



Equine hoof slip distance during trot at training speed: Comparison between kinematic and accelerometric measurement techniques



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ABSTRACT

Longitudinal sliding of horse's hooves at the beginning of stance can affect both performance and orthopaedic health. The objective of this study was to compare two measurement methods for quantifying hoof slip distances at training trot. The right front hoof of four French Trotters was equipped with an accelerometer (10 kHz) and kinematic markers. A firm wet sand track was equipped with a 50 m calibration corridor. A high-frequency camera (600 Hz) was mounted in a vehicle following each horse trotting at about 7 m/s. One of the horses was also trotted on raw dirt and harrowed dirt tracks. Longitudinal slip distance was calculated both from kinematic data, applying 2D direct linear transformation (2D-DLT) to the markers image coordinates, and from the double integration of the accelerometer signal. For each stride, both values were compared. The angle of the hoof with respect to the track was also measured.

There was 'middling/satisfactory' agreement between accelerometric and 2D-DLT measurements for total slip and 'fairly good' agreement for hoof–flat slip. The influence of hoof rotation on total slip distance represented <6% of accelerometric measures. The differences between accelerometric and kinematic measures (from –0.5 cm to 2.1 cm for total slip and from –0.2 cm to 1.4 cm for hoof–flat slip) were independent of slip distance magnitude. The accelerometric method was a simple method to measure hoof slip distances at a moderate training speed trot which may be useful to compare slip distances on various track surfaces.

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Introduction

Ground surfaces properties may contribute to the incidence of musculoskeletal injuries, which are the main cause of disability in athletic horses, especially racehorses (Henley et al., 2006). Sliding of the horse's hooves on the ground at the onset of the stance phase is an important component of hoof–ground interaction. Theoretically, hoof slip could be considered as a possible factor contributing to injuries since a slippery surface represents a risk during a race. However, moderate longitudinal hoof sliding can also improve performance, especially in trotters, as it increases stride length. Sliding of the hoof allows energy dissipation as it tends to lower the rate of application of the longitudinal ground reaction force (GRF) on the limb, meaning that moderate slip places less stress on the limb tissues during initial loading (Nigg and Segesser, 1988).

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In human and animal biomechanics, position and displacement measurements are usually undertaken using kinematic methods and mainly at low speed (Troy and Grabiner, 2006; Li et al., 2008). In the horse, Pardoe et al. (2001) studied the effect of shoe material on hoof slip at impact on concrete in horses trotting at very low speed (less than 3 m/s) with a 3-dimensional (3D) motion capture system (240 Hz). Parson et al. (2011) measured hoof slip distance in elite galloping horses (about 16 m/s) on an all-weather training track using a stationary video camera (250 Hz). The distances between the vertical bars of the side rails and the position of the horse in the track (near, middle and far) were used to obtain an approximation of the scaling factor. Harvey et al. (2012) studied the effect of lateral heel studs on the digital kinematics of horses cantering (at about 11 m/s) on grass with the help of a stationary camera (125 Hz) and a marker painted on the hoof. The scaling factor was obtained using a calibration stick of known length. However, sources of errors in these methods included camera calibration (approximate scaling factor) and detection of the beginning and end of the slip phenomenon from the images at these low frame rates.

Measuring hoof slip distance in the horse at training speed brings several constraints. The use of a stationary camera limits the number of recorded strides for a same horse. Furthermore, most classical 3D motion capture systems require a setting of multiple cameras and a cumbersome calibration, and are not well suited for measurements in outdoor conditions. Knowing these constraints, 2D direct linear transformation (Brewin and Kerwin, 2003) with a camera following the horse during the run is a good kinematic solution, as slip is a mainly planar phenomenon. The use of this method was recently validated in the horse (Holden-Douilly et al., in press). The use of an accelerometer installed on the hoof is also a conceivable solution. Burn (2006) used two accelerometers (10 kHz) to measure slip acceleration, speed and position (vs. time) on the front hooves of three horses trotting at low speed (3.6 ± 0.4 m/s) on a sand and a tarmac surface, but focussed on time domain characteristics and vibratory phenomena.

Considering the potential benefit of accelerometry (easy to perform, without calibration, possible recording of successive strides), the objective of the present study was to compare the accelerometric technique with 2D-DLT kinematics with a moving camera, to measure the longitudinal front hoof slip distance in horses trotting at training speed.

Materials and methods

Materials and experimental protocol

Four harness French Trotters (mean body mass $\pm$ standard deviation [SD]: 550 ± 22 kg, 10 ± 7 years old) were trotted by an experienced driver at 7 m/s over a distance of 50 m on a firm wet sand (FWS) track delimited on a natural sand beach. One of the horses was also trotted at the same speed on a dirt surface tightly packed down. One portion of this track was left untreated and called raw dirt (RD) while another part was superficially harrowed (harrowed dirt (HD)). At least three trials were performed for each horse and surface.

The right front hoof of each horse was equipped with one triaxial piezo-electric accelerometer (Model 356B20, PCB Piezotronics). This device (frequency response: 2–10,000 Hz) was fixed rigidly to the dorsal hoof wall by use of a shaped metal plate screwed into the horn. The toe angle was measured with a goniometer and used to express hoof acceleration in a reference frame in which vertical acceleration was perpendicular to the sole and longitudinal acceleration was palmaro-dorsal. Accelerations directed forward, lateral and downward were denoted positive (Fig. 1A). The right front hoof was also equipped with a dynamometric horseshoe composed of four triaxial piezoelectric force sensors (Model 260A11, PCB Piezotronics) (Chateau et al., 2009). The data acquisition devices were fitted in a box on the sulky. Data acquisition was performed at 10 kHz. The speed of the horse was recorded by use of a third wheel equipped with a hub dynamo (Nabendynamo, Schmidt) fixed behind the sulky.

Calibration markers (51 pairs) were installed at every meter on each track, using two parallel and tightened cables 2.9 m apart (Fig. 1D). Three circular and reflective kinematic markers were stuck on a T-shaped aluminium plate screwed on the right front hoof (Fig. 1A). The only hoof marker used to compute slip distance was the lowest marker of the hoof, which was positioned at the same height as the calibration plane during the stance phase. A high frequency camera (600 Hz, resolution: 1024×640 , field: 4.5 m wide; Phantom v5.1, Vision Research) mounted in a vehicle following the horse was used to film the trotting horse during successive strides (about eight strides per acquisition).

Synchronization between the accelerometric signal and camera images was performed with a LED fixed on the horse, triggered during the acquisition and from which voltage was recorded simultaneously with the accelerometric signal.

Data processing

Characteristic events

As the hoof's first contact on the ground is mainly at the heels (Chateau et al., 2010), slip comprises two phases. During the first phase, the hoof slides while it is not completely flat on the ground. The second phase begins at the time when the hoof is in full contact with the ground, defined as hoof-flat time, and lasts until the end of the slip phenomenon, defined as slip-stop. The time at the very first appearance of high-frequency vibrations on the accelerometric signal is defined as the impact time, which corresponds to the very first contact of the hoof on the ground. The occurrence of the hoof-flat time was identifiable using the instrumented horseshoe by the detection of the concomitant loading of the four force sensors at the beginning of the stance phase. This event was synchronous with the peak of maximal vertical deceleration after the impact. This accelerometric event was then used to obtain the hoof-flat time (Fig. 2). The time when the longitudinal

acceleration becomes nil was defined as the slip-stop event. In order to be consistent, these three accelerometric events were used to mark out the boundaries of slip distance for both accelerometric and kinematic measurements.

The value defined as 'total slip' was the longitudinal (X direction) distance travelled by the hoof between the impact and the slip-stop event. The value defined as 'hoof-flat slip' was the distance travelled between hoof-flat time and slip-stop.

Accelerometer

A mathematical correction was applied to the Internal Electronics Piezo Electric (IEPE) signal before its double-integration in order to cope with the discharge phenomenon of the capacitor in the internal electronics of the accelerometer (Holden et al., 2010). A double integration of the longitudinal acceleration was performed, for each stride, between impact and slip-stop event (Fig. 2), to obtain longitudinal speed and longitudinal position. The following boundary conditions were used: (1) Longitudinal speed at slip stop ($v_{\text{slip stop}} = 0$ m/s, as the hoof becomes stationary at this time; (2) Longitudinal position at impact ($t_{\text{impact}} = 0$ m, as the longitudinal position is interesting from this moment on.

Kinematics

To compute slip distances from the kinematic data, calibration markers and markers placed on the hoof were tracked using a custom-made software (Matlab, The MathWorks). Knowing the actual coordinates of the calibration markers, the 2D-DLT parameters could be determined for each image from the 2D-DLT equations linking actual coordinates (X, Y) and image coordinates (u, v). Then, the actual coordinates of the lowest hoof marker were computed (Holden-Douilly et al., in press). The longitudinal (X) coordinate of this marker was then filtered with a low-pass filter (cut-off frequency = 60 Hz) and resampled at 10 kHz. Finally, slip distances were determined between the same boundaries as for the accelerometric measurements using the same events (impact, hoof-flat and slip-stop).

Data analysis

Agreement between techniques

A total of 62 strides were analysed on firm wet sand for the four horses. The correlation between the two methods was mathematically assessed with the help of the Concordance Correlation Coefficient (CCC; Crawford et al., 2007). Bland and Altman style plots (Bland and Altman, 1986) were also used to study the agreement of the two measurement techniques: it consisted in representing, for all strides, the difference between accelerometric and kinematic slip distances as a function of the mean of both results (representing slip distance for the given stride).

For the horse used to test three surfaces, 54 strides were measured (firm wet sand, $n = 20$; harrowed dirt, $n = 11$; raw dirt, $n = 23$). Mean slip distances given by each measurement technique and mean differences between accelerometric and kinematic measures were calculated for each surface.

Effect of hoof rotation on total slip distance

As the accelerometer and the hoof marker could not be placed at the centre of rotation of the hoof, this rotation occurring at the onset of the stance phase induces two kinds of errors on accelerometric and kinematic total slip distances. The effects of hoof rotation on both measurements were assessed on the data obtained on the firm wet sand for which the four horses were used.

In the accelerometer reference frame, this rotation generates a centripetal acceleration (Fig. 3) which magnitude was calculated for each stride as follows:

$$a_c = d_{\text{heel-acc}} \times \omega^2$$

where $d_{\text{heel-acc}}$ is the distance between the centre of hoof rotation (located at the heels) and the centre of the accelerometer and ω is the rotation speed (rad/s, calculated from kinematic measurements) of the hoof between impact and hoof-flat time. For each stride, the projection of this calculated centripetal acceleration onto the longitudinal axis of the hoof reference frame was then added to the measured longitudinal acceleration between impact and hoof-flat time. Double-integration of this corrected longitudinal acceleration was used to calculate a corrected total slip distance.

Hoof rotation also has an effect on kinematic measurements as the hoof marker is turning around the heels. The horizontal and vertical displacements of the marker due to rotation were calculated using the angle of the rotation (calculated from kinematic measurements) and the distance between the centre of rotation (located at the heels) and the centre of the hoof marker (Fig. 3).

Results

Agreement between techniques

On firm wet sand, mean speed $\pm$ SD at the trot was 7.3 ± 0.5 m/s for the four horses on the 62 studied strides. Mean $\pm$ SD kinematic total slip distance was 3.61 ± 1.49 cm and kinematic hoof-flat slip distance was 2.70 ± 1.28 cm (Table 1). Accelerometric slip

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