Effect of walking velocity on ground reaction force variables in the hind limb of clinically normal horses

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Objective—To measure the effect of subject velocity on hind limb ground reaction force variables at the walk and to use the data to predict the force variables at different walking velocities in horses.

Animals—5 clinically normal horses.

Procedure—Kinematic and force data were collected simultaneously. Each horse was led over a force plate at a range of walking velocities. Stance duration and force data were recorded for the right hind limb. To avoid the effect of horse size on the outcome variables, the 8 force variables were standardized to body mass and height at the shoulders. Velocity was standardized to height at the shoulders and expressed as velocity in dimensionless units (VDU). Stance duration was also expressed in dimensionless units (SDU). Simple regression analysis was performed, using stance duration and force variables as dependent variables and VDU as the independent variable.

Results—Fifty-six trials were recorded with velocities ranging from 0.24 to 0.45 VDU (0.90 to 1.72 m/s). Simple regression models between measured variables and VDU were significant ($R^2 > 0.69$) for SDU, first peak of vertical force, dip between the 2 vertical force peaks, vertical impulse, and timing of second peak of vertical force.

Conclusion and Clinical Relevance—Subject velocity affects vertical force components only. In the future, differences between the forces measured in lame horses and the expected forces calculated for the same velocity will be studied to determine whether the equations can be used as diagnostic criteria. (*Am J Vet Res* 2001;62:901–906)

In the past 3 decades there has been an explosion of interest in equine locomotion and biomechanics. Early studies on the biomechanics of the horse investigated the basic structure and function of the musculoskeletal system and postulated how it would influence the movement of individual limbs. Recent studies of equine biomechanics have included more theoretic analyses of musculoskeletal properties of the limbs and have examined normal and abnormal functions of selected joints and limb segments.[1]

Ground reaction force (GRF) is equal in magnitude and opposite in direction to the force exerted by the hoof against the ground. Ground reaction force represents kinetic and gravitational forces and is measured by use of a force plate. Standard software packages resolve the GRF vector into the following 3 mutually perpendicular components: vertical, longitudinal, and transverse. Ground reaction force analysis has been used to describe normal locomotion[2,3] and the effects of supporting limb lameness[4,5] in horses at the walk.[4,5] Induction of lameness caused decreases in the longitudinal and vertical GRF magnitudes. The transverse GRF, which is much smaller in magnitude than the other 2 components of GRF, revealed minimal change after lameness induction.[4] The vertical and longitudinal components, which are considered in sagittal plane analysis, have the greatest changes in response to lameness. Even subtle lameness has been demonstrated objectively by GRF analysis of the walk, using an adapted quantitative procedure.[6] The peak magnitudes of the GRF components and their times of occurrence, together with the impulses, which are derived by time integration of GRF, are used for objective evaluation of equine locomotion.[7]

Force plate analysis of lameness usually involves comparison of force variables measured in a lame horse with force data of clinically normal horses moving at the same gait and velocity. In a research setting data may be collected from the same horses before and after induction of lameness. In a clinical environment, however, it is not possible to obtain data from a clinically normal horse for comparison with the lame condition. This problem is circumvented by comparing data from the lame horse with force data from a pool of clinically normal horses moving at the same gait and velocity. Factors that have to be accounted for in the comparison include body size and subject velocity. Body mass is straightforward in terms of standardization of force data; the force variables are divided by mass and expressed as N/kg.[8] Velocity affects force data in dogs and horses. In the hind limb of walking dogs, an increase in subject velocity is associated with an increase in peak vertical force and a decrease in vertical impulse and stance duration.[9] There is a correlation between subject velocity and longitudinal force data, but the correlation coefficient is low. In the hind limb of walking horses, the findings are similar to those in dogs, except that the correlation coefficient between the vertical force and subject velocity is lower.[10] These findings indicate that comparisons of force data between lame and clinically normal horses must be made within the same range of velocity, which requires the development of reference range values from a pool of sound (ie, not lame) horses to match the velocity of individual lame horses. It is possible but difficult to provide clinically normal horse data to match the walking velocity for each lame horse. The ability to predict the

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normative data is more convenient and less time consuming than developing such an extensive database.

The purpose of this investigation was to study the effect of subject velocity on GRF variables in the hind limbs of walking horses with the objective of developing a model for calculating the expected GRF at any walking velocity. The hypothesis was that subject velocity influences values of GRF variables in a predictable manner.

Materials and Methods

Subjects—Five horses weighing 451 to 561 kg and measuring 1.42 to 1.59 m at the shoulders were used for this study. All horses were assessed as clinically sound (ie, not lame) by 2 veterinarians and had no recent history of lameness. The data protocol was approved by the All University Committee on Animal Use and Care at Michigan State University.

Video technique—A circular retroreflective marker 2.5 cm in diameter was attached to the midlateral distal hoof wall. A super-VHS camcorder[a] placed 8.17 m from and perpendicular to the walkway at a height of 0.95 m was used to record the horses' movement at 60 frames/s. A 500 W halogen light placed beside the camcorder illuminated the retroreflective marker. Six poles with 30 retroreflective markers at known locations were used to calibrate the study field of 2.12 × 4.75 m.

Force platform technique—A 60 × 120-cm force platform[b] embedded in the middle of the walkway was used to collect GRF data with a sampling frequency of 1,000 Hz. Forces in the longitudinal and vertical directions and location of the center of pressure were recorded for each trial.

Data collection—The calibration frame was recorded and then removed from the walkway. Each horse was led over the force plate at the walk at slow, medium, and fast velocities. Force data were collected simultaneously with kinematic data. A trial was considered to be successful when the right hind hoof hit the force plate and no other limb was in contact with the force plate at the same time. Data collection was continued until at least 3 successful trials had been recorded at slow, medium, and fast velocities from each horse.

Data processing—A computerized gait analysis system[c] was used to analyze the videographic data. The analysis sequence involved video image grabbing, digitization, data transformation, and data smoothing. Kinematic data from videotape were grabbed and stored in digital format with resolution of 640 pixels wide × 480 pixels high. With the approximately 5-m-wide field of view, the digitizing accuracy was estimated to be ± 4 mm. The retroreflective marker was digitized during successive trials. Direct linear transformation[11] was used to combine the on-screen locations of the calibration frame markers and the digitized hoof markers to determine stride length. Stride duration was determined from the number of frames elapsing between successive ground contacts of the right hind hoof. Velocity of each stride was calculated by dividing stride length by stride duration. Stance duration was measured as the time elapsing from ground contact to lift off of the right hind hoof. The accuracy of detecting hoof contact and lift off videographically was ± 8 milliseconds.

The GRF data from each trial were analyzed to determine the magnitudes of the force peaks and their time of occurrence. The vertical GRF had 2 peaks; the first peak for decelerating downward motion of the body during the period of weight acceptance and the second peak for accelerating the body upward during the period of forward propulsion. There was a dip between the 2 vertical force peaks. The vertical force values were recorded for the **first peak vertical force (V_1)** value, minimal **intervening dip vertical force (V_2)** value, and **second peak vertical force (V_3)** value. The longitudinal GRF had an initial **longitudinal braking peak force (L_1)** value followed by a **longitudinal propulsive peak force (L_2; Fig 1)** value. Impulses were calculated by time integration of the force curves and expressed as **vertical impulse (VI)**, **braking impulse (L_1I)**, and **propulsive impulse (L_2I)**. Force variables were standardized to stance duration, and the **time of occurrence (T)** of each force peak was determined and expressed as percentage of stance duration (TV_1, TV_2, TV_3, TL_1, and TL_2 for the force peaks V_1, V_2, V_3, L_1, and L_2, respectively). The time when longitudinal force changed direction (**zero longitudinal force [TL_0]**) was also recorded.

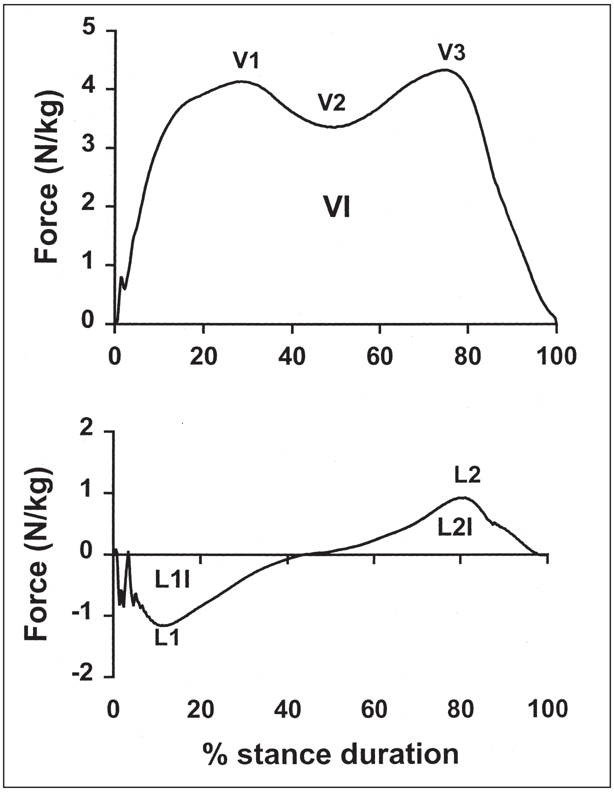

Figure 1—The vertical (upper panel) and longitudinal (lower panel) ground reaction force patterns during the stance phase of the walk. V_1 = First peak of vertical force. V_2 = Vertical dip. V_3 = Second peak of vertical force. VI = Vertical impulse. L_1I = Braking impulse. L_2I = Propulsive impulse. L_1 = Longitudinal braking force. L_2 = Longitudinal propulsive force.

Data standardization—When height at the withers increases, the time scale is made longer, and this affects stride length and stride duration in horses moving at the same velocity. To compensate for this effect, the data must be scaled such that the kinetic and gravitational forces are proportional for horses of different sizes.[12] The temporal variables that adjusted for height at the withers were obtained from the equations for acceleration and velocity:

$$\text{Acceleration} = \frac{\text{distance}}{\text{time}^2}\text{, then}\quad \text{time} = \sqrt{\frac{\text{distance}}{\text{acceleration}}} = \sqrt{\frac{l_0}{g}}$$

$$\text{Velocity} = \frac{\text{distance}}{\text{time}} = \frac{\text{distance}}{\sqrt{\frac{\text{distance}}{\text{acceleration}}}} = \sqrt{\text{distance} \times \text{acceleration}} = \sqrt{l_0 \times g}$$

Stance duration was standardized by dividing measured stance duration by the adjusted time and expressed as

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Table 1—Pearson correlation coefficients (*r*) between subject velocity, velocity in dimensionless units, stance time, and stance time in dimensionless units

Variables	Velocity (m/s)	VDU
Stance time (s)	–0.89	–0.92
SDU	–0.93	–0.95

VDU = Velocity in dimensionless units. SDU = Stance time in dimensionless units.
All correlations were significant ($P < 0.05$).

Table 2—Pearson correlation coefficients (*r*), simple regression equations, and coefficient of determination (R^2) between velocity in dimensionless units and other variables

Variable	r	Equation	R^2
V_1	0.78	7.35 – 26.48 X VDU + 48.66 X VDU^2	0.70
V_2	–0.87	5.22 – 6.19 X VDU	0.75
V_3	0.27	3.65 + 1.28 X VDU	0.07
VIDU	–0.83	1.05 – 1.18 X VDU	0.69
L_1	0.62	0.42 + 2.76 X VDU^2	0.40
L_2	0.56	0.16 + 1.53 X VDU	0.31
L_2IDU	–0.30	0.04 – 0.06 X VDU^2	0.09
SDU	–0.95	3.88 – 5.06 X VDU	0.90
TV_1	–0.53	35.69 – 40.80 X VDU	0.28
TV_2	0.48	42.69 + 25.07 X VDU	0.23
TV_3	0.85	52.66 + 57.98 X VDU	0.72
TL_1	–0.31	18.07 – 7.15 X VDU	0.09
TL_2	0.57	70.72 + 23.21 X VDU	0.33
TL_0	–0.46	50.78 – 22.24 X VDU	0.22

V_1 = First peak of vertical force. V_2 = Dip between vertical peaks. V_3 = Second peak of vertical force. VIDU = Vertical impulse in dimensionless units. L_1 = Braking peak force. L = Propulsive peak force. L_2IDU = Propulsive impulse in dimensionless units. SDU = Stance duration in dimensionless units. TV_1 = Time of V_1. TV_2 = Time of V_2. TV_3 = Time of V_3. TL_1= Time of L_1. TL_2 = Time of L_2. TL_0 = Time of zero longitudinal force.
All correlations and equations were significant ($P < 0.05$).
See Table 1 for remainder of key.

Table 3—Mean and SD of variables that have R^2 values for regression equations equal to or less than 0.40

Variable	Mean	SD
V_3 (N/kg)	4.10	0.29
L_1 (N/kg)	0.77	0.19
L_2 (N/kg)	0.69	0.17
L_1IDU (Ns/Ns)	0.04	0.01
L_2IDU (Ns/Ns)	0.04	0.01
TV_1 (% stance duration)	21.46	4.90
TV_2 (% stance duration)	51.49	3.29
TL_1 (% stance duration)	15.55	1.44
TL_2 (% stance duration)	78.90	2.53
TL_0 (% stance duration)	42.99	3.02

See Table 2 for key.

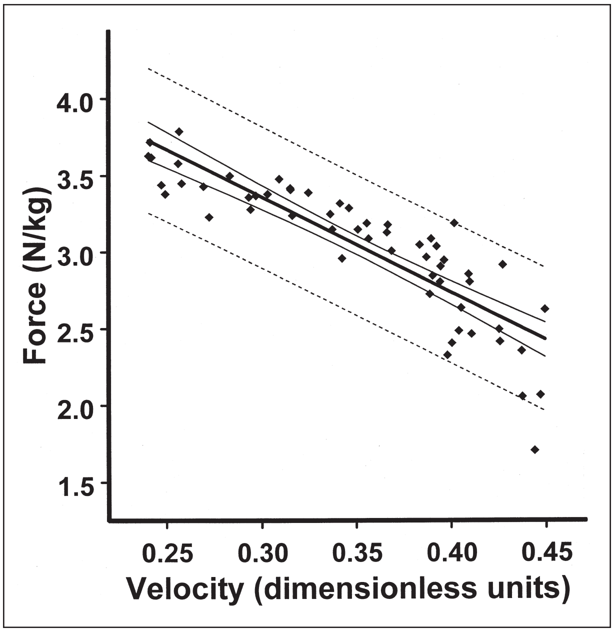

Figure 2—The estimated regression line (bolded line), 95% confidence interval band (solid lines), and 95% prediction interval band (dashed lines) of the minimal force during the vertical dip (V_2) and velocity in dimensionless units (VDU). Diamond = Raw data.

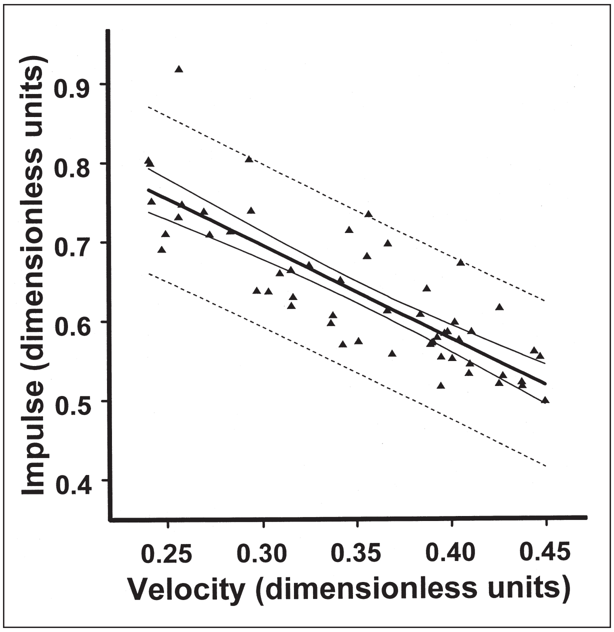

Figure 3—Vertical impulse in dimensionless units (VIDU) and VDU. Triangle = Raw data. *See* Fig 2 for key.

stance time in dimensionless units (SDU).[12] Similarly, subject velocities were standardized by dividing measured velocity by adjusted velocity and expressed as **velocity in dimensionless units (VDU).**[12] The equations used to calculate SDU and VDU were:

$$\text{SDU (s/s)} = \frac{\text{stance duration (s)}}{\sqrt{l_0/g}}$$

$$\text{VDU (ms/ms)} = \frac{\text{velocity (m/s)}}{\sqrt{l_0 \times g}}$$

where l_0 is subject height at the withers (m), and g is gravitational acceleration (9.8 m/s^2).

Ground reaction forces were standardized to subject body mass and expressed as force per kg of body weight (N/kg). Impulses were affected by mass and height at the withers. They were standardized by dividing the measured impulse (force × stance duration) by the force caused by body mass (weight × g) and adjusted time and were expressed as the **impulse in dimensionless units (IDU)**. The equation to obtain IDU was:

$$\text{IDU (Ns/Ns)} = \frac{\text{force} \times \text{stance time}}{\text{weight} \times g \times l_0/g}$$

The units in which the variables were expressed were as follows: force (N), stance time (s), weight (kg), g (m/s^2), and

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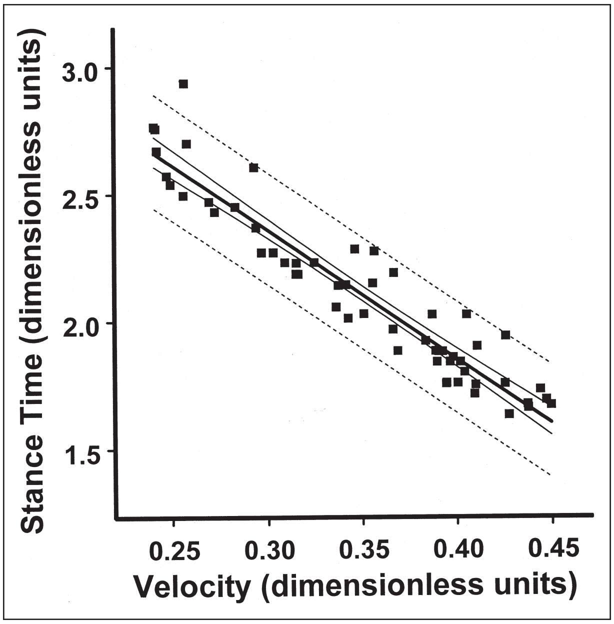

Figure 4—Stance time in dimensionless units (SDU) and VDU. Square = Raw data. *See* Fig 2 for key.

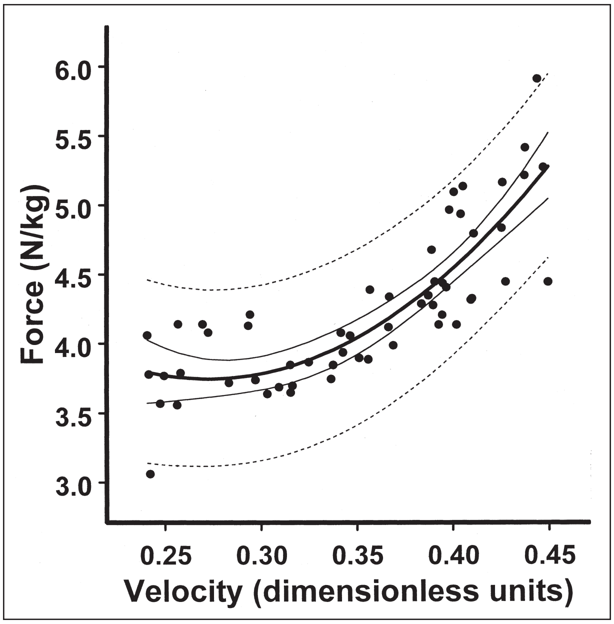

Figure 6—First peak of vertical force (V_1) and VDU. Circle = Raw data. *See* Fig 2 for key.

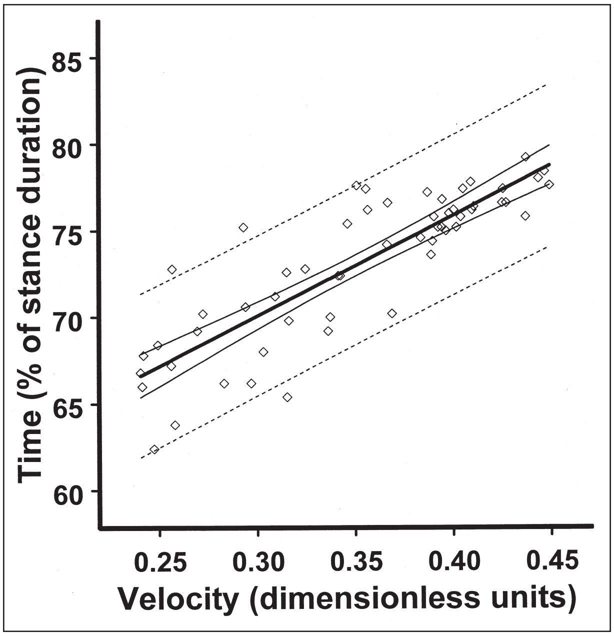

Figure 5—Time of occurrence of the second peak of the vertical force (PV_3) and VDU. Diamond = Raw data. *See* Fig 2 for key.

l_0 (m). The values of VI, L_1I, and L_2I were expressed in dimensionless units (VIDU, L_1IDU, and L_2IDU, respectively).

Statistical analysis—Statistical software[d] was used to analyze the data, using correlation and simple regression analysis between VDU as the independent variable and other variables as dependent variables. For longitudinal force components, the absolute values of the peak magnitudes were used for analysis. A value of $P < 0.05$ was used as the level of significance.

Results

A total of 56 successful trials were recorded, with velocities ranging from 0.24 to 0.45 VDU (0.90 to 1.72 m/s). Velocity and VDU had significant negative correlations with stance time and SDU (**Table 1**). Because VDU had higher correlation coefficients with stance time and SDU than did velocity, VDU was selected to be the independent variable in a simple regression model. The significant correlation and simple regression equation for expected value of each variable were calculated (**Table 2**). The correlations and simple regression equations were significant for all variables except L_1IDU ($P = 0.24$). Correlation coefficients and **coefficient of determination (*R^2*)** values of V_3, L_1, L_2, L_2IDU, TV_1, TV_2, TV_3, TL_1, TL_2, and TL_0 were in the low to intermediate range ($r \le 0.62$, $R^2 \le 0.40$). The means and SD of these variables were reported (**Table 3**). Regression analysis indicated that an increase in VDU was associated with linear decreases in V_2 (**Fig 2**), VIDU (**Fig 3**), and SDU (**Fig 4**), a linear increase in TV_3 (**Fig 5**), and an increase in V_1 in a quadratic manner (**Fig 6**).

Discussion

Biomechanical gait analysis is a useful tool for evaluation of equine locomotion, providing quantitative data for measuring subtle changes in movement and forces acting on the limb. The mechanisms of lameness can be studied by comparing data from lame horses with normative data. Results of our study revealed the effect of increasing subject velocity on some GRF measurements and confirmed that subject velocity must be controlled in studies that compare GRF under various conditions. Clinical evaluation of lame horses is performed at a velocity that is comfortable for the patient, which varies with the degree of lameness. The simple regression analysis developed in our study may be useful for calculating the expected normal force variables for lame horses moving within the velocity range in our study, which covers the normal walking velocity range used in lameness examinations.

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The negative correlation between subject velocity and stance time in our study was higher than in a previous study,[10] which may reflect differences in the method of measuring subject velocity. Measurement of mean velocity as the horses walked between 2 photoelectric switches[10] does not register the exact velocity when the horse passes over the force plate. The video method used in our study should register a more accurate velocity, resulting in a higher correlation with other variables. The fact that stance time was more highly correlated with VDU than subject velocity reflected the fact that height at the withers influenced subject velocity, and standardization should be used to eliminate this effect. In humans, it has been recommended that time and velocity should be standardized by $(\text{length})^{0.5}$. This approach leads to dynamic similarity of walking patterns, and it is recommended for standardization in people with different linear characteristics, such as leg length.[13] In this study standardization of velocity and stance time according to $(\text{height at the withers})^{0.5}$ gave the highest correlation between VDU and SDU (–0.95). The strongly negative correlation indicated that these 2 variables could be used interchangeably as the control variable in force plate studies of horses, which is similar to the situation in dogs.[14] From the equation (Table 2), we can inversely calculate VDU from SDU in walking horses, which allows prediction of subject velocity from stance duration obtained during force plate analysis. However, stance duration may change with fitness. In clinically normal horses trotting on a treadmill, hind limb stance duration decreased after a period of training.[15] If it was shown that there is a training effect on stance duration at the walk, then this should be accounted for in the calculation of VDU from SDU.

All variables except L_1IDU had a significant correlation with VDU, but the expected correlation lines of V_3, TL_1, and L_2IDU with VDU had very little slope, resulting in low correlation coefficients. This indicated that there was linear correlation between VDU and the variables, but VDU did not affect those variables. Thus, correlation analysis should not be the sole criterion to judge the effect of velocity on these GRF variables. The coefficient of determination (R^2) is the criterion to judge the slope and how well the expected regression line fits the raw data. Higher R^2 values are associated with less dissipation of the raw data from the expected line and more deviation of the expected line from the horizontal. Although the variables V_3, L_1, L_2, L_2IDU, TV_1, TV_2, TL_1, TL_2, and TL_0 were significant in the regression analysis, the low R^2 values (≤ 0.40) indicated that the regression equations for these variables may not be strong enough or appropriate for calculating the expected variables from VDU. Therefore, V_3, L_1, L_1I, L_2, L_2I, and their times of occurrence may be considered constant for clinically normal horses walking at any velocity.

With regard to the longitudinal force components, walking velocity did not affect the percentage of stance time spent in braking and propulsion in Greyhounds.[16] In Dutch Warmblood horses walking at 1.44 to 1.79 m/s, the longitudinal forces and impulses had lower SD than the vertical force and impulse.[2] This could be interpreted as supporting our finding that velocity had more effect on the vertical force component than the longitudinal component. The GRF distribution between the 4 limbs of walking horses is such that only 1 limb provides braking forces and 1 limb provides propulsive forces at any time.[3] Therefore, the longitudinal forces of different limbs act in opposition to each other, and this is why changes in velocity do not depend on increases in longitudinal GRF. It is not surprising, therefore, that longitudinal GRF peaks in the right hind limb did not change with velocity. Theoretically, a prerequisite for maintaining a constant speed of progression is that the L_1I and L_2I are equal,[17] which was found to be true in the right hind limb (Table 3).

The effect of VDU on the vertical force variables was most apparent in the first half of stance. The V_1 increased in a quadratic manner with VDU. A similar relationship has been described in humans walking at different velocities.[17] The quadratic regression pattern of V_1 mirrors the pattern of kinetic energy, which is proportional to velocity squared.[13] Results of electromyographic studies of hind limb muscles in walking horses indicate that there is activity in several muscles (eg, gluteus medius, biceps femoris, semitendinosus, gastrocnemius, etc) during early stance with the activity ceasing just before mid stance.[18] The quadratic regression pattern of V_1 may reflect greater muscle activation associated with increasing kinetic energy of the limb during early stance as velocity increases. During late stance, fewer muscles (eg, tensor fascia latae, tibialis cranialis) are active,[18] which suggests that V_3 may reflect the release of elastic energy that was stored in tendons earlier in stance.[19] The fact that V_3 does not change significantly with velocity is probably a consequence of the limb being loaded passively at this stage of the stride, with the peak force reflecting body weight rather than velocity of movement.

The negative correlation of V_2 with VDU indicated that the dip between the 2 peaks of vertical force became more distinct as velocity increased. In normal locomotion, the equine limb acts as a mass-spring mechanism during stance.[20] An increase in subject velocity is associated with an increase in V_1, which indicates more loading in early stance. The limb is then unloaded more at midstance (V_2), caused partly by rebound of the more heavily loaded limb spring, combined with the effect of raising the contralateral hind limb in its midswing phase. In our study, when the horse moved at very slow velocities, the vertical dip almost disappeared, presumably as the result of less kinetic loading in early stance resulting in less unloading at midstance.

A negative relationship between VI and velocity has also been found in humans and in other animals at a variety of gaits.[9,10,16,17] The decrease in VI with increasing velocity, which occurs despite the increase in V_1, probably reflects the reduction in stance time, together with the fact that the increase in V_1 is compensated by the decrease in V_2. It is interesting, however, that the total L_1I and L_2I were maintained as stance time decreased. Because the peak values of the longitudinal forces did not change, there must be an overall increase in magnitude of the longitudinal forces throughout stance.

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In conclusion, the hypothesis that subject velocity influences GRF variables in a predictable manner was found to be true, though at the walk subject velocity affected only the vertical component of the GRF. The equations to calculate expected normal values of SDU, V_1, V_2, VIDU, and TV_3 have been determined. The wide range of walking velocities obtained in our study covers the reference range used in lameness examinations. Following verification of these results, the ability to estimate force variables may be useful as a quantitative tool to detect pathologic deviations from expected values.

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[a] Panasonic AG-450, Matsushita Electric Corp., Secaucus, NJ.
[b] AMTI LG6, AMTI, Watertown, Mass.
[c] APAS, Ariel Dynamics Inc, Trabuco Canyon, Calif.
[d] SAS, SAS Institute Inc, Cary, NC.

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