Instrumented treadmill for measuring vertical ground reaction forces in horses

Michael A. Weishaupt, Dr med vet; Hermann P. Hogg, El Ing HTL; Thomas Wiestner, El Ing HTL; Jachen Denoth, Dr Phys; Edgar Stüssi, Dr Phys; Jörg A. Auer, Dr med vet, MS

Objective—To develop and validate a novel instrumented treadmill capable of determining vertical ground reaction forces of all 4 limbs simultaneously in horses.

Sample Population—Data obtained while a horse was walking and trotting on the treadmill.

Procedure—18 piezo-electric force transducers were mounted between the treadmill frame and supporting steel platform to measure the actual forces at the corresponding bearing points. Each of the 18 sensor forces is equal to the sum of the unknown hoof forces weighted with the transfer coefficients of the corresponding force application points. The 4 force traces were calculated, solving at each time point the resulting equation system, using the Gaussian least-squares method. System validation comprised the following tests: determination of the survey accuracy of the positioning system, determination of the natural frequencies of the system, linearity test of the force transfer to the individual sensors, determination of superimposed forces with the treadmill-integrated force measuring system (TiF) in a static configuration, and comparison of vertical ground reaction forces determined simultaneously by use of TiF and force shoes mounted on the forelimbs of a horse.

Results—Comparison between static test loads and TiF-calculated forces revealed deviations of < 1.4%. Force traces of TiF-calculated values and those recorded by use of the force shoes were highly correlated ($r \geq 0.998$).

Conclusions and Clinical Relevance—This instrumented treadmill allows a reliable assessment of load distribution and interlimb coordination in a short period and, therefore, is suitable for use in experimental and clinical investigations. (*Am J Vet Res* 002;63:520–527).

Disorders of the equine locomotor apparatus are the most widespread cause of wastage in sports horses.[1,2] It is estimated that three fourths of poorly performing horses have subclinical musculoskeletal problems.[3] Therefore, the early detection and resolution of these conditions have high priority within the context of sport medical care and animal welfare. Traditionally, the evaluation of gait abnormalities is based on subjective assessments and, therefore, relies strongly on the expertise of orthopedic clinicians.[4] Various kinetic techniques for gait analysis such as force plates,[5-11] force-measuring horseshoes,[a] the Kaegi Equine-Gait-Analysis system,[12] and accelerometric devices[13,14] have been used to quantify locomotor unsoundness and provide additional assistance in the interpretation of delicate subclinical conditions.[15] Advanced diagnostic procedures or therapeutic interventions could be monitored more objectively.[16-18] However, to date, clinical application of all these techniques including kinematic gait analysis has been limited.

Basically, all of the aforementioned kinetic measuring concepts are confined by the number of ground contacts of simultaneously measured limbs. When using force plates, problems in obtaining repeatable constant speed trials[19] or targeting the platform may pose substantial limitations, especially when dealing with quadrupeds. Two to 6 attempts are needed to assess a single valid foot strike, depending on whether the horse is walking, trotting, or cantering.[20-22] Consequently, data acquisition and processing are extremely time consuming. Therefore, time-related distributions of ground reaction forces for concurrently loaded limbs are still poorly documented, and alterations attributable to locomotor disorders have not been systematically studied.[7,23] With the use of force-measuring horseshoes, the number of consecutive strides is unrestricted, but the instrumentation is delicate, and weight and height of the horseshoe may alter the physiologic motion pattern of a horse.

High-speed treadmills for horses are an established instrument in equine exercise physiology and have proven useful for visual gait and kinematic assessments.[24] Once adapted to a treadmill, horses have regular gait patterns with minimal interindividual variations.[25] External factors such as ground condition, environment, and subject velocity[19,26] that influence gait characteristics can be highly standardized.

The objective of the study reported here was to develop a system that would combine the advantages of a treadmill with a force-measuring system able to record the vertical ground reaction forces of all 4 limbs simultaneously over multiple strides.[b] Instrumentation of a horse was to be held to a minimum, and the data were to be available instantly. The design and validation of the system were documented, and possible applications were proposed.

Received May 7, 2001.
Accepted Nov 6, 2001.
From the Department of Veterinary Surgery, University of Zurich, Winterthurerstrasse 260, CH-8057 Zurich, Switzerland (Weishaupt, Hogg, Wiestner, Auer); and the Laboratory for Biomechanics, ETH Zurich, Wagistrasse 4, CH-8952 Schlieren/Zurich, Switzerland (Denoth, Stüssi).
Supported by Kagra AG and Kistler Instruments AG.
The authors thank Vreni Hänni and Rainer Vogt for technical assistance.
Address correspondence to Dr. Weishaupt.

Unauthenticated | Downloaded 09/25/23 11:43 PM UTC

Materials and Methods

Compared to the classic force-plate system, the **treadmill-integrated force measuring system (TiF)** is based on a completely different measuring principle. Single detached sensing components for each individual hoof do not exist. On the contrary, horses walk entirely on a single load-sensitive platform. Because up to 3 hoof forces are acting simultaneously on this platform during locomotion, the direct determination of the various forces is not feasible. However, if each **force application point (FAP)** of the acting forces is known, the individual forces can be calculated from the entire ground reaction force by solving a linear equation system for the unknown hoof forces. Thus, the required components of TiF were a load-sensitive treadmill platform, a positioning system to localize the FAP on the treadmill platform, a force-transfer coefficient matrix that represents the transfer characteristics from every possible FAP to every sensor of the load-sensing treadmill platform, a measuring system for time-locked data acquisition, and a fast computer system for calculation of the 4 individual force traces of each limb.

Treadmill and force measuring system—An equine high-speed treadmill[c] was modified. The standard traction motor was exchanged for an engine with larger mass and 50% more power (30 kW) to ensure constant velocity of the treadmill belt.[27] The original treadmill platform was replaced by a custom-designed lightweight steel plate of only 5 mm in thickness and transversally reinforced with underlying T-shaped steel supporting structures. This plate had a high transversal (370 cm^4/m) and low longitudinal (1.04 cm^4/m) moment of inertia. On each long side, the platform was affixed to the treadmill frame at 12 equally distributed bearing points. At each bearing point, a damping element (70 shore, spring constant of 3 kN/mm) was inserted. Eighteen bearing points (9 on each side) were supplied with piezoelectric force sensors,[d] which measured the vertical force component at the respective location **(Fig 1)**. Force sensor outputs were amplified with charge amplifiers.[e] The determined temperature behavior of this sensor-amplifier arrangement was ± 0.3 N per degree Celsius for temperatures between 20 and 50 C, and baseline drift was ± 6.0 N/30 min.

Positioning system—The x- and y-coordinates of the FAP (ie, the position of each hoof on the treadmill platform) were calculated by use of trigonometry on the basis of angles determined with incremental angular encoders.[f] The com-

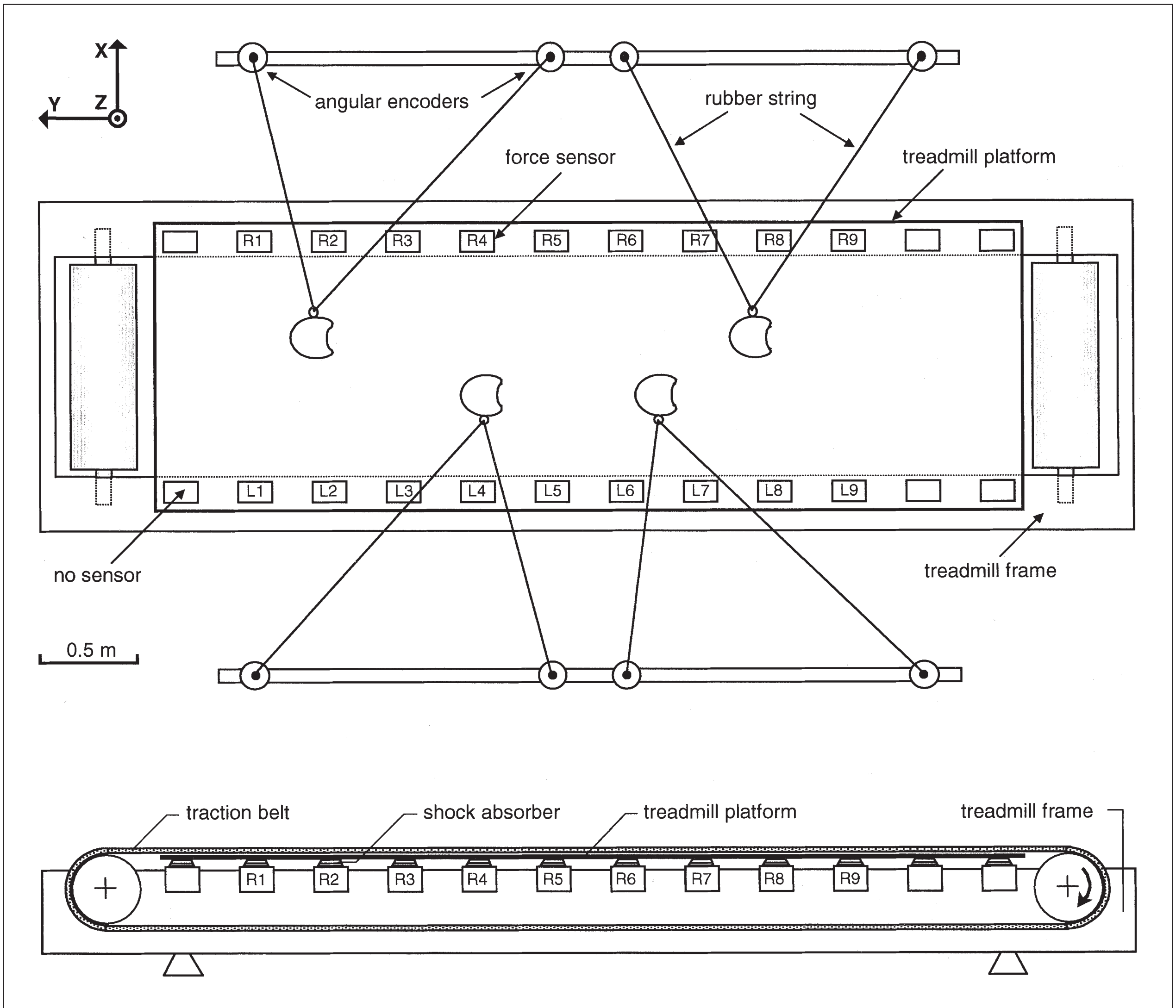

Figure 1—Schematic illustrations representing the overhead (top) and cross-sectional lateral (bottom) views of the instrumented treadmill for use in determination of vertical ground reaction forces in horses. Notice the 18 force sensors and the 4 triangulation units used to determine coordinates of each hoof.

Unauthenticated | Downloaded 09/25/23 11:43 PM UTC

bined quadrature outputs of each encoder had an angular resolution of 0.09°. The goniometers were mounted on aluminum rails, which were placed in parallel orientation and defined positions relative to the treadmill's system of coordinates. For each limb, a thin rubber string connected 2 goniometers via the corresponding hoof (Fig 1). Shafts of the goniometers had lightweight needles (6 cm long) to which the rubber strings were affixed. At each hoof, the rubber string was attached to a hook on an L-shaped stainless-steel plate, which was inserted between the bearing surface of the lateral hoof wall and the horseshoe. Mean outward tension of this rubber string was 5 N.

Computer hardware and signal processing—Force-sensor signals were filtered by a 200-Hz anti-aliasing low-pass filter (Bessel, second-order) and digitized by a 12-bit analog-to-digital converter. The incremental angular values from the 8 encoders were processed by a hardware decoder to yield continuous absolute values. All channels were sampled within 30 µs at a rate of 433 Hz. Input and timing operations were executed by a single-board high-performance microprocessor.[g] The resulting data were transferred over a link (20 megabytes/s) to a host computer.[h] The measuring software[i] was programmed in C++ to perform calculations of the 4 vertical ground reaction force traces and their analysis.

Force-transfer coefficient matrix—To calculate the forces acting on the treadmill platform, force-transfer coefficients from each spot on the running area of the treadmill to each of the 18 force transducers must be known. This array of coefficients was generated by rolling a single-wheel calibration trolley with a weight of 2.85 kN longitudinally over the entire treadmill platform. The procedure was repeated for approximately every 3 cm in a transverse direction, resulting in a dense array of calibrated points. The coefficient matrix then was scanned for missing items, completed by linear interpolation, and smoothed. The matrix covered a total walking sector of 3.5 × 1.3 m and had a resolution of 0.5 cm. It also implemented the constructive characteristic of the platform suspension and had nonmeasuring bearing points and, therefore, force shunts at both edges of the platform.

Data processing and principles of the TiF force-calculation procedure—Data processing started immediately after initiation of a measurement and involved several steps. The 18-force and 4 x- and y-positional data strings were filtered, using a **Finite Impulse Response (FIR)** low-pass filter with a cutoff frequency of 20 Hz (Kaiser-Bessel window; 129 taps; transition range 5 to 95% attenuation, 14.5 to 25.5 Hz; sampling frequency, 433 Hz). The x- and y-positions were corrected for the distance between the point of attachment of the rubber string at the lateral hoof wall to the center of the hoof. Preliminary tests revealed that for multiple forces at various FAP, the response of a specific sensor was the linear superposition of the respective weighted input forces. Therefore, for each sampling moment, 18 linear equations can be formulated, each containing 1 of the 18 sensor forces and the 4 unknown hoof forces:

$$S_n + r_n = F_{fl}\, C_{n\,(xfl;\,yfl)} + F_{fr}\, C_{n\,(xfr;\,yfr)} + F_{hl}\, C_{n\,(xhl;\,yhl)} + F_{hr}\, C_{n\,(xhr;\,yhr)}$$

where S_n is the sensor response of the force transducer n; n is the number of the force sensor (1 to 18); r_n is the error term of the corresponding equation; F_{fl}, F_{fr}, F_{hl}, and F_{hr} are the 4 unknown forces for the left forelimb, right forelimb, left hind limb, and right hind limb, respectively, at each of their respective x- and y-positions; and $C_{n\,(xfl;\,yfl)}$, $C_{n\,(xfr;\,yfr)}$, $C_{n\,(xhl;\,yhl)}$, and $C_{n\,(xhr;\,yhr)}$ are the transfer coefficients from the 4 x- and y- positions for the left forelimb, right forelimb, left hind limb, and right hind limb, respectively, to the force transducer n. This equation system was highly overdetermined. On the basis of positional data, only the hooves at stance were considered in the equation system; this controled the number of unknowns in the equations. Furthermore, the calculation algorithm included only those force sensors in the equation system that were in close vicinity to the hoof positions; this reduced the number of equations. The linear equation system was solved, using the Gaussian least-squares method.

As reported elsewhere,[28] the center of pressure moves during stance phase within the hoof (ie, from the heel region to the toe region). Because the goniometer positioning system supplied the coordinates of the center of the hoof, the FAP had to be corrected. For each time sample, the entire calculation procedure was iteratively repeated while adjusting the hoof coordinates in the horizontal plane by increments of 0.5 cm until the sum of the absolute values of the residuals (r_n in the equation) attained a minimum value. For each of the 4 resulting force curves, stance phases were detected, and temporal (stride frequency, stance time, time to peak vertical force), spatial (stance length), and force (peak vertical force, vertical impulse) variables as well as the left-right symmetry indices were extracted automatically **(Fig 2)**. The numeric results and a selection of graphic displays were available immediately after data collection.

Accuracy of the goniometer positioning system—Because the distance between the paired goniometers and their lateral distance to the treadmill were identical for all 4 pairs of goniometers, the accuracy test was conducted only for a single pair. Nine predetermined positions within the

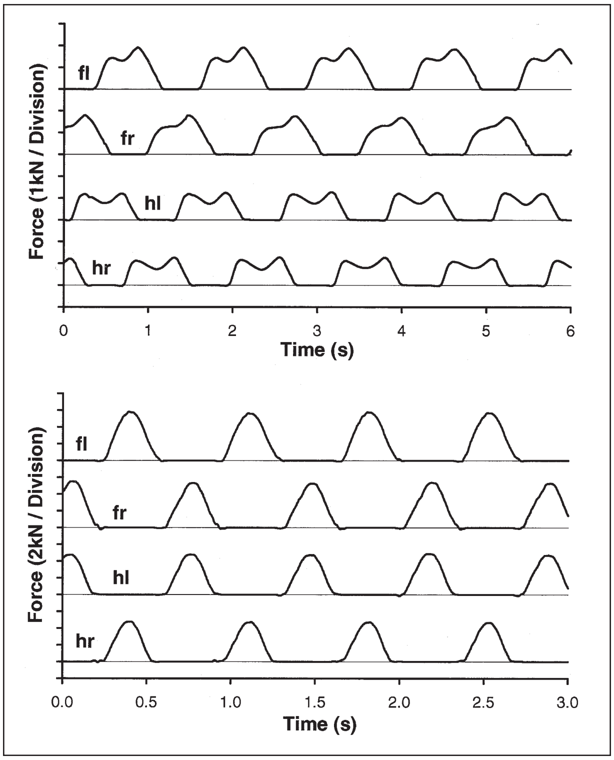

Figure 2—Representative curves of calculated vertical ground reaction forces of all 4 limbs of a horse when walking (top) and trotting (bottom). Notice the differing force patterns between the left and right forelimbs during walking. The left forelimb has a normal force dip at approximately midstance, whereas it is missing in the right forelimb because of mechanically limited hyperextension of the right metacarpophalangeal joint of this specific horse. fl = Left forelimb. fr = Right forelimb. hl = Left hind limb. hr = Right hind limb.

Unauthenticated | Downloaded 09/25/23 11:43 PM UTC

stance area of the left hind limb were surveyed repeatedly (n = 10), using the goniometer system. Target points were approached in the direction that the treadmill belt moves as well as alternatively from the opposite direction. Averaged goniometer coordinates were compared with known x- and y-positional coordinates.

Determination of the natural frequency of the system—The natural frequency spectrum of the treadmill platform was determined by **Fast Fourier Transformation (FFT)** amplitude-spectrum analysis of the raw sensor outputs (20-Hz FIR software filter was disabled). Sensor responses were recorded during a mechanical stimulus (ie, the treadmill was hit with a rubber mallet) and while a horse was trotting on the treadmill.

Linearity test of the force transfer to the individual sensors—The individual sensor responses were recorded while test loads ranging from 0.1 to 2.6 kN were applied to a defined location on the treadmill. The procedure was repeated along the longitudinal axis of the treadmill; loads were placed at the level of and between each sensor row (y-direction). Two series of measurements were made with respect to the x-direction.Test loads were placed exactly in the middle of a row and at positions one fourth of the distance between sensors of a row. Linearity was assessed by use of linear regression and qualified by the **coefficient of determination (R^2)**.

Determination of superimposed forces by use of TiF in a static configuration—Test loads were positioned within the running area of the treadmill platform to simulate realistic footfall combinations for horses that were walking, trotting, and galloping. For each record, the location within the corresponding sector of a specific limb and the magnitudes of the loads (range, 0.4 to 1.2 kN) were varied. Various 1-, 2-, and 3-test load configurations were investigated. Positions of the test loads and force-sensor data were sampled and processed with TiF. Correspondence was tested, using a 2-sided *t*-test with significance defined as $P \leq 0.05$.

Comparison of vertical ground reaction forces determined by use of a force shoe and TiF—Vertical ground reaction forces were measured simultaneously with TiF and 2 strain-gauge force shoes[a] that were tightly screwed to the horseshoes of the forelimbs of a horse. The force shoes were calibrated with a calibration press[j] up to 7 kN. Within this range, the force shoes had fully linear characteristics ($R^2 >$ 0.999) and a calibration error of ± 0.25%. To guarantee time synchronicity, signals of the force shoes were sampled and processed under equal conditions and with the same software as that used for sensor signals of the treadmill. However, unlike the sensor forces of the treadmill, bandwidth of the force shoe signals was 200 Hz. Forces for the horse were measured when the horse was walking (1.5 m/s) and trotting (3.4 m/s) over 20 and 30 strides respectively; forces were obtained twice for 20 and 30 strides for walking and trotting, respectively. Correlations between the force curves of the 2 measuring methods was assessed by use of the Pearson correlation matrix. Correspondence between results of the main temporal, spatial, and force variables were tested by use of a 2-sided *t*-test or a Wilcoxon signed-rank test, depending on results of preceding tests for normality of distribution. Values were considered significant at $P \leq 0.05$.

Results

Accuracy of the goniometer positioning system—Mean (± SD) absolute difference between known coordinates of the target points and those measured by use of the goniometer positioning system (n = 90) amounted to –0.8 ± 3.0 mm in the x-direction and –2.3 ± 1.6 mm in the y-direction. Extremes were 4.8 and 4.4 mm for the x- and y-direction, respectively.

Determination of the natural frequency of the system—For both testing conditions, main natural frequencies were observed between 40 and 60 Hz. In contrast, the relevant harmonic components of the information signal of the horse when it was trotting were < 15 Hz (**Fig 3**).

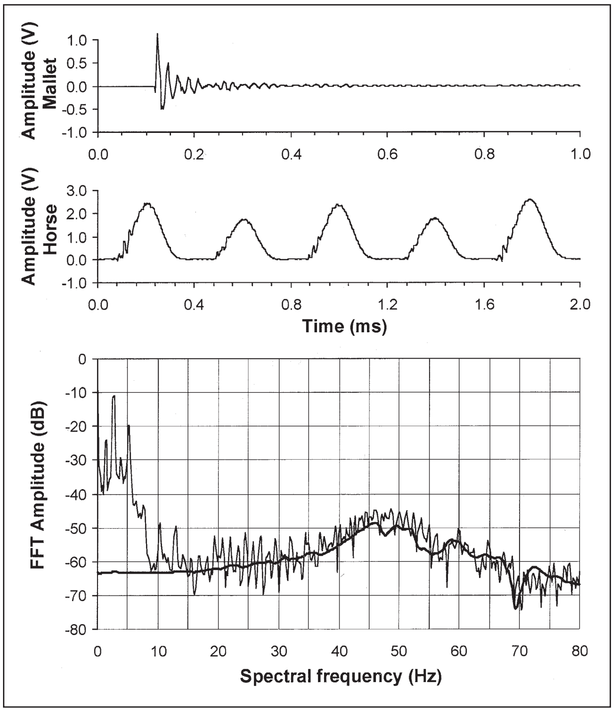

Figure 3—Response of force sensor L3 after a mallet thump (top) and while a horse was trotting on the treadmill (middle). The superimposed amplitude spectra of these 2 signals are depicted in the bottom graph; mallet, thick line; horse, fine line). Notice the frequency components of the information signal during trotting are in the band between 0 and 12.5 Hz, whereas the mechanical noise is located between 40 and 60 Hz.

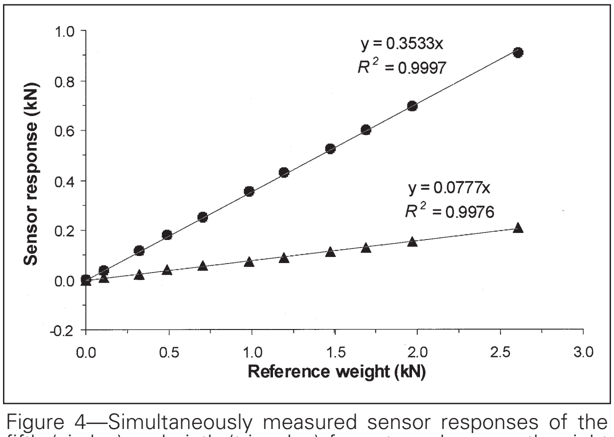

Figure 4—Simultaneously measured sensor responses of the fifth (circles) and sixth (triangles) force transducer on the right side of the treadmill to increasing loads. Test loads were applied in the center of the treadmill on the fifth sensor row. Thus, the loaded sensor row measured 70.7% of the input weight, and the adjacent row measured 15.5% of the input weight.

Unauthenticated | Downloaded 09/25/23 11:43 PM UTC

Linearity test of force transfer to individual sensors—For any test location, output voltage of each sensor was highly linear with increasing test loads ($R^2 > 0.995$; **Fig 4**). The longitudinal spread of the input load from a single FAP to the various sensors revealed the nature of the force-transfer coefficient matrix (**Fig 5**).

Determination of superimposed forces by use of TiF in a static configuration—In the 1-test load configuration, loads were determined with a mean (± SEM) precision of 100.3 ± 0.76% (n = 10). In the 2-test load configuration, loads were determined with a mean precision of 99.7 ± 0.47 and 99.5 ± 0.33% (15), and in the 3-test load configuration, loads were determined with a mean precision of 98.9 ± 0.36, 98.6 ± 0.50, and 99.0 ± 0.37%, respectively (10). Two of the 3 calculated forces differed significantly from the test loads in the 3-test load configuration.

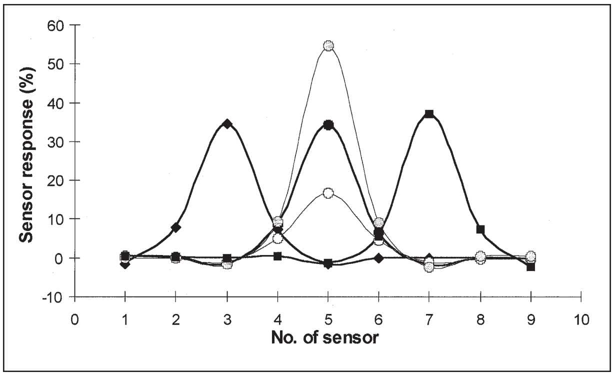

Figure 5—Longitudinal spread of the force of a test load as applied at 4 locations on the instrumented treadmill. A test load was centered on the third (diamond), fifth (solid circle), and seventh (square) sensor row, and corresponding responses were measured in the sensors on the left side of the treadmill. In addition, the test load was placed halfway between the center and the left sensor in row 5, and responses of the left (gray circle) and right (open circle) sensors were measured. Sensor responses were normalized relative to the test load. Notice the symmetric spreading independent of the position of the test load and the negative forces at the subsequent alternate rows from the point of load application.

Comparison of vertical ground reaction forces determined by use of a force shoe and TiF—Examples of directly measured ground reaction forces recorded with the force shoes were superimposed on calculated force curves obtained with TiF (**Fig 6**). The **Pearson product-moment correlation coefficient (*r*)** of force curves when the horse was walking and trotting was ≥ 0.999 and ≥ 0.998, respectively. Absolute values and percentage differences of the main temporal, spatial, and force variables were calculated (**Table 1**). Mean differences did not exceed 4.5%. Nevertheless, values for all variables differed significantly.

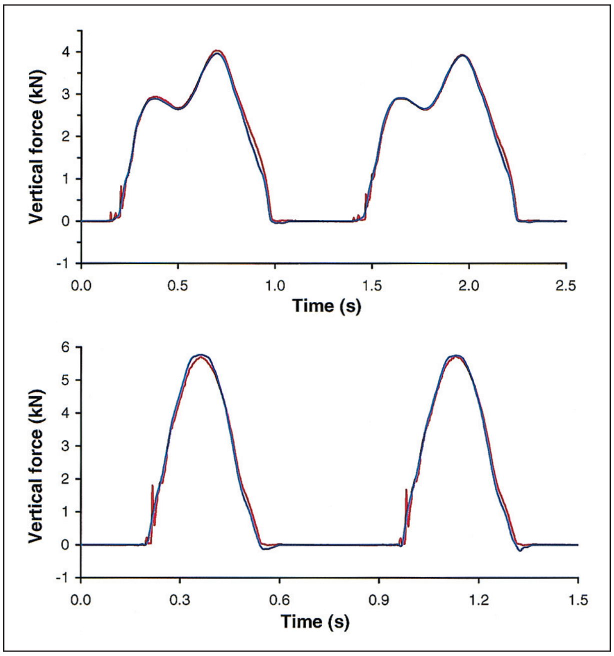

Figure 6—Comparison between vertical force curves measured by use of a force shoe (red line) and the treadmill-integrated force measuring system (blue line) for the left forelimb of a horse when walking (top) and trotting (bottom). Notice the small force spikes on the force shoe curve at impact when the horse was walking and the more prominent impact peaks when the horse was trotting.

Table 1—Comparison between mean ± SD values of temporal, spatial, and force variables measured by use of the treadmill-integrated force (TiF) measuring system or force shoes in a horse walking (40 strides) or trotting (60 strides).

	Left forelimb			Right forelimb		
Variable	Force shoe	TiF	Mean difference*	Force shoe	TiF	Mean difference*
Walk						
T_{stance} (ms)	801 ± 12	791 ± 11	–1.2%	811 ± 11	796 ± 9	–1.8%
T_{Fmax} (ms)	513 ± 11	508 ± 10	–1.1%	507 ± 11	498 ± 9	–1.9%
SL (m)	1.177 ± 0.020	1.165 ± 0.017	–1.0%	1.225 ± 0.016	1.217 ± 0.016	–0.7%
Fz_{max} (N)	3,906 ± 82	3,852 ± 83	–1.4%	3,765 ± 58	3,612 ± 54	–4.1%
Iz (N·s)	2,041 ± 28	2,008 ± 29	–1.6%	1,913 ± 26	1,824 ± 24	–4.5%
Trot						
T_{stance} (ms)	347 ± 11	337 ± 8	–2.8%	334 ± 7	333 ± 7	–0.3%
T_{Fmax} (ms)	172 ± 6	166 ± 5	–3.6%	160 ± 4	161 ± 4	+1.1%
SL (m)	0.983 ± 0.025	0.966 ± 0.022	–1.7%	0.982 ± 0.025	0.976 ± 0.024	–0.7%
Fz_{max} (N)	5,566 ± 189	5,679 ± 197	+2.0%	5,687 ± 168	5,698 ± 157	+0.2%
Iz (N·s)	1,136 ± 43	1,143 ± 43	+0.6%	1,110 ± 44	1,099 ± 40	–0.9%

*Mean differences were calculated relative to values of force shoes.
T_{stance} = Stance time. T_{Fmax} = Time to peak force. SL = Stance length. Fz_{max} = Peak vertical force. Iz = Vertical impulse.

Unauthenticated | Downloaded 09/25/23 11:43 PM UTC

Discussion

To achieve a high standard in safety and locomotor convenience for horses, the running platform was mounted on elastic shock-absorbing bearings that compress slightly under a load. This allows training, exercise physiology, and sport medical investigations without causing harm to any horses. Because of the high forces involved, the platform bent locally at each place where the hoof was in contact with the treadmill. This type of construction has an inherent tendency to oscillate. From the technical point of view, the flexibility of the bearing-platform construction appeared to be suboptimal. Normally, a force-measuring system for undistorted signals should have maximal rigidity and be lightweight to attain a high resonant frequency. Also, the 15-mm textile-armored rubber belt of the treadmill contributed to damping characteristics of the treadmill. This limited the frequency components of the hoof forces and, therefore, decreased the requirements for signal bandwidth of the measuring system. Whereas a classic force plate immediately supplies the contact force of a hoof strike, TiF must calculate the input forces from numerous sensor responses. Each of these signals is contaminated by mechanical vibration noise, which differs at each bearing point as well as being phase-shifted. We redesigned the platform construction for one fourth less weight and increased the longitudinal flexibility and number of bearing points. This resulted in more-localized less-energetic oscillations. Analysis of the results revealed that the natural frequencies were located between 40 and 60 Hz, which was 3 times higher than the frequency components of the information signal (< 15 Hz; Fig 3). To eliminate noise from the raw sensor signals, a steep 20-Hz FIR filter was used. In comparison to the 200-Hz bandwidth signal of the force shoe, this did not alter the principal characteristics of the force curve (eg, slope rate, peak values) and, therefore, had an insubstantial influence on the main variables (Fig 6; Table 1). The only exception was the impact peak, which was smoothed, compared with the signal obtained by use of the force shoe.

We observed only a narrow spread of forces to adjacent rows of sensors. Almost the total force was detectable within 3 sensor rows (ie, the force spreads out from the FAP over a distance of 36 cm in either direction; Fig 5). The loaded sensor row measured approximately two thirds of the input weight, and the adjacent rows each recorded one sixth of the input weight. This resulted in high force amplitudes of selected sensors and, therefore, a favorable signal-to-noise ratio. On the other hand, this sharp force distribution enhanced the demands on determination of the FAP. Because of the resolution of the coefficient matrix, the accuracy and repeated precision of the positioning system must be < 0.5 cm. This prerequisite was met. As during the stance phase, the center of pressure moved through the hoof in the longitudinal axis by approximately 5 cm,[28] the x- and y-coordinates measured by the goniometer positioning system must be corrected.

The validation experiments revealed a good correlation between static test loads and TiF-calculated forces (deviations ≤ 1.4%) as well as high correspondence between continuous force data of TiF and force shoes ($r \geq 0.998$). Maximal mean differences of temporal variables between the 2 measuring methods did not exceed 1.9% when the horse walked and 3.6% when it trotted. Maximal mean differences of spatial variables were ≤ 1% when walking and < 2% when trotting. Mean differences of force variables did not exceed 4.5% when walking and 2.0% when trotting. However, all mean differences reported were significant (Table 1). Because of the high reproducibility of the 2 measuring systems, their differences had narrow standard errors. Therefore, even marginal differences (< 1%) between the input and output values were significant. For biomedical measurements, an error of 2 to 5% is typically acceptable. Also, some of the differences between reference and calculated loads of the 3-load configuration in the static configuration were significant, although the mean precision was ≥ 98.6%.

The force shoe was calibrated for full ground contact and the vertical component only. Especially during the late stance, when the hoof tilts over the toe region of the force shoe, the force vector moves out of the calibrated central area (42 mm in diameter) of the force shoe; additionally, a fraction of the fore-aft push-off force was transmitted erroneously as vertical values. This may have explained a certain amount of the slight divergence between the 2 curves (Fig 6).

Extrapolation of treadmill data to equivalent data for horses running on the ground is inadequate. Although the patterns of TiF-measured force curves resembles closely force traces obtained from locomotion on the ground,[20,21] small differences in peak force magnitudes between these 2 approaches, similar to those observed in humans,[29,30] should be expected in horses. Lower push-off forces should be considered when interpreting treadmill data, particularly for higher speeds and heavier horses, since forces associated with belt friction increase with body mass. However, this does not disqualify this measuring system, especially when looking for left-right asymmetries. Because the treadmill belt imposes the path of the limbs, horizontal forces (fore-aft and lateral) are not measurable with this concept. This limits certain applications in gait analyses (eg, advanced inverse dynamic calculations).

One of the main operational areas of TiF is in the field of orthopedic diagnostics and research, where quantification of load distribution within the 4 limbs is essential. The ability to discriminate between physiologic left-right asymmetry or natural predisposition for a limb[31] from mild pathologic deviations in the locomotion pattern may be addressed more objectively with this measuring system. In general, horses with marked lameness should not be exercised on a treadmill. This implies that use of TiF or gait analyses in general make more sense when performed on horses with subtle or mild lameness of complex nature. During an orthopedic work-up, the degree of lameness can be quantified and documented. Within sport medical care and preventive medicine, general locomotion status can be assessed periodically. Finally, curative procedures as well as rehabilitative training can be monitored more closely.

Horses are carefully adapted to walking on a treadmill during short sessions of 10 to 20 minutes. Most horses appear comfortable after 2 to 3 repeated ses-

Unauthenticated | Downloaded 09/25/23 11:43 PM UTC

sions of walking and trotting and will have their characteristic gait pattern, similar to that manifested on a concrete runway. Frequently, lameness is more pronounced on a treadmill. The gait rhythm is more regular, especially at lower velocities, which decreases intersubject variability. Horses have to be minimally equipped with a hook for attachment of a rubber string. The outward tension of the rubber string is minimal, and it was tolerated well by all horses in our study. Data acquisition can be performed in a short time frame. Typically, for walking and trotting horses, up to 50 strides can be recorded for each speed of locomotion within < 5 minutes. This and the rapid availability of temporal, spatial, and kinetic data can be important advantages in a clinical situation and when dealing with orthopedic or other rehabilitation patients that cannot physically tolerate long periods of trotting during examinations. The large number of successive strides can be averaged to determine more representative values, thereby increasing statistical power. The distribution of load between the 4 limbs can be assessed for highly standardized conditions. With regard to drift, the noticeable stability of the charge amplifiers we used allowed us to conduct repeated measurements for up to 30 minutes without resetting the force sensors.

Information on load distribution and interlimb coordination creates novel perspectives for assessing gait quality and efficiency. The influence of a rider on the horse's center of mass and the effect of fatigue on the impulse pattern are interesting aspects that can be studied.

The measurement system described here has the capability to measure the vertical ground reaction force of all 4 limbs simultaneously and to assess interlimb coordination during successive strides. Factors influencing the pattern of ground reaction forces such as soil condition, velocity of locomotion, and duration of exercise can be strictly controlled by this experimental configuration, guaranteeing high reproducibility and standardization. This allows reliable follow-up studies of a subject as well as comparison among subjects.

[a]Hugelshofer J. Vergleichende Kraft- und Belastungszeit-Messungen an den Vorderhufen von gesunden und an Podotrochlose erkrankten Pferden. Vet med thesis, Zurich University Press, 1982.
[b]Weishaupt MA, Hogg HP, Wiestner T, et al. Development of a technique for measuring ground reaction force in the equine on a treadmill (abstr), in *Proceedings. 3rd Int Workshop Anim Locomotion* 1996;1.
[c]Mustang 2200, Kagra AG, Fahrwangen, Switzerland.
[d]Type Z17135, Kistler Instruments, Winterthur, Switzerland.
[e]Type 5037A3, Kistler Instruments, Winterthur, Switzerland.
[f]Type TK 162/1000, Tekel Instruments, Roletto, Italy.
[g]Inmos T805-30MHz, STMicroelectronics, Genève, Switzerland.
[h]IBM compatible PC (Intel PIII, 512 kB cache, 1.2 GHz, 128 kB RAM), Micropose AG, Zurich, Switzerland.
[i]HP2, Department of Veterinary Surgery, University of Zurich, Zurich, Switzerland.
[j]Zwick 1484, Zwick GmbH & Co, Ulm, Germany.

References

1. Jeffcott LB, Rossdale PD, Freestone J, et al. An assessment of wastage in Thoroughbred racing from conception to 4 years of age. *Equine Vet J* 1982;14:185–198.
2. Rossdale PD, Hopes R, Wingfield Digby NJ, et al. Epidemiological study of wastage among racehorses 1982 and 1983. *Vet Rec* 1985;116:66–69.
3. Morris EA, Seeherman HJ. Clinical evaluation of poor performance in the racehorse: the results of 275 evaluations. *Equine Vet J* 1991;23:169–174.
4. Keegan KG, Wilson DA, Wilson DJ, et al. Evaluation of mild lameness in horses trotting on a treadmill by clinicians and interns or residents and correlation of their assessments with kinematic gait analysis. *Am J Vet Res* 1998;59:1370–1377.
5. Morris EA, Seeherman HJ. Redistribution of ground reaction forces in experimentally induced carpal lameness. In: Robinson NE, Gillespie JR, eds. *Equine exercise physiology 2*. Davis, Calif: ICEEP Publications, 1987;553–563.
6. Merkens HW, Schamhardt HC. Evaluation of equine locomotion during different degrees of experimentally induced lameness. I: Lameness model and quantification of ground reaction force patterns of the limbs. *Equine Vet J Suppl* 1988;6:99–106.
7. Merkens HW, Schamhardt HC. Evaluation of equine locomotion during different degrees of experimentally induced lameness. II: Distribution of ground reaction force patterns of the concurrently loaded limbs. *Equine Vet J Suppl* 1988;6:107–112.
8. Merkens HW, Schamhardt HC, Hartman W, et al. The use of H(orse) INDEX: a method of analyzing the ground reaction force patterns of lame and normal gaited horses at the walk. *Equine Vet J* 1988;20:29–36.
9. Dow SM, Leendertz JA, Silver IA, et al. Identification of subclinical tendon injury from ground reaction force analysis. *Equine Vet J* 1991;23:266–272.
10. Williams GE, Silverman BW, Wilson AM, et al. Disease-specific changes in equine ground reaction force data documented by use of principal component analysis. *Am J Vet Res* 1999;60:549–555.
11. Clayton HM, Schamhardt HC, Willemen MA, et al. Kinematics and ground reaction forces in horses with superficial digital flexor tendinitis. *Am J Vet Res* 2000;61:191–196.
12. Huskamp B, Tietje S, Nowak M, et al. Fussungs- und Bewegungsmuster gesunder und strahlbeinkranker Pferde—gemessen mit dem Equine-Gait-Analysis-System (EGA-System). *Pferdeheilk* 1990;6:231–236.
13. Weishaupt MA, Schatzmann U, Straub R. Quantifizierung der Stützbeinlahmheit mit Hilfe akzelerometrischer Messungen am Kopf des Pferdes. *Pferdeheilk* 1993;9:375–377.
14. Barrey E, Debrosse F. Lameness detection using an accelerometric device. *Pferdeheilk* 1996;12:617–622.
15. Weishaupt MA, Wiestner T, Hogg, HP, et al. Assessment of gait irregularities in the horse: eye versus gait analysis. *Equine Vet J Suppl* 2001;33:135–140.
16. Auer JA, Fackelman GE, Gingerich DA, et al. Effect of hyaluronic acid in naturally occurring and experimentally induced osteoarthritis. *Am J Vet Res* 1980;41:568–574.
17. Goodship AE, Brown PN, MacFie HJH, et al. A quantitative force plate assessment of equine locomotor performance. In: Snow DH, Persson SGB, Rose RJ, eds. *Equine exercise physiology 1*. Cambridge, England: Granta Editions, 1983;263–270.
18. Keg PR, van den Belt AJM, Merkens HW, et al. The effect of regional nerve blocks on the lameness caused by collagenase induced tendonitis in the midmetacarpal region of the horse: a study using gait analysis, and ultrasonography to determine tendon healing. *Zentralbl Veterinarmed A* 1992;39:349–364.
19. McLaughlin RM Jr, Gaughan EM, Roush JK, et al. Effects of subject velocity on ground reaction force measurements and stance times in clinically normal horses at the walk and trot. *Am J Vet Res* 1996;57:7–11.
20. Merkens HW, Schamhardt HC, Hartman W, et al. Ground reaction force patterns of Dutch Warmblood horses at normal walk. *Equine Vet J* 1986;18:207–214.
21. Merkens HW, Schamhardt HC, van Osch GJVM, et al. Ground reaction force patterns of Dutch Warmblood horses at normal trot. *Equine Vet J* 1993;25:134–137.
22. Merkens HW, Schamhardt HC, van Osch GJVM, et al.

Unauthenticated | Downloaded 09/25/23 11:43 PM UTC

Ground reaction force patterns of Dutch Warmbloods at the canter. *Am J Vet Res* 1993;54:670–674.

23. Merkens HW, Schamhardt HC. Distribution of ground reaction forces of the concurrently loaded limbs of theDutch Warmbloodhorse at the normal walk. *Equine Vet J* 1988;20:209–213.

24. Seeherman HJ. The use of high-speed treadmills for lameness and hoof balance evaluations in the horse. *Vet Clin North Am Equine Pract* 1991;7:271–309.

25. Buchner HHF, Savelberg HHCM, Schamhardt HC, et al. Habituation of horses to treadmill locomotion. *Equine Vet J Suppl* 1994;17:13–15.

26. Khumsap S, Clayton HM, Lanovaz JL. Effect of walking velocity on ground reaction force variables in the hind limb of clinically normal horses. *Am J Vet Res* 2001;62:901–906.

27. Buchner HHF, Savelberg HHCM, Schamhardt HC, et al. Kinematics of treadmill versus overground locomotion in horses. *Vet Q* 1994;16:S87–S90.

28. Wilson AM, Seelig TJ, Shield RA, et al. The effect of foot imbalance on point of force application in the horse. *Equine Vet J* 1998;30:540–545.

29. Kram R, Griffin TM, Donelan JM, et al. Force treadmill for measuring vertical and horizontal ground reaction forces. *J Appl Physiol* 1998;85:764–769.

30. White SC, Yack HJ, Tucker CA, et al. Comparison of vertical ground reaction forces during overground and treadmill walking. *Med Sci Sports Exerc* 1998;30:1537–1542.

31. Drevemo S, Fredricson I, Hjerten G. Early development of gait asymmetries in trotting Standardbred colts. *Equine Vet J* 1987;19:189–191.

Unauthenticated | Downloaded 09/25/23 11:43 PM UTC