TECHNIQUE FOR MEASURING VERTICAL GROUND REACTION FORCES OF A HORSE ON A TREADMILL

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Introduction
Traditionally, the evaluation of gait inadequacies in horses is based on subjective assessments and is therefore relying strongly on the expertise of the orthopaedic clinician. Kinetic gait analysis devices as force plates, force-measuring horseshoes and the Kaegi Equine-Gait-Analysis System have been used to quantify locomotor unsoundness reliably. However, these measuring concepts are confined by the number of ground contacts and limbs measured simultaneously. When using force plates, problems of obtaining repeatable constant speed trials or targeting the platform may present a significant restriction, especially when dealing with quadruped animals. Two to six attempts are needed for a single valid foot strike, depending on the gait (walk, trot or canter). Data acquisition and processing are consequently extremely time consuming. Equine highspeed treadmills are established instruments in equine exercise physiology and proved to be also very useful for visual gait and kinematic assessments. External factors influencing gait characteristics as ground condition, environment and especially subject velocity can be highly standardised.

The aim of this development was to 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 at the walk, trot and gallop.

Methods
An equine high-speed treadmill (Mustang 2200, Kagra AG, Fahrwangen, Switzerland) was modified. At 18 bearing points of the treadmill platform a force sensor block was inserted that measures the vertical component of the force at the respective location. One sensor block consists of two piezoelectric shear-stress sensitive force cells (Typ Z17135, Kistler Instruments, Winterthur, Switzerland). As during locomotion up to three hoof forces are acting simultaneously on this platform, the direct determination of the different forces is infeasible. However, if the force application points of the acting forces are known, the unknown hoof forces can be calculated from the entire ground reaction by weighting the sensor forces with their transfer coefficients of the corresponding force application points. The XY-co-ordinates of each hoof on the treadmill surface are calculated by triangulation, based on angle values determined with a pair of incremental angular encoders (Typ TK 162/1000, Tekel Instruments, Rololetto, Italy), connected to the corresponding hoof with a thin rubber string. All signals are sampled within 30 µs at a rate of 433 Hz. Force and positional strings are filtered using a low pass filter with a cut-off frequency of 20 Hz. The coefficient matrix was generated by rolling a single-wheel calibration trolley with a known weight longitudinally over the whole treadmill platform. It covers a total walking sector of 3.5 x 1.3 m and has a resolution of 0.5 cm. In the case of multiple forces at different force application points, the response of a specific sensor is the linear superposition of the respective weighted input forces. Therefore, for each sampling moment 18 linear equations can be formulated, each containing one of the 18 sensor forces and the four unknown hoof forces:

$$S_n + r_n = (F_{fl} x_{1,y1} \times C_{n x1,y1}) + (F_{fr} x_{2,y2} \times C_{n x2,y2}) + (F_{hl} x_{3,y3} \times C_{n x3,y3}) + (F_{hr} x_{4,y4} \times C_{n x4,y4})$$

where $S_n$ is the sensor response of the force transducer $n$ ($n=1, 2 \ldots 18$); $r_n$ is the error term of the corresponding equation; $F_{fl}, F_{fr}, F_{hl}$, and $F_{hr}$ are the 4 unknown forces (left front, right front, left hind and right hind limb) at their respective XY-positions and $C_{n x1,y1}, C_{n x2,y2}, C_{n x3,y3}$ and $C_{n x4,y4}$ are the transfer coefficients from the 4 XY-positions to the force transducer $n$. 
This linear equation system is highly over-determined and is solved using the Gaussian least squares method. For each of the 4 resulting force curves (Fig. 1) stance phases are detected and temporal (stride frequency, stance time), spatial (stride length) and force parameters (peak vertical force, vertical impulse) as well as their left-right symmetry indices are extracted automatically. The numeric results and a selection of graphic displays (Fig. 2a, 2b) are available immediately after data collection.

**Figure 1:** Representative curves of calculated vertical ground reaction forces of all 4 limbs (fl, left front; fr, right front; hl, left hind; hr, right hind) at the walk.

In order to verify the treadmill integrated force measuring system (TiF), vertical ground reaction forces were measured simultaneously with two strain-gauge force shoes screwed tightly to the horseshoes of the front limbs of a horse. The horse was measured at walk (1.5 m/s) and trot (3.4 m/s) twice over 20 and 30 strides, respectively.
Results & Discussion
An example of directly measured ground reaction forces recorded with the force shoe superimposed with the TiF calculated force curve is presented in Fig. 3.

Figure 3: Comparison between vertical force traces measured with the force shoe (red curve) and TiF (blue curve) of the left front limb at the trot. Note the prominent impact peak on the force shoe curve at impact.

The validation experiments showed a very good correspondence between force shoe parameters and those determined by TiF. Maximal differences of temporal variables between the two measuring methods did not exceed 1.8% at the walk and 2.8% at the trot; maximal differences of spatial parameters were <1% at the walk and <2% at the trot and differences of force parameters did not exceed 4.5% at the walk and 2.0% at the trot. Though the impact peak is almost filtered away, the slope rate of the TiF calculated force curves are nearly identical compared to the force shoe traces (Fig. 3).

One of the main operational areas of TiF lies in the field of orthopaedic diagnostics and research, where quantification of load distribution within the 4 limbs is essential. The question to discriminate between physiologic left-right asymmetry or "leggedness" from mild pathologic deviations in its locomotion pattern may be addressed more objectively. During an orthopaedic work-up the degree of lameness can be quantified and documented. Within sports medical care and preventive medicine a general locomotor status can be assessed periodically. Curative procedures as well as rehabilitation training can be monitored more closely. Information on load distribution and inter-limb co-ordination opens novel perspectives in assessing gait quality and efficiency. The influence of a rider on the horse's centre of mass or the effect of fatigue on the impulse pattern are further interesting aspects to be studied. 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 as e.g. advanced inverse dynamic calculations.

The presented treadmill integrated force measuring system, TiF, has the capability to measure the vertical ground reaction force of all 4 limbs simultaneously and assess inter-limb co-ordination over successive strides reliably and is therefore suitable for experimental as well as for clinical investigations. Data acquisition can be performed in a very short period of time. Within less than 5 minutes the necessary strides (up to 50), each at the walk and trot are recorded. The large number of successive strides can be averaged to determine more representative values, thereby increasing statistical power. Factors influencing the GRF pattern critically, such as soil condition, running velocity and duration of exercise, are strictly controlled in this set-up, guaranteeing high reproducibility and standardisation of the trial run. This allows reliable follow-up studies of a subject and comparison between individuals.

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