Effect of three types of horseshoes and unshod feet on selected non-podal forelimb kinematic variables measured by an extremity mounted inertial measurement unit sensor system in sound horses at the trot under conditions of treadmill and soft geotextile surface exercise

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ABSTRACT

Therapeutic farriery is part of the management of certain orthopaedic conditions. Non-podal parameters are important as most horses shod with therapeutic shoes are expected to perform again and the choice of shoe type may be influenced by the effects they may have on gait. The aim of this prospective study was to evaluate the effects of three different shoe designs and unshod front feet on forelimb non-podal kinematic variables using an extremity mounted inertial measurement unit (IMU) system under conditions of treadmill and overground exercise on a soft geotextile surface at the trot. Ten sound horses with no underlying orthopaedic problem were instrumented with eight IMUs at distal radii, tibia and third metacarpal/tarsal regions. Measurements were performed during four consecutive days. During the first three days, the three shoe types were randomly selected per horse and day. On the fourth day, all horses were tested unshod. Data were collected at the trot on a treadmill, and on a soft geotextile surface. Specifically designed software and a proprietary algorithm processed the accelerometer and gyroscope signals to obtain orientation and temporal data to describe selected kinematic variables predetermined by the system. Repeated-measures analysis of variance (ANOVA) was used to assess differences between shoe type and surface. The presence of shoes produced significant changes in spatiotemporal variables which seemed to be related to shoe mass rather than shoe design as there were no significant differences found between different shoe types. Shod horses showed a gait characterised by an increased range of motion (ROM) of the fore limbs. Previously reported effects of the investigated shoes on podal kinematics do not seem to affect the investigated kinematic variables indicating perhaps a compensatory effect occurring at some level in the extremity.

INTRODUCTION

Proper and adequate shoeing is important for a horse's soundness, promotes a functional foot, may prevent lameness and influences a horse's performance.[1,2] Shoes affect the hoof expansion mechanism, and have a direct biomechanical influence on the inertia of the distal and proximal limb loading.[3] Therapeutic farriery is part of the management of certain orthopaedic conditions due to its ability to modify the kinematics and kinetics of the hoof-ground interaction[4,5] by manipulating shoe weight, shoe length, shoe width, hoof pads, toe of the shoe and toe/heel/side wedges.[6–9]

Numerous types of shoes have been developed and their use is implemented worldwide as an important part of the treatment regime of horses affected with some equine lameness.[10] Kinematic measures of the effect of shoe by means of an optical system has shown an increase in maximal height of the flight arc of the hoof, greater flexion of the coffin, fetlock and carpal joints during the swing phase, which provide an 'animation' of the trot attributed to the weight of the shoe.[8] Doubling the weight however, did not show any changes in stride length, stride duration or breakover time, but increased maximal height of the hoof, fetlock and carpus during the swing phase, which is in agreement with the previous observation.[9]

During recent years, there has been an increasing interest in the quantitative

evaluation of the relevant biomechanical effects of different shoes on horse locomotion through the study of kinematics, kinetics and neuromuscular control.[1 11–13] The egg bar shoe (EBR) and rockered toe shoes (RTS) are two of the most commonly used therapeutic shoes in the front limbs to support the treatment of palmar heel pain and navicular disease.[14–16] Their individual effects on some podal kinematics have been documented in several studies.[12 17–19] However, non-podal parameters such as, range of motion (ROM) of the carpus and tarsus and protraction and retraction of metacarpals and metatarsals, are also important as they further define the gait pattern as most horses shod with therapeutic shoes are expected to perform again and the choice of shoe type may be influenced by the effects they may have on gait.

The aim of the present study was to quantify the effects on selected non-podal forelimb kinematic variables of three different types of commonly used shoes versus unshod condition in sound horses trotting on a treadmill and on a soft geotextile surface using an extremity mounted IMU system, to complement the current body of knowledge regarding the effect of shoeing on horse's kinematics.

MATERIALS AND METHODS
Subjects
Ten healthy adult Franches-Montagne stallions of similar size and mass were randomly selected out of a herd at the Swiss National Stud Farm in Avenches, Switzerland. Stallions were evaluated to be sound and healthy based on a thorough clinical examination by a qualified veterinarian. All horses used in this experiment were regularly shod every six weeks using regular open shoes by a professional blacksmith. Horse's age was 11.8±4.9 years (mean±sd) with a body mass of 534.5±31.3 kg and a height at the withers of 156.8±4.1 cm. Horses were in good physical condition, disease and medication free and got exercised daily. Additionally, to define morphological similarity of leg segments, the lengths of both radii and metacarpi bones were measured using a flexible measuring tape and using the following palpable landmarks:

Radii: from the lateral tuberosity of the proximal radius to the lateral styloid process of the ulna.

Metacarpi: from the base of the fourth metacarpal bone to the palpable condylar fossa of the third metacarpal bone.

Hoof data
Twenty-four hours before the dynamic part of data collection, the shoes were removed from the front limbs and the hoof capsule was trimmed appropriately by an experienced blacksmith to restore and/or maintain hoof balance. The trimming aimed visually to achieve the desired hoof-pastern axis, location of the centre of rotation of the distal interphalangeal joint (DIP) and hoof capsule extension to the base of the frog. By visual evaluation the dorsal hoof wall and the dorsal surface of the

pastern region were aligned in parallel planes. The widest part of the foot ('Duckett's bridge'), theoretic centre of rotation of the DIP joint, coincides with the middle one-third of the frog. The heels were set at the widest part of the frog, to maintain a relationship of 1:1 between the width and the length of the hoof and to aim for a 66/33 distribution of the hoof mass dorsal and palmar to the hoof's widest point, and a 66/33 distribution of the solar length dorsal and caudal to the apex of the frog respectively, with a dorsal hoof angle approximately between 53° and 55°. From a dorsopalmar view, appropriate trimming aimed to maintain an equal length of the lateral and medial hoof walls.[20 21] Trimming was the same for all test conditions. Shoes were hot-fitted to the outline of the prepared hoof wall with the shoe centred to the widest part of the foot. The abaxial end of each branch at the heels was rounded to provide sufficient space between the frog and the branches of the shoe to pass a hoof pick. For the RTS, the toe quarter of the shoe fitted to the groomed toe quarters of the foot, and the widest part of the shoe aligned with the widest part of the foot. The profile of the shoe was round on the foot surface with a slight boldness to the toe. Before nailing the shoe a thin slice of sole adjacent to the white line from quarter to quarter was removed to discourage sole pressure. Two nails (MX nails Mustad) were driven into each branch of the shoe and passed through the hoof wall and exited approximately 2 cm above the junction of the shoe and the hoof. Nails were placed without specifically paying attention to the previous nail holes. The end of the nails was bent and cut to protrude 3 mm. A standard hoof gauge was used to remove the disrupted horn from under the nail where it emerges from the hoof. Standard clinching tongs were used to pull down the nail clinch firmly against the hoof wall. Finally, the hoof wall and clinches were smoothed with a rasp.

The hind feet of all horses remained normally trimmed and shod. Standardised lateromedial and solar photographs and lateromedial radiographs of each front foot before and after trimming and each shoeing were taken by the same individual to quantify hoof morphology by means of a previously validated software (Metron PX, Epona TechCreston, California, USA).[22 23] All radiographs were acquired with a computed radiography system using a portable x-ray unit (meX+20 BT lite, Medical Econet, Oberhausen, Germany) and a cassette reader (FUJI-Film FCR XG-1, FUJI-Film, Nishiazabu 2-chome, Minato-ku, Tokyo, Japan). Morphological hoof data collection included dorsal hoof angle, heel hoof angle and sole length from a lateral view; surface contact length, apex of the frog to toe length and heel separation from a solar view; medial and lateral hoof wall length and angle from a dorsopalmar view and palmar angle of the coffin bone on the radiograph from a lateral view (Fig 1).

The standard forelimb flat open shoe (FOS) (Kerckhaert DF, size 2, dimensions: length=142–146; section=22 mm, thickness=8 mm) was made of a curved steel bar, rectangular in cross-section and shaped to
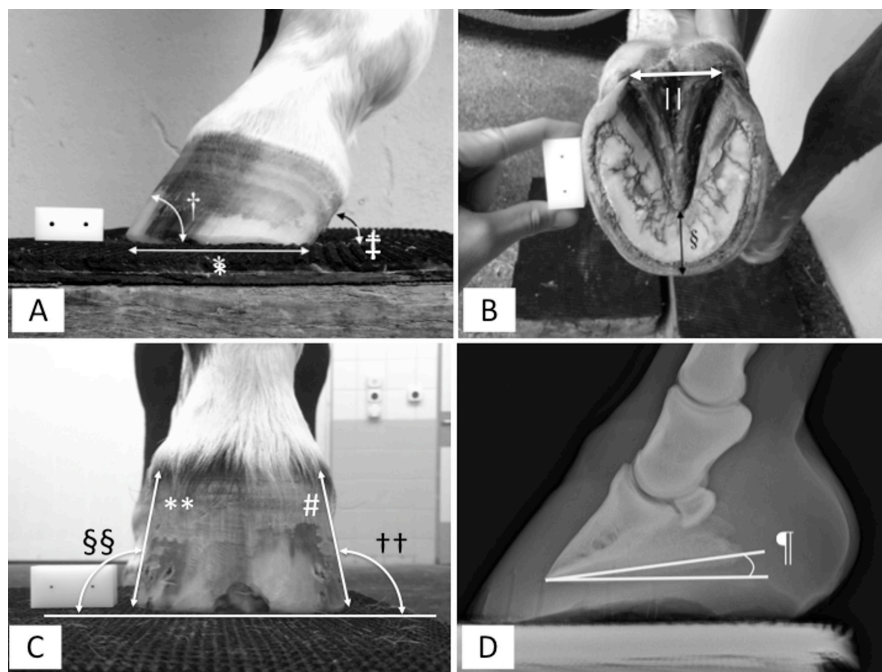
FIG 1: Quantification of hoof morphology using previous validated software. The pictures show a lateromedial view (a), a solar view (b), a dorsopalmar view (c) and a lateromedial radiograph (d) of the left forelimb hoof correctly positioned on a wooden block or held up. A marker (white block with two black points in a 2 cm distance) is necessary for the system's calibration. Following measurements were determined: (a) dorsal hoof angle (†), heel hoof angle (‡) and sole length (*); (b) frog to toe length (§), heel separation (‖); (c) medial wall length (#), lateral wall length (**), medial wall angle (††), lateral wall angle (§§); (d) palmar angle (¶).

conform to the contour of the ground surface of the hoof wall, the sole-wall junction (white line) and the adjacent sole. The toe or branches of the shoe had no toe clip and each branch of the shoe had a crease with machine stamped three or four nail holes.

The forelimb EBS (Kerckhaert DF, size 2, dimensions: length=146 mm, section=22 mm, thickness=8 mm) was similar to the standard flat shoe with extended branches that curved inward and connected to each other at the heels giving it an egg-like shape. EBRs provide a large stable base that extends behind the heels, provide longer base support to the heels in soft footing, prevents the hoof from rocking back and takes some stress off the palmar structures.[15 24]

The RTS was a standard RTS (Kerckhaert DF, size 2, dimensions: length=132 mm, section=22 mm, thickness=10 mm) applied with the trim described above (Fig 2).

Inertial measurement unit

The system used in this study is a patented and commercially available extremity mounted IMU system (Pegasus GaitSmart, European Technology for Business (ETB), Codicote, UK) capable of simultaneously capturing selected kinematic variables of all four instrumented extremities, in particular the radii, tibia, metacarpi/metatarsi, carpal and tarsal joints. The system consists of eight synchronised IMUs with a dimension of 73×36×19 mm and a mass of 54 g each (Fig 3). Every IMU sensor contains a 32 GB memory storage card (SD card)
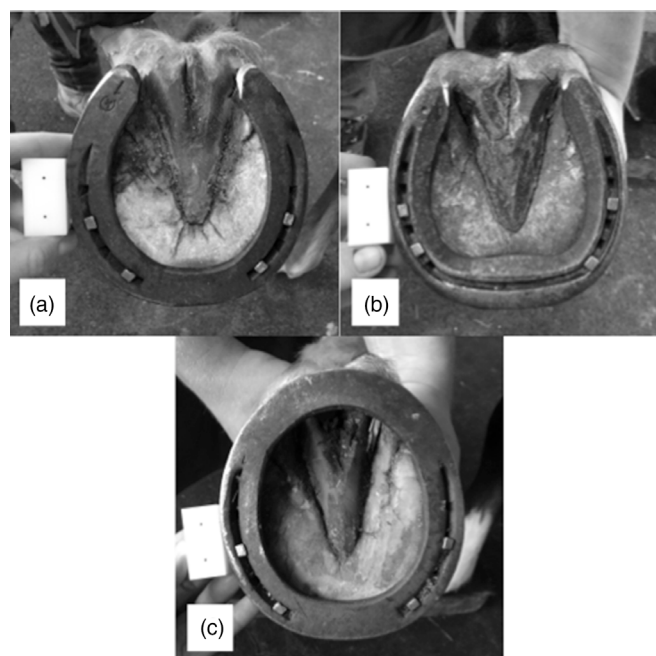

FIG 2: Quantification of hoof morphology using previous validated software. The pictures show the surface contact length of all three shoe types (FOS, RTS, EBS) in a solar view. The two black points on the white marker indicate a distance of 2 cm.

and a precision clock. The units incorporate three single axis 1200 degrees/s gyroscopes and a triaxial 5 g accelerometer, which enable the collection of six degrees-of-freedom (6 DOF) linear and rotational data on three

orthogonal axes mounted into a brushing boot, tibia and radius straps. No magnetometer is included. The output is sampled by a 12-bit analogue-to-digital converter at a frequency of 102.4 Hz and anti-aliasing digital filters with a cut-off frequency of 50 Hz are used to filter the transformed data. During the factory settings, each IMU is set to within 1 ppm (3.6 milliseconds per hour) of a reference to achieve less than 10 milliseconds per/ hour relative drift between each unit after synchronisation. At the start of each data acquisition, sensors are time stamped and synchronised with a computer clock by sending a simultaneous pulse to the respective units and therefore allowing calibration for recording using specifically written software (Poseidon V.4.0, ETB). The same software is used for automatic processing of the recorded data via a proprietary algorithm.[25]

Kinematic data

Temporal data of all four extremities and spatial data of the fore limbs were collected and analysed. The spatial-temporal variables reported, define aspects of the fore limb kinematic characteristics of the trot and include:

I. *Temporal* (12 variables): limb phasing variables (phasing is defined through a cross-correlation approach of the rotation velocity around the lateromedial axis of the inertial sensor, on a stride-by-stride basis, and is used to calculate the temporal phase-lag between respective limb cycles. Therefore, phase-lag is expressed as a percentage of the stride duration on a reference limb for each limb),[26] stride duration (in seconds) and percentage timing of maximal metacarpal protraction and retraction, within a
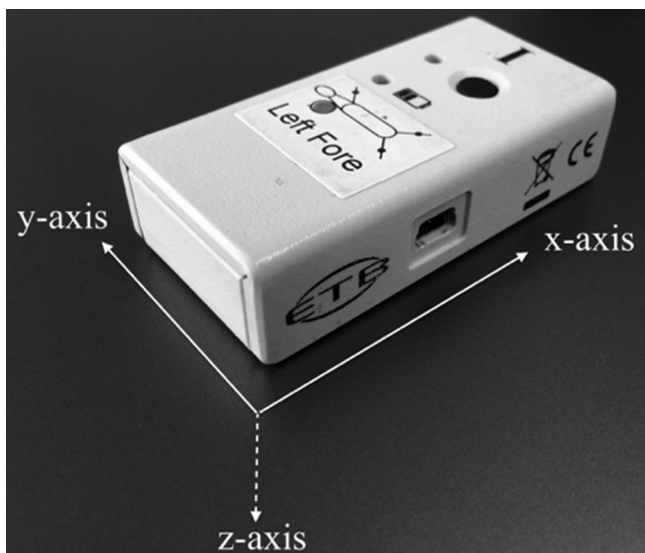

FIG 3: The wireless inertial measurement unit (IMU) sensor containing three single axes 1200 degrees/s gyroscopes and a triaxial 5 g accelerometer recording in six degrees-of-freedom (6 DOF) linear and rotational data on three orthogonal axes: x-axis: proximodistal, y-axis: caudocranial, z-axis: mediolateral. The rotation around the three axes are measured as: x-axis: yaw, y-axis: roll, z-axis: pitch.
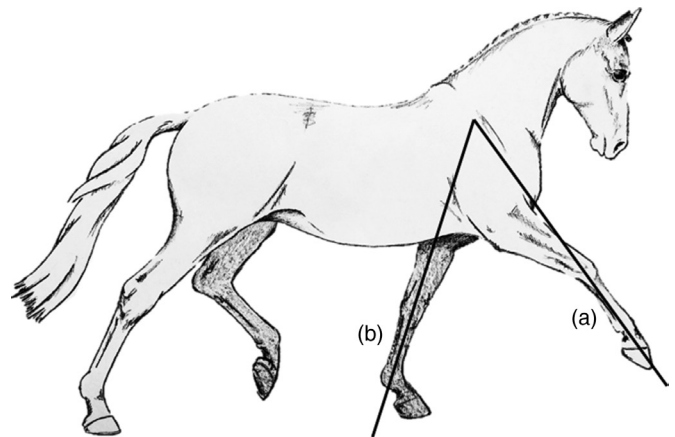

FIG 4: The range of motion (ROM) in the sagittal plane, by means of an example of the right fore limb's metacarpi. The sagittal ROM of the metacarpi results from the segmental angle that subtends from its maximum protracted position (a) to its maximum retracted position (b) through one stride. *(Drawing by Joëlle Stutz).*

stride.[26] Velocity data (m/s) and stride duration (in seconds and calculated by the software) were used to calculate stride length (m). Velocity data on the soft geotextile surface was determined by means of a chronometer and a known distance of 10 m. The diagonal asymmetry was calculated as the difference between the diagonal limb phasing timing couplets: diagonal asymmetry (per cent) = (LF – RH) – (RF – LH), where LH is always 0 as it is the reference limb. A perfectly symmetric diagonal should have a value of 0.

II. *Spatial* (13 variables): the ROM in degrees referring to the sagittal angles of carpi and segment angles of radii and metacarpi, the abduction-adduction ROM of radii and metacarpi in degrees, the symmetry (per cent) of each segment ROM was calculated as the difference of left minus right divided by the mean. With the exception of the carpal joint angle ROM, the rest of the angles, which defined the ROM in this study, were segment angles. A segment angle is the resulting angle that the segment subtends from its maximum retracted position to its maximum protracted position (Fig 4). A joint angle is the angle subtended between two segments. For the abduction-adduction angle it is the maximum range the segment moves through the stride in the frontal plane (Fig 5).

Experimental design

The study was a randomised controlled trial carried out over a period of two weeks. For the purpose of the study, horses were preconditioned to work on a high-speed treadmill (Mustang 2000, Kagra, Graber, Fahrwangen, Switzerland) as per standard procedure.[27] Horses were randomly divided in two groups of five horses the first week and five horses the second week. Each week, five horses were randomly assigned to one type of the three
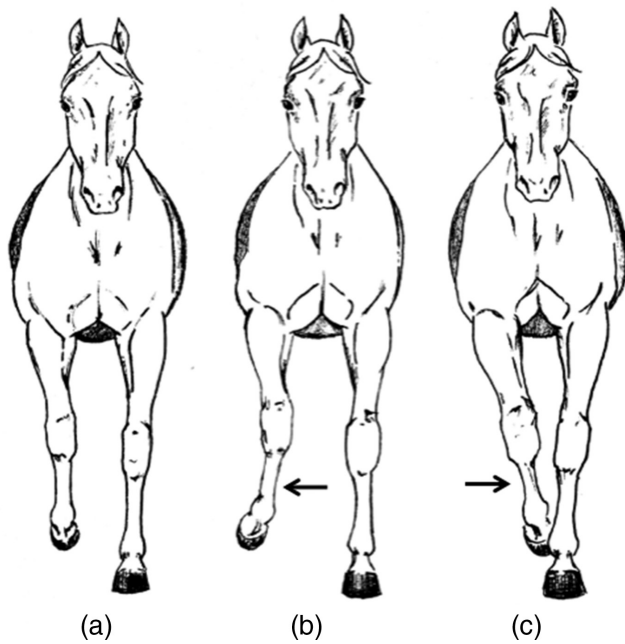
FIG 5: The range of motion (ROM) in the frontal plane shows the movement of abduction and adduction, by means of an example of the right forelimb's metacarpi. The angle results from the segmental angle that subtends from the maximum abducted metacarpi position (b) to the maximum adducted metacarpi position (c) through one stride. (a) straight metacarpi position during the swing phase. *(Drawing by Joëlle Stutz).*

FIG 6: A horse instrumented with four standard brushing boots (white arrows), one on each third metacarpal/metatarsal bone and four custom-made elastic straps (grey arrows), two on the distal part of each radii just above the lateral radial epicondyle and two on the distal part of each tibia, in the groove just dorsal to the gastrocnemius tendon.

shoes, regular FOS, RTS, EBS, (Kerckhaert DF, Hufshop Herrmann, Oftringen, Switzerland) each day in three consecutive days in a randomly assigned order. The fourth and last day was not randomised and was always unshod (NS). Randomisation was done by drawing pieces of paper out of an urn.

Gait analysis protocol

Immediately before the data collection session, each horse was warmed-up by walking 20 minutes in a horse walker, which started always on a clockwise direction and changed direction every 5 minutes. Following, all horses continued the warm-up by 10 minutes of walk and 5 minutes of trot on treadmill to accomplish steady state locomotion.[27] On treadmill same speed was used for walk (1.88 m/s) and trot (3.33 m/s) for all horses. Then, standard brushing boots were mounted on the third metacarpal/metatarsal bone of each limb of the horses and custom-made elastic straps were attached to both distal radii just proximal to the lateral styloid process of the ulna and proximal to the lateral malleolus of the fibula, in the groove just dorsal to the gastrocnemius tendon. Standard brushing boots had a length of 23.5 cm on the outside and 14.5 cm on the inside. The straps had a width of 5 cm and both were provided with Velcro fasteners and equipped with a small custom fitted pouch on the lateral aspect of each boot (15 cm proximal of the fetlock joint) and strap (Figs 6 and 7) (10 cm proximal to the carpus or tarsus joints) designed to hold the sensor

firmly to reduce motion and to facilitate synchronicity with limb movement throughout the data collection period. Before sensor placement horses were walked and trotted on the treadmill to get the horse accustomed to the boots and straps, until the gait appeared visually normal. In the meantime, all eight sensors were synchronized and time stamped by the system's software (Poseidon V.4.0, ETB) and were turned on immediately before inserting them one by one into each labelled pouch on radii, metacarpi, tibia and metatarsi. In total eight sensors were used. The sensors were aligned to the long axis of the bone segment by eye. The horse then remained still for 10 seconds, to give the sensors a

FIG 7: An exemplar of the custom fitted pouches, which are attached to the lateral aspect of each boot and strap to hold the IMU sensors firmly to reduce motion and to facilitate synchronicity with limb movement throughout the data collection period. Left: sensor is inserted into its pouch. Right: pouch is closed and Velcro strap is fastened over the sensor-pouch.

stationary period to self-calibrate. This short stationary period is a prerequisite to data analysis to obtain qualitative data as it allows the system to define the gravitational vector. Once on the treadmill horses were walked a few strides and then trotted for a minimum of 30 strides at a velocity of 3.33 m/s determined by the treadmill's calibrated speedometer. Data collection was repeated three times with a walking interval between them. Following treadmill data collection, horses were led into a 44×24 m arena, which consisted of an all-surface soft geotextile polymer mix (Terra-tex, Terra-Bausysteme, Hardt, Germany) where horses were walked and trotted an average of 18 strides three consecutive times on the diagonal of the arena (50 m) on a straight line at a naturally selected speed. This speed was calculated by means of a chronometer over a marked 10 m distance located in the middle of the trotting line and was 3.51 m/s±0.33 on the soft geotextile surface. The objective was to select a minimum of 8–10 strides to be analysed. On a steady state locomotion, characterised by a steady stride duration, seen in the graphic output of the system, the users can select a continuous segment of strides to analyse. From this selection, the system then works through a cross-correlation approach and selects the stride that is most representative by comparing each stride with each other doing minimal square difference calculations. The fewer strides available for selection, the higher the chances that the representative strides chosen will not be adequate. The selection of 8–10 strides during steady state locomotion and with steady sensor signal is enough to ensure the resulting stride being representative of the horse's movement as 3–5 strides have been reported as the minimal number of strides needed for kinematic evaluation of horse's movement.[28]

Throughout data collection, the same person was responsible for handling and leading the horses on both surfaces. Horses were always held or led on the left side using a normal halter and rope. The handler kept attention that the rope did not influence the movement of the horse's head. External factors, such as noise or moving objects, which could have influenced the measurement results were eliminated when at all possible. If a horse's level of distraction or excitement was significant, the measurement was discarded and repeated immediately after once the conditions were optimal. After all exercise data collection was successfully completed, the eight sensors were turned off immediately after removal from their pouches for subsequent data analysis on a personal computer. Immediately after completion of data collection, each horseshoe was removed, cleaned of debris and weighed using a calibrated electronic scale (Soehnle, Freienbach, Switzerland), whereas the mass of the nails was considered to be constant. Horseshoes were replaced the following day according to the randomisation process and data collection repeated under identical conditions. On the fourth day, data collection was performed in all horses unshod.

Data analysis

Sensors were connected to a personal computer via a USB. Proprietary software (Poseidon V.4.0, ETB) was used to convert the accelerometer and gyroscope signals into orientation and temporal outputs. From this display of temporal and orientation output, the authors manually and visually selected a window of data with steady locomotion including at least 8–10 strides to perform the analysis and avoiding the beginning and the end of the trial where acceleration and deceleration may have affected steady state locomotion. For the purpose of this study, steady locomotion was characterised by a regular signal from each sensor, as well as a regular stride duration, as could be seen in the graphic output of the recording period during the analysis procedure. The system measures the orientation and temporal events of each segment, then calculating the joint angles as a relationship of two adjacent segments and the limb phasing as the relative timing of segments between each other.[25] The preselected kinematic variables that the system produces define spatial orientation of each limb, plus temporal data that defines the relative intralimb and interlimb movement.

Statistical analysis

All data from the gait analysis were imported and managed in a spreadsheet program (Excel 2010, Microsoft, Redmond, Washington, USA). The data were analysed using commercial software (NCSS, V.10 and PASS, V.3, Kaysville, Utah, USA) First, normal plots, histograms and box plots were created to visualise the distribution of the data. Normality was confirmed using the Shapiro-Wilk test. Descriptive statistics mean and sd were calculated. The effect of shoe type and surface on gait variables was analysed with repeated measures analysis of variance (ANOVA) models with horse as a subject random variable and shoe type (NS, FOS, RTS, EBS) and surface type (treadmill vs soft geotextile) as within fixed factors. Bonferroni correction was used as post hoc test. This first set of ANOVA models were of the form:

$$y_{ijk} = \mu + horse_i + shoetype_j + surface_k + \in_{ijk}$$

Where y_{ijk} is each of the gait analysis measurements considered, μ is the general mean, $horse_i$ is the random effect of horse i (i=1…10), $shoetype_j$ is the shoe type (j=1…4), $surface_k$ is the surface (j=1,2) and $\in_{ijk}$ is the random residual error.

In an effort to describe the effect of the slightly different speed on the soft geotextile surface, it was categorised in <3.5 and >3.5 m/s groups and analysed with an additional repeated measures ANOVA models with horse as a subject random variable and shoe type and speed as within fixed factors. This second set of ANOVA models were of the form:

$$y_{ijk} = \mu + horse_i + shoetype_j + speed_k + \in_{ijk}$$

Finally, the influence of the mass of each shoe type was evaluated excluding barefoot data and by computing repeated measures ANOVA models with horse as a

subject random variable and surface type and shoe mass as a within fixed factors. This third set of ANOVA models were of the form:

$$y_{ijk} = \mu + horse_i + surface_j + shoemass_k + \in_{ijk}$$

Where $shoemass_k$ is the weight measured in g of the three types of shoes used (k=FOS 383.9, RTS 352.5, EBS 422.6).

Level of significance was always set at P<0.05.

RESULTS

All 10 horses completed the study with all three shoe types and unshod on treadmill and soft geotextile surfaces. All the variables were normally distributed. Descriptive statistics including mean and sd for all gait parameters, as well as the corresponding overall P values of the effect of the three different shoe types adjusted for the surface effect are presented in Table 1.

The Bonferroni correction confirmed that the differences for 'shoe type' were mostly due to the presence of the shoe. The three shoe types did not render significantly different results between each other.

The segmental leg length data showed little variability within the selected horse population and mean and sd were as follows: radii 39±0.9 cm, metacarpi 25.3±0.6 cm, tibia 39.1±0.8 cm and metatarsi 29.7±0.6 cm. The foot morphological data showed little variability regardless of horse, the shoe type or each horse's left and right foot. Dorsal hoof angle was 53.63°±0.04, heel hoof angle was 42.87°±5.27, solar length was 11.07 cm±0.68, frog to toe length was 4.3 cm±0.13 and palmar angle was 7.64°±2.3.

Shoe mass varied between 330 and 486 g and mean±sd for each shoe type were 383.9 g±11.7 for FOS, 352.5 g±14.9 for RTS and 422.6 g±30 for EBS. The shoe-ground contact length was 11.19 cm±0.46 for the FOS, 10.05 cm±0.57 for the RTS and 11.86 cm±0.6 for the EBS.

Although horses moved with slightly different speeds on the soft geotextile surface, these differences were non-significant for most parameters. Speed explained the variability of stride parameters such as stride duration, stride length and stride frequency, but no differences could be found in the limb phasing, the timing and symmetry. Therefore, speed effects were considered negligible and the main model focused on shoe and surface effects.

Overall, there were significant differences between shod and unshod horses but not between the three shoe types, after having adjusted for surface. The presence of a shoe had a significant effect (P≤0.05) in 19 out of 25 (76 per cent) of the measured kinematic (spatial and temporal) variables in the forelimb. Unshod horses showed overall smaller sagittal ROM of the forelimb, such as metacarpi, carpi and radii, compared with shod horses. This effect was seen on both surfaces, but slightly more pronounced on the soft geotextile surface. Temporal variables demonstrated that unshod horses showed a shorter stride duration, shorter stride length

and a higher stride frequency, regardless of speed and their maximum point of protraction and retraction was reached with an average of 15.8 ms earlier and 12.78 ms respectively compared with the shod horses. Shoe mass had an overall significant effect (P≤0.05) on 21 out of the 25 (84 per cent) measured spatial (11/13) and temporal (10/12) variables.

This study also found a significant effect of surface (after having adjusted for shoe type, P≤0.05) in 20 out of 25 spatiotemporal variables (80 per cent) resulting in greater sagittal ROM of carpi and radii, and smaller ROM of metacarpi overall in the soft geotextile surface. In the abduction-adduction plane horses showed more latero-medial motion of radii and metacarpi during treadmill locomotion.

DISCUSSION

This study has shown that the presence of shoes produced significant changes in over 75 per cent of the analysed spatiotemporal variables (19/25) in comparison with unshod horses. These changes were independent of the geometry of the shoes investigated as there were no differences found between shoes on the non-podal kinematic variables investigated. Even though sagittal plane motion of the carpus during swing has been shown to be driven by inertia[29] the difference of mass between shoes (330–486 g) may not have been enough to produce detectable changes in non-podal kinematic parameters as the minimal foot mass to produce detectable kinematic changes has not been clearly defined. A previous study doubled the shoe mass from 348 to 869 g and could not find any changes in stride characteristics such as stride length, stride duration or breakover,[9] but found increases in maximal height of the hoof, fetlock and carpus during the swing phase. Previously reported studies investigating the effect of shoeing (without accounting for type of shoe) on foot kinetics and kinematics have shown similar results, even though different methodologies were used.[1 11 12 30] One study[11] showed that shod horses had an increased carpal ROM of 13.3 per cent and the present study showed a 7.9 per cent increase when compared with unshod horses. This slight disparity could be explained by methodological differences such as different horses and different trotting velocities, 3.3 m/s in this study vs 4.0 m/s in the comparable study or different shoe mass. The effect of shoes on the non-podal gait parameters may be attributed to the increased hoof's mass as the model used in the current study was adjusted for surface. In general terms adding mass to the hoof alters its moment of inertia, resulting in an increased carpal flexion with the metacarpi following passively as a pendulum and a higher flight arc of the hoof,[11] which is also in agreement to the findings in the present study as the authors observed differences between shod and unshod horses. However, lack of detectable kinematic effects between shoes on the upper extremity in this study, in light of changes seen at the hoof capsule level documented in

TABLE 1: Mean and sd of spatial and temporal forelimb gait variables by the four shoe types for the trotting gait

			Shoe type (mean±sd)				P values	
		Surface	FOS	RTS	EBS	NS	Shoe	Surface
Spatial variables								
Sagittal range of motion (°)	ROM carpus left	Treadmill	74.54±6.14	73.53±6.69	72.36±7.97	68.61±5.73	<0.001*	<0.001*
		Geotextile	79.75±4.92	81.51±5.75	79.90±4.65	74.36±3.61		
	ROM carpus right	Treadmill	73.60±8.95	73.20±7.80	71.94±6.99	66.98±5.81	<0.001*	<0.001*
		Geotextile	76.32±5.94	78.62±4.72	80.05±4.46	76.21±4.26		
	ROM radius left	Treadmill	60.48±3.17	60.75±3.57	59.70±3.11	60.46±2.51	0.09	<0.001*
		Geotextile	64.15±5.34	62.25±2.83	62.16±4.03	61.83±4.60		
	ROM radius right	Treadmill	61.77±2.79	60.64±3.22	62.35±4.19	63.89±4.34	<0.001*	<0.001*
		Geotextile	63.66±3.74	62.36±2.55	63.38±3.08	64.77±4.16		
	ROM metacarpi left	Treadmill	82.05±3.06	82.01±4.85	82.41±3.86	77.07±3.56	<0.001*	<0.001*
		Geotextile	79.90±4.65	80.31±4.61	80.15±4.51	76.61±3.51		
	ROM metacarpi right	Treadmill	83.49±3.25	83.29±3.55	83.65±3.49	78.29±3.01	<0.001*	<0.001*
		Geotextile	80.63±4.74	81.11±4.03	81.38±4.83	76.99±3.19		
Abduction-adduction range of motion (°)	ML radius left	Treadmill	20.01±6.31	18.35±3.32	21.53±4.27	22.50±5.53	<0.001*	<0.001*
		Geotextile	19.10±4.61	17.47±4.92	18.15±3.80	20.75±6.94		
	ML radius right	Treadmill	13.82±2.59	14.99±3.06	13.16±2.03	12.83±4.87	0.01*	0.67
		Geotextile	14.19±3.54	13.96±3.59	12.71±2.98	13.34±3.46		
	ML metacarpi left	Treadmill	15.06±5.86	13.88±3.62	15.64±5.25	17.24±5.98	0.05	<0.001*
		Geotextile	14.09±4.56	15.83±6.80	10.99±3.38	13.87±4.64		
	ML metacarpi right	Treadmill	14.64±4.71	12.64±4.65	11.03±3.23	13.26±4.53	<0.001*	0.29
		Geotextile	13.00±6.41	12.65±7.97	9.77±2.84	13.62±4.59		
Symmetry (%)	Carpus	Treadmill	0.41±8.05	0.18±6.52	0.22±5.51	1.16±9.94	0.02*	0.26
		Geotextile	4.53±6.68	3.54±5.60	−0.04±4.43	−2.42±5.25		
	Radius	Treadmill	−1.67±6.28	−0.02±6.43	−3.37±4.62	−3.52±7.62	<0.001*	0.47
		Geotextile	0.97±8.64	−0.21±6.16	−2.27±5.27	−4.74±7.36		
	Metacarpi	Treadmill	−1.73±3.28	−1.64±3.47	−1.51±2.51	−1.61±3.42	0.86	0.09
		Geotextile	−0.91±3.51	−1.04±3.33	−1.51±2.82	−0.52±2.87		
Temporal variable								
Stride parameters	Stride duration (s)	Treadmill	0.70±0.02	0.70±0.02	0.70±0.02	0.69±0.02	<0.001*	<0.001*
		Geotextile	0.68±1.91	0.69±0.03	0.70±0.02	0.68±0.03		
	Stride length (m)	Treadmill	2.33±0.09	2.33±0.10	2.34±0.07	2.33±0.09	<0.001*	<0.001*
		Geotextile	2.45±0.24	2.37±0.23	2.43±0.21	2.39±0.17		
	Stride frequency (min⁻¹)	Treadmill	85.77±2.37	86.3±2.76	85.69±2.61	87.29±2.95	0.24	<0.001*
		Geotextile	88.25±4.56	86.52±3.43	86.40±3.05	88.46±4.33		
	Speed (m/s)	Treadmill	3.35±0.00	3.35±0.00	3.35±0.00	3.35±0.00	0.12	<0.001*
		Geotextile	3.60±0.40	3.41±0.31	3.49±0.28	3.53±0.32		
Limb phasing (%)	LF	Treadmill	62.35±2.08	62.14±2.43	62.55±1.58	59.97±2.77	<0.001*	<0.001*
		Geotextile	65.04±1.91	65.58±1.08	65.61±1.74	63.38±1.71		
	RF	Treadmill	12.92±1.91	12.57±2.30	12.94±1.31	10.43±2.54	<0.001*	<0.001*
		Geotextile	15.41±1.44	15.21±1.39	15.72±1.47	13.67±1.79		
	RH	Treadmill	49.82±0.86	49.73±1.16	49.56±1.26	49.73±0.97	0.42	<0.001*
		Geotextile	49.32±1.32	48.86±0.94	49.36±1.17	49.12±1.10		
Symmetry (%)	Diagonal asymmetry	Treadmill	0.39±1.13	0.16±1.15	−0.06±1.37	0.19±1.37	0.04*	<0.001*
		Geotextile	−0.30±1.69	−1.51±1.34	−0.54±1.82	−0.60±1.94		

Continued

TABLE 1: Continued

			Shoe type (mean±sd)				P values	
		Surface	FOS	RTS	EBS	NS	Shoe	Surface
Protraction and retraction (%)	Timing A left	Treadmill	47.27±2.32	47.47±2.10	48.07±2.26	47.07±2.27	0.01*	0.50
		Geotextile	47.60±3.38	47.27±3.13	48.27±2.39	47.33±3.54		
	Timing A right	Treadmill	47.00±2.33	47.67±1.83	48.13±1.89	47.67±2.11	<0.001*	0.02*
		Geotextile	47.07±3.26	47.67±3.37	49.33±2.70	47.80±3.54		
	Timing B left	Treadmill	51.60±2.19	52.67±1.99	53.07±2.61	50.60±3.37	<0.001*	<0.001*
		Geotextile	55.93±3.13	56.67±2.99	56.73±2.85	54.40±3.98		
	Timing B right	Treadmill	52.33±2.47	52.47±2.15	53.27±2.95	51.00±4.39	<0.001*	<0.001*
		Geotextile	55.67±2.97	55.27±2.95	56.80±1.94	52.80±4.19		
	Timing C left	Treadmill	4.13±2.16	4.00±2.63	4.60±2.53	4.73±2.60	0.13	<0.001*
		Geotextile	5.00±2.15	4.73±2.00	5.53±2.21	5.20±2.01		
	Timing C right	Treadmill	4.87±2.66	4.00±2.78	4.47±2.45	4.80±2.66	<0.001*	<0.001*
		Geotextile	4.93±2.77	4.40±2.31	6.60±2.36	5.53±2.01		
	Timing D left	Treadmill	17.80±1.85	18.13±1.74	19.20±1.63	16.40±1.43	<0.001*	<0.001*
		Geotextile	20.27±2.86	20.87±2.50	21.80±2.48	19.53±2.21		
	Timing D right	Treadmill	18.33±2.04	18.07±1.53	18.80±1.24	16.40±1.61	<0.001*	<0.001*
		Geotextile	20.13±2.46	19.93±1.86	21.53±1.63	18.67±2.25		

For the overall effects of shoe and surface, overall ANOVA P values are presented. The Bonferroni correction for the different types of shoe and barefoot confirmed that the differences are due to barefoot/non-barefoot. The three shoe types were not significantly different between each other (results are not shown).

Gait variables with a ° unit represent an angular ROM of the particular segment or joint. Variables with a per cent unit represent a relative value of a stride always referring to the left hind limb (LH=0 per cent).

*Denotes statistical significance.

EBS, egg bar shoe; FOS, regular flat open shoe; LF, left fore; ML, mediolateral; NS, no shoe; RF, right fore; RH, right hind; ROM, range of motion; RTS, rockered toe shoe; Timing A, maximal metatarsi protraction; Timing B, maximal metacarpi protraction; Timing C, maximal metatarsi retraction; Timing D, maximal metacarpi retraction.

previous studies[17 19 31] points towards a compensatory mechanism at the elbow or the digital joints and associated soft tissues[29] functioning as a damping mechanism. Simultaneously measuring effects (ie, net joint power) in the upper extremity and digit would help to ascertain whether this hypothesis could be true and within which range of alterations can the extremity efficiently compensate. In the case of the digit also perhaps by acting as a hinge modifying flexion and extension accordingly to prevent changes occurring at the hoof and digit levels from reaching more proximal segments, thus neutralising changes to the upper extremity. It can be expected that selected therapeutic shoes produce the previously described effects on the hoof and digit,[15 17 19] but no change occurs to the part of the limb investigated in this study.

Horses showed predominant more abduction-adduction motion during treadmill locomotion, possibly due to movement transfer from the moving treadmill belt back to the horse's limb. To the author's knowledge, the abduction-adduction motion of radii and metacarpi for the entire stride has not been documented previously. However, during the stance phase only, the metacarpi abduction-adduction ROM has been documented to be 11.9°±2.3,[31] which is similar to the present study which showed it to be 13.6°±1.9 for the entire stride. These results seem comparable and the difference seen may be due to abduction-adduction motion occurring during the swing phase of the stride or to horse population differences as carpal abduction-adduction has also been documented with a high range of variability.[32] The kinematics of the carpus might be affected by laxity of the stabilising soft tissues, which could contribute to the differences between individuals.[32] Since the current system at the moment cannot detect foot-on/foot-off accurately the abduction-adduction ROM during swing and stance phases cannot be determined separately, limiting the comparison between the mentioned studies.

Also, this study found that the presence of a shoe produced a reduction in abduction-adduction ROM of the metacarpi and radii, independent of the type of surface a finding that has not been previously documented. It seems that the mass of the shoe may be responsible for a reduction of the abduction-adduction movement perhaps through an increase of muscle work of the proximal extremity. This hypothesis could be the rationale behind the practice of shoeing young Standardbreds with heavier shoes to help balance their gait.[33] The explanation for this possible mechanism can only be rationalised by investigating the response to different weight of the muscles responsible for controlling the extremity's motion.

It has been shown by several studies that surface properties have significant influence on the horse's gait parameters.[15 27 34] Horses trotting on a treadmill tend to increase the ROM of carpi and fetlock joints and also show an increased height of hoof flight arc.[35] As the treadmill belt drives the hooves backwards the treadmill transfers some mechanical energy to the hooves of the horse, which in turn reacts by an exaggerated limb flexion.[36] Horses in this study showed greater ROM of metacarpi while on the treadmill, probably due to a backwards shift of the limb, resulting in a larger retraction and thus longer stance phase.[37] However, contrary to previous studies, this study found that horses showed greater sagittal ROM of the carpi and radii on the soft geotextile surface.[34]

Temporal variables include the stride timing characteristics, the limb phasing, the diagonal asymmetry and the percentage timing of maximal metacarpal/metatarsal protraction and retraction within a stride. Limb phasing remained the same regardless of the applied shoe. The difference observed in the timing of protraction and retraction may be extremely difficult to be detected by visual perception,[38] and despite the IMU system being able of identifying such minimal disparities, their significance remains unknown.

The symmetry variables were calculated for each segment ROM and expressed as a percentage of the duration of one stride, which varied between 720 and 740 ms in total time. Values fluctuated within a maximum of −5 to +5 per cent change, representing an absolute timing change of 36–37 milliseconds. The significance of this finding remains unknown but this level of variation has been documented previously in this breed and in normal horses.[39]

The extremity mounted IMU system used in the present study is capable of capturing predetermined spatial and temporal variables, such as sagittal and abduction-adduction ROM of metacarpi and radii segments, limb phasing and maximal protraction and retraction of metacarpi segments as a percentage of a stride. Recent studies in horses using this extremity mounted IMU systems support the accuracy of this technology when measuring segment displacement, angular range of motion, stride frequency, its repeatability and had little bias in sagittal parameters investigated.[39–44] Additionally, studies in humans have shown comparable joint ROM data between the system used in this study and optical kinematics[42] and the use of this technology is well reported and established as acceptable and reliable.[45 46] Despite this information and even though the results of sagittal and lateromedial (abduction-adduction) ROM and temporal parameters of the stride are comparable to previously published information,[32 47] a full comparison of this system with a 3D optical system would be indicated before clinical implementation.[48] The effect of shoes in some of the variables reported in this study have not been documented previously and a comparison with other studies is not possible, constituting therefore new information.

In this study, the authors decided to allow every horse to trot at its natural comfortable speed on the soft geotextile surface. This rendered differences in speed between treadmill and over ground. Speed on the treadmill was selected based on a pilot project where it was found the minimal speed that the horses used showed a comfortable and regular trot and that none of the horses would break into canter or walk. The authors believe that naturally selected speed is beneficial as the horse may move closer to its normal movement rather than obliging a horse to trot to a fixed speed that may result in artificially affected stride kinematics. A linear relationship between the change in speed and stride length has been reported[49] and the results concur with that finding. Further research would be required with horses trotting at an equal speed on all investigated surfaces to properly assess the effect of surface.

From an experimental point of view, the authors made some decisions that may represent certain limitations of this study. The authors chose to randomise only the order of the shoes and to leave the NS group as the last group. While it would have been more appropriate to randomise all the groups, the authors were anticipating that due to the management of these horses, some of them might have gone lame without a shoe, which would have forced them to change the timing in the experiments and potentially be highly disruptive to the experimental design. The choice of treadmill speed could have been based on the naturally selected speed at the soft geotextile surface, but due to a previous pilot study, the authors were afraid that some horses might have had an unstable gait during treadmill exercise while trotting properly in the soft geotextile surface. Nonetheless, the speed differences seen between both surfaces were minimal and non-significant for spatial variables. A limitation of this study regarding the results detected concerning the effect of shoes, is that data extrapolation to other breeds should be done carefully and considering that the authors only used Franches Montagne horses. Lastly, the authors chose to perform the study on a period of four days per horse and evaluate the gait immediately after shoeing based on a previously performed linear six-week study (unpublished) in the same population of horses, to investigate whether horses need a period of adaptation postshoeing. In this study, the authors failed to observe a need for such period.

CONCLUSIONS

In conclusion, the mass of the shoe seems to be more important than shoe geometry in affecting non-podal kinematic variables when this extremity mounted IMU system is used. Previously documented kinematic effects associated with different shoe geometries seem to remain at a local level and have no specific changes in the investigated upper extremity spatiotemporal parameters. The non-podal kinematic differences between the selected shoes and unshod horses seem to be small, challenging to detect by the naked

eye and are in agreement with other previously documented studies.

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