generating system that is less economical because the muscle will have to produce force more rapidly. In fact, it was observed both in the first part of our study and in the second experiment that a higher exercise capacity was associated with longer strides and lower stride frequency. It is possible that an increase of stride length arose from a longer stance phase as a direct result of a longer toe length and that the higher vertical oscillation of the body that should accompany the longer stride came from an increase in the energy storage of tendons. If the energy-saving mechanism observed in running turkeys¹⁵ operates in horses, then a more favourable hoof balance could have acted in our study perhaps by increasing the length of the time during which the muscle operated near isometrically.

It is difficult to compare our results with findings of other studies done on horses because other authors

did not use unshod horses or the selective balance change produced in this study. Clayton² found a delay in breakover with an acute toe wall angulation, but the acute angle was produced by allowing the toe to grow more than the heel and this is not comparable with the results obtained here in the unshod test, where the toe was naturally worn. Feet with higher values for Height are associated with higher exertion, have lower run time and shorter strides in the unshod experiment; in two studies^{5,17} where hoof pads were applied no changes in stride length were recorded but only an increase in breakover time. While this finding was not significant in one of the studies¹⁷, the hooves were also weighted in the other, so even these results cannot be compared with ours.

Balancing front hooves should be a practice in which soundness and performance are optimized¹⁸; however, from literature reports and the results obtained in this study the two goals perhaps cannot be achieved with all possible strategies. If prolonged near-isometric muscle contraction plays a role in increasing exercise capacity through the hoof balance changes performed in this study, this would lead to a (even if not increased) prolonged application of tension to tendons that in turn would predispose these structures to damage. Moreover, while a positive correlation was found between $La_{10ms^{-1}}$ and DC° in our study, Kane *et al.*¹ found that lower toe angles were associated with an increased risk for some catastrophic musculoskeletal injuries in Thoroughbred racehorses. Thus, even if the horses in Kane *et al.*'s study¹ were shod (and they may have had long toe associated with low toe angle), the same condition (low foot angle) that leads to an increase in exercise capacity could be a risk factor for injuries.

In conclusion, it has been shown that an association exists between some aspects of hoof longitudinal balance and exercise capacity in unshod horses. A change in a selected aspect of longitudinal balance (Breakover index2) produced a change in exercise capacity that was not in the same direction in all horses; the reason for this was that horses with different DC° angles responded differently to the treatment applied. Considering the limitations on the results of the unshod experiment, the practical guideline that can be drawn from our study is that decreasing the toe length is beneficial in terms of exercise capacity only for horses with DC° greater than 45° , and the benefit will be accompanied by an increase in stride length. It could also be supposed that such a front feet longitudinal balance alteration could lead to an increased risk for musculoskeletal injury. A final major caveat applies to all these results: altering the performance and decreasing the risk for injury in an athlete is a very complex procedure and can be achieved only with multiple actions on each of the

systems and structures involved. We have investigated just one very small part of one of the many biomechanical aspects of horse locomotion, so any conclusion about our results and performance alteration has to be done cautiously.

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References

- 1 Kane AJ, Stover SM, Gardner IA, Bock KB, Case JT, Johnson BJ *et al.* (1998). Hoof size, shape, and balance as possible risk factors for catastrophic musculoskeletal injury of thoroughbred racehorses. *American Journal of Veterinary Research* **59**: 1545–1552.
- 2 Clayton HM (1987). Comparison of the stride of trotting horses trimmed with a normal and a broken-back hoof axis. *Proceedings of the American Association of Equine Practice* **32**: 289–298.
- 3 Colahan P, Leach D, and Muir G (1991). Center of pressure location of the hoof with and without hoof wedges. In: Persson SGB, Lindholm A & Jeffcott LB (eds), *Equine Exercise Physiology* 3. Davis, CA: ICEEP Publications. pp. 113–119.
- 4 Riemersma DJ, van den Bogert AJ, Jansen MO and Shamhardt HC (1996). Influence of shoeing on ground reaction forces and tendon strains in the forelimbs of ponies. *Equine Veterinary Journal* **28**: 126–132.
- 5 Balch O, Clayton H and Lanovaz J (1996). Weight- and length-induced changes in limb kinematics in trotting horses. *Proceedings of the American Association of Equine Practice* **42**: 218–219.
- 6 Wilson AM, Seelig TJ, Shield RA and Silverman BW (1998). The effect of foot imbalance on point of force application in the horse. *Equine Veterinary Journal* **30**: 540–545.
- 7 Willemen MA, Salveberg HHCM, and Barneveld A (1999). The effect of orthopaedic shoeing on the force exerted by the deep digital flexor tendon on the navicular bone in horses. *Equine Veterinary Journal* **31**: 25–30.
- 8 Clayton HM, Willemen MA, Lanovaz JL and Shamhardt HC (2000). Effects of a heel wedge in horses with superficial digital flexor tendonitis. *Veterinary Comparative Orthopaedics and Traumatology* **13**: 1–8.
- 9 Crevier-Denoix N, Roosen C, Dardillat C, Pourcelot P, Jerbi H, Saana M *et al.* (2001). Effects of heel and toe elevation upon the digital joint angles in the standing horse. *Equine Veterinary Journal Supplement* **33**: 74–78.
- 10 Eliashar E, McGuigan MP, Rogers KA and Wilson AM (2002). A comparison of three horseshoeing styles on the kinetics of breakover in sound horses. *Equine Veterinary Journal* **34**: 184–190.
- 11 Billat LV (1996). Use of lactate measurements for prediction of exercise performance and for control of training. *Sports Medicine* **22**: 157–175.
- 12 Persson SGB (1983). Analysis of fitness and state of training. *Equine Exercise Physiology*. In: Cambridge: Granta Editions.
- 13 Tacchio G, Davies HMS, Morgante M and Bernardini D (2002). A radiographic technique to assess longitudinal balance in front hooves. *Equine Veterinary Journal Supplement* **34**: 368–372.

- 14 Daniels J and Daniels N (1992). Running economy of elite male and elite female runners. *Medicine and Science in Sports and Exercise* **24**: 483–489.
- 15 Roberts TJ, Marsh RL, Weyand PG and Taylor CR (1997). Muscular force in running turkeys: the economy of minimizing work. *Science* **275**: 1113–1114.
- 16 Pennisi E (1997). A new concept of how leg muscles operate on the run. *Science* **275**: 1067.
- 17 Balch O, Clayton H and Lanovaz J (1994). Effects of increasing hoof length on limb kinematics of trotting horses. *Proceedings of the American Association of Equine Practice* **40**: 43–44.
- 18 Balch O, White K and Butler D (1991). Factors involved in the balancing of equine hooves. *Journal of the American Veterinary Medical Association* **198**: 1980–1989.