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Hoof Landing Velocities in Trotting Horses

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ABSTRACT. Cinematographic determinations of vertical and horizontal hoof landing velocities, as well as the angle of the lower extremity to the vertical at hoof strike, were made. The longitudinal hoof velocity was then calculated from these variables. Four horses trotting at various velocities were used in this study. The results showed significant linear relationships between the variables and trotting velocities with the exception of the vertical velocity of the hind hoof. These results may provide a basis for further studies of impact and the ensuing damage related to hoof strike

Key words Landing velocities; hoof strike; horses; impact

INTRODUCTION

Human locomotion analysis, because of its relative sophistication, has introduced many concepts into equine locomotion analysis. One such concept that has been intensively studied in humans is heel strike or foot strike. The term heel strike is anatomically ambiguous,[2] and the term foot strike is applicable only to humans. Thus, the term hoof strike is used here for the horse.

The start of hoof strike is kinematically defined as the onset of a rapid angular deflection of the fetlock joint at the beginning of the support phase (Hjertén and Drevemo, unpublished data). Hoof strike is observed kinetically as the initial inflexion in the vertical force traces due to the rapid negative acceleration of the hoof as it contacts a force measuring device.[7,14–16] The term used here for this initial inflexion is impact force. The vertical impact force at foot strike has been proposed as a determinant in pathological changes in the lower extremity in humans due to physical activity.[13] If this correlative between foot strike and pathological changes in the lower extremity is correct the need for an understanding of hoof strike in equine athletes is important. The purpose of this study was to investigate the kinematics of the hoof at impact in trotting horses.

MATERIALS AND METHODS

Four Standardbred colts, approximately 18 months of age, were filmed at the trot from 4.0–9.6 m s^{-1} on a treadmill under standardized conditions.[5,6] The colts were filmed from the left side during 6 consecutive strides at each of the velocities. The frame frequency was 250 fps. Film and equipment are described elsewhere.[5] Prior to the cinematographic recordings the animals were observed for lameness and were found to be sound. Additionally, all horses were acclimatized to trot with ease on the treadmill before the film recordings were undertaken. Reference discs were attached to the skin, over well-defined skeletal structures to facilitate quantitative photographic analysis.[3] The limb movement subsequent to hoof strike was analysed with a computer based film reading system.[5]

During the film analysis the coordinates of the 3 reference discs (i.e. glued to the skin at the proximal extremity of the fourth metacarpal/metatarsal bones, the middle of the lateral collateral ligaments of the fetlock and pastern joints) and the frame number of each frame analysed were read and stored in a minicomputer for subsequent analysis. The film readings were carried out for approximately 80 milliseconds (ms) before full sup-

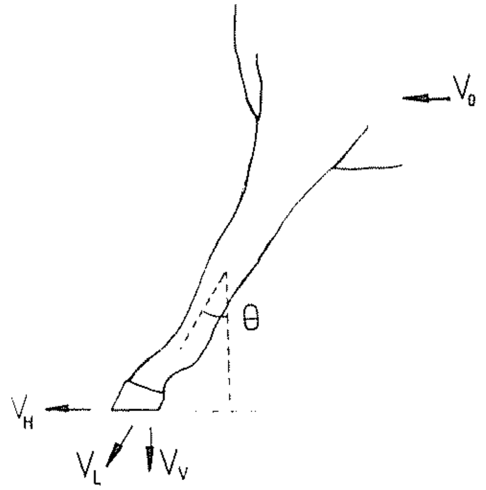

Fig 1 Representation of the variables measured. V_0, trotting velocity of the horse; V_v, vertical velocity of the hoof at hoof strike's start; V_h, horisontal velocity of the hoof at hoof strike's start; V_l, longitudinal velocity of the hoof at hoof strike's start; Θ, angle of the lower extremity to the vertical at hoof strike's start. Longitudinal velocity is calculated according to the following equation:

$$V_l = V_v \cos\Theta + V_h \sin\Theta$$

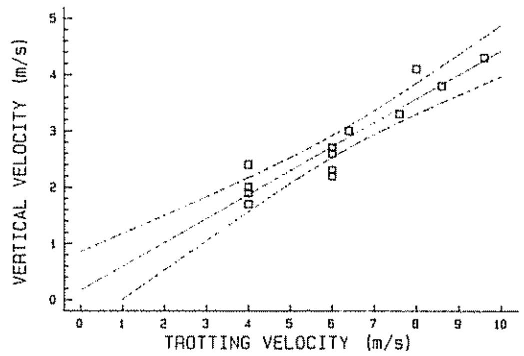

Fig 2 The regression equation for trotting velocity and vertical hoof velocity at hoof strike in the left forelimb. The dotted lines are the 95% confidence limits.

port and 10 ms after. Full support was defined as the time when a sudden increase in the fetlock joint angle was observed. The frame number following full support was noted manually and stored in the data file. The computer program calculated the velocities and angles (Fig. 1) and assumed that the time of full support fell approximately 2 ms (i.e. 1/2 frame) before the frame manually selected for full support. A numeric value for the fetlock angle was displayed for each frame and was recorded.

Before further calculations were performed the raw vertical and horizontal hoof velocity data were plotted as a function of time. Examination of 6 strides in 4 horses showed that the vertical and horizontal velocities changed almost linearly (i.e. constant acceleration) during the last milliseconds before full support. Based on the knowledge of the event of full support, when the longitudinal forces begin, the vertical and horizontal velocities were calculated by regression analysis during the period of 32 to 8 ms before full support. The indata for these calculations were the film coordinates of the reference markers at the proximal extremities of the fourth metacarpal/metatarsal bones and at the fetlock, the camera speed, a constant for the camera-film reading system, the distance between the camera and the horse and the speed of the treadmill. Fig. 1 illustrates hoof strike and the velocity and angular components investigated.

A statistical program (Statgraphics®, STSC Inc., Rockville, MD) was used to derive the regression equations and statistical significance of the individual variables to trotting velocity.

Errors of method

Systematic and random errors for landing velocities are presented in Table 1. Another source of error is the minor nonlinearity in velocity just prior to full support. This is presently under study. A random error in angle Θ (Fig. 1) introduced by the film reading operator when reading the film coordinates is determined to be 1.2° in the forelimbs and 0.4° in the hindlimbs.

RESULTS

Results with respect to the influence of trotting velocity are presented in Table 2. In-

Table 1. *Errors in determinations of landing velocities ($m\ s^{-1}$) at hoof strike*

Vert.: vertical forces; Horitz.: horizontal forces; Long. longitudinal forces

	Landing velocities ($m\ s^{-1}$)					
	Forelimb			Hindlimb		
Type of error	Vert.	Horiz.	Long.	Vert.	Horiz	Long.
Random errors						
Errors introduced by the operator at film reading	0.29	0.69	0.08	0.43	1.06	0.18
Error introduced by variations in the horse/camera distance (±0.05 m)	0.03	0.05	0.03	0.03	0.04	0.03
Error in determination of full support due to the time increment	0.10	0.35	0.12	0.10	0.25	0.12
Total random errors square mean	0.31	0.78	0.15	0.44	1.09	0.22
Systematic errors						
Errors caused by speed differences (±0.1 $m\ s^{-1}$)	–	0.10	0.05	–	0.10	0.05
Errors caused by variations in camera speed (±1 fps)	0.02	0.03	0.02	0.01	0.02	0.01
Errors caused by error in the horse/camera distance	0.06	0.10	0.06	0.06	0.08	0.06
Total systematic errors square mean	0.06	0.14	0.08	0.06	0.13	0.08

creases in trotting velocities resulted in a linear increase in the vertical velocity at hoof strike in the forelimb (Fig. 2). This was not a statistically significant correlation for the hindlimb (Table 2). As with vertical velocity the hoof's horizontal velocity increased linearly with increases in trotting velocity (Fig. 3). The angle of the lower extremity to the vertical became more obtuse with increases in velocity (Fig. 4). The longitudinal velocity increased linearly with increasing trotting velocity in the forelimb (Fig. 5) and the hindlimb.

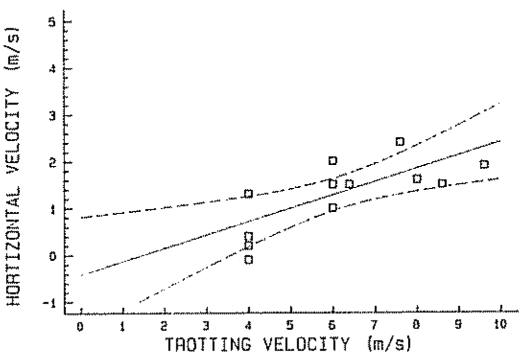

Fig. 3. The regression equation for trotting velocity and horizontal hoof velocity at hoof strike in the left forelimb. The dotted lines are the 95% confidence limits

DISCUSSION

Heel strike studies of humans have linked the impact force of the strike to pathological changes in the lower extremity of active individuals.[9] Similar information concerning horses is lacking.

Vertical velocities at hoof strike increased linearly with increases in trotting velocities in the left forelimb (Fig. 2). The relationships of increases of vertical velocity and

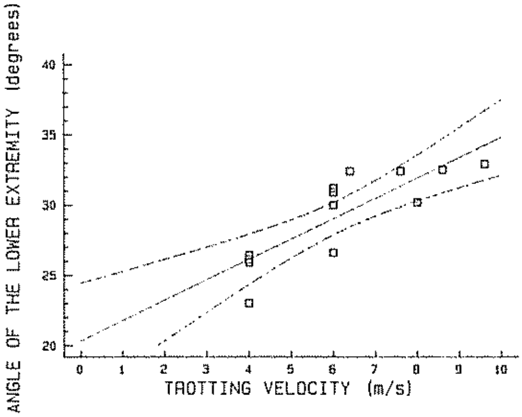

Fig 4 The regression equation for trotting velocity and angle of the lower extremity to the vertical at hoof strike in the left forelimb. The dotted lines are the 95% confidence limits.

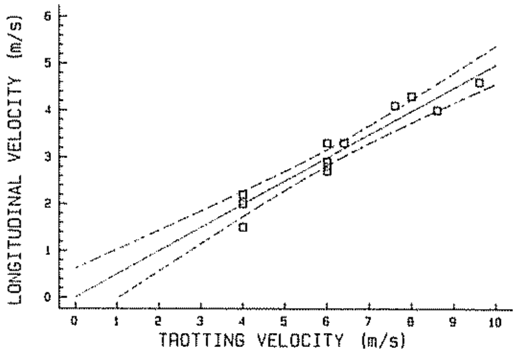

Fig 5 The regression equation for trotting velocity and longitudinal velocity at hoof strike in the left forelimb. The dotted lines are the 95% confidence limits.

impact force with increases in running velocity have been shown in humans. It would seem feasible that these relationships might also hold in trotting horses.

From Fig. 3 it is apparent that horizontal velocities at hoof strike increase significantly with trotting velocities. The forward motion of the hoof at impact has been observed from films in fast trotting horses (Drevemo, unpublished data). At hoof strike it was observed in this study that the hoof moved slightly forward relative to the craniocaudal moving treadmill belt causing a momentary displacement of the belt. These observations imply that kinetic frictional forces arise in the initial phase of the craniocaudal force. Kinetic frictional forces are theoretically defined by the equation:

$$F_k = U_k R \tag{1}$$

where F_k is the kinetic frictional force, U_k is the coefficient of kinetic friction, and R is the normal (i.e. vertical) force. The magnitude of kinetic friction is thus dependent upon the physical properties of the interacting surfaces (U_k) and the instantaneous vertical force (R). This force is directed opposite to the relative velocity of the sliding surface. The nature of frictional forces is very complex and drawing conclusions from this equation may be misleading because of the simplicity of the model. The elastic and plastic properties of the track surface as well as the frictional properties of the hoof and track surface may influence the nature of the hoof strike pattern and thus need to be further investigated.

High frequency wave formations are observed in the initial segments of the horizontal force traces.[1,7,14,16,17] These wave forma-

Table 2. *Regression equations and statistics for hoof landing velocities and angles of the lower extremities as functions of trotting velocity*

Variable	Slope	Intercept	Correlation coefficient	Probability
V_v (fore)	0.424	0.168	0.935	<0.001
V_v (hind)	0.172	1.121	0.537	=0.058[a]
V_h (fore)	0.282	−0.418	0.701	<0.01
V_h (hind)	0.682	−1.460	0.903	<0.001
Θ (fore)	1.449	20.331	0.833	<0.001
Θ (hind)	1.842	22.358	0.856	<0.001
V_l (fore)	0.500	−0.007	0.958	<0.001
V_l (hind)	0.577	−0.153	0.972	<0.001

[a] $p > 0.05$ is not significant.

tions occur simultaneously with impact force transients and may be explained in part by the vertical force transients at hoof strike.

Increases in trotting velocity result in a more cranial placement of the hoof. This may lead to a greater ventral excursion of the center of mass and greater demands of mechanical and metabolic energy. Trotting velocities between 3.3 and 11.1 m s^{-1} resulted in near linear increases in heart rate.[11]

The moments at the fetlock and carpal joints are nearly zero during the time of hoof strike.[7] This implies that the impact force during hoof strike is in the longitudinal direction and it is therefore of interest to study longitudinal velocity at hoof strike. The nature of this transmission is however not well studied in the horse. Presuming an elastic behavior of the ground, the maximum impact force (F_{max}) between a solid and the ground can be calculated according to:

$$F_{max} = v\sqrt{fm} \quad (2)$$

where F_{max} is the force, v is the velocity of the solid when it hits the ground, f is the spring constant and m is the mass of the solid. When impact occurs between the hoof and the ground a part of the horse limb is considered to behave as a solid with an effective mass equal to m and where the longitudinal direction is valid for both the velocity and the force. Thus, increases in the longitudinal velocity would result in increases in the longitudinal force if the equation satisfactorily describes these forces at hoof strike.

Studies in humans have shown high frequency transients in the skeleton at heel strike,[10,18] which have been suggested as factors involved in pathological changes in the extremities of active humans.[4,8,12] Recently, a significant decrease in overuse injuries as correlated to heel pad shock absorbency has been shown.[8]

CONCLUSIONS

Linear correlations between trotting velocity and vertical, horizontal, and longitudinal hoof velocities, and angle of the lower extremity at hoof strike have been demonstrated. The correlative between vertical velocity and trotting velocity for the hind limb was not found to be significant. These correlatives may provide fundamental information on hoof strike and impact forces which have been suggested as determinants in the development of pathologies in the limbs of animals. More study is needed however to determine the kinetics and possibilities for manipulation of the forces coincident with hoof strike.

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