Power Output Measurement on Draught Horses

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ABSTRACT

Experiments were conducted on a highland pony. Special instruments were designed to measure how the forces acting on each foot changed while the animal was in motion. Effects of external load and the angle of the traces were studied. The results showed that the vertical ground reaction on the rear leg showed two peaks with a dip in the middle, whereas the front leg had a single peak. The horizontal force profile was similar on all feet. It has two separate phases; negative (braking) and positive (propulsive). As the applied load increased the positive portion increased while the negative portion decreased. At draught levels below 300 N the forelegs and the hind legs made equal contribution to the propulsion force, whereas at 710 N the hind legs contributed 57% of total horizontal pull. At all draught levels the forelegs carried the greater weight. Both front and rear legs produced negative as well as positive power. As the draught load increased the negative power fell and the positive power increased. The hind legs developed more power than the front legs. The point of zero negative power corresponded to that where the tractive effort was 15% of body weight.

Keywords: Horsepower, horseshoes, forces, dynamometers, traction, animal draft power, Mexico

1. INTRODUCTION

Most research on draught animals has been concerned with their overall draught capabilities and with harness and implements design, but very little on how they actually produce tractive force. When it is realised what little power is available from draught animals compared with tractors, it becomes much more important to make sure that it is used effectively.

Although there tends to be a preponderance of weight on the forelegs, there does not seem to be unanimous support for the hypothesis that the forequarters of a horse are of prime importance in determining tractive capability. Instead, it has been maintained that the tractive force exerted by a horse originates mainly from the hindquarters (Björck, 1958).

An interesting comparison has been made of the muscle distribution in racehorses and draught horses (Anonymous, 1990). This indicates that in racehorses 16.6% of the muscle is in the rear quarters compared with 12.8% in draught horses. The shoulders of thoroughbreds have 3.6% of muscle compared with 4.5% in draught horses. This suggests either that the forequarters are of particular importance in draught work, or the hindquarters are of special importance for running and jumping.

Most testing methods used hitherto only permit the total force developed by all limbs combined to be determined, usually by means of a tension link dynamometer acting along the axis of the traces. The measurement of draught force coupled with measurement of forward speed determines the animal's capacity for work or power output. Both the speed of an animal and the force it exerts vary with time as it puts one foot in front of the other; little research appears to have been carried out so far as to how speed and force vary throughout a full walking sequence.

Since vertical load is important in determining the amount of horizontal traction that can be generated at the ground contact area, the greater the load on a limb the greater the thrust it is capable of producing before slippage occurs. It might therefore be supposed that when pulling a load, weight transfer to the rear limbs results in the rear limbs being of greater importance in producing traction.

A widely used instrument for investigating the forces acting under the feet of bovines and equines is the force plate (Alexander, 1982; Pratt & O'Connor, 1976; Prentice & Wright, 1971; Webb & Clark, 1981). This device is a platform set down into the floor, supported by transducers which give electrical signals proportional to any force exerted by the feet of animals walking or running over it. It was developed for use in clinical and injury prevention work on quadrupeds. However, stationary force plates set in the ground over which the animal walks are not well suited to making continuous simultaneous measurements on all four feet whilst the animal is pulling a load for a sustained period. Dynamometers attached to each foot offer a better solution.

Against this background the objective of this work was to examine the practicability of measuring both vertical and horizontal forces at the point of contact between ground and feet of a horse during draught work and explore the implications of the results.

Special measuring devices have been designed, manufactured and tested to enable exact information of how these forces change while the animal is in motion. Instruments fitted to the hooves of the horse (one per foot) created minimum interference with the animal at work, and did not impose undue stress. Detailed information on design and construction of these apparatus items is given in Ortiz-Laurel and Cowell, 2004.

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2. MECHANICS OF ANIMAL TRACTION

An animal can be considered as a four legged vehicle. Unlike a wheeled vehicle the legs are not in contact with the ground all the time. The body moves in a discontinuous fashion, thus the tractive effort that it produces varies all the time it is in motion. The alternating support and swing phases of the legs while the animal is in motion result in a periodic intermittent application of the forces beneath the feet.

The external forces acting on an animal are the reactions at the surfaces of contact of the feet with the ground, the force through the traces and gravity. For convenience in Figure 1, both front legs and both rear legs are shown side by side. The various components of force may be defined as follows (Inns, 1990).

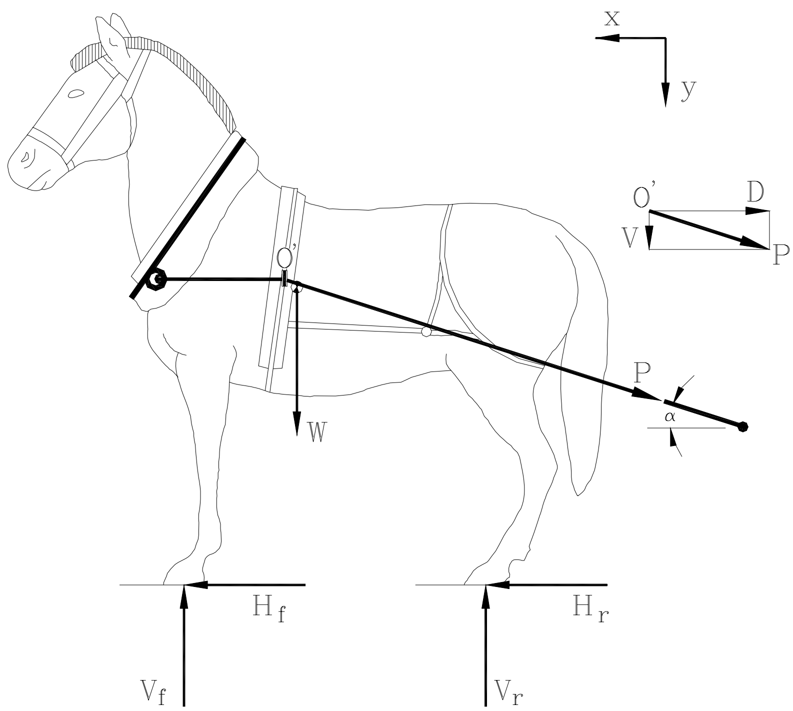

Figure 1. External forces acting on a horse at work.

P = the pull force. This is the force generated in the traces (or beam) and is equal to the resultant of the soil, gravitational, and inertia force acting on the implement and the force exerted by the operator.
V = effective vertical force. This is the vertical component of the pull force.
D = draught force. This is the horizontal component of the pull force.
α = the angle of inclination to the horizontal of the pull force.
H_f = the horizontal force exerted by the front limbs.
H_r = the horizontal force exerted by the rear limbs.
V_f = the support force on the front limbs.
V_r = the support force on the rear limbs.
W = weight of the animal.
$H_f + H_r$ is referred to as the tractive effort and, in the absence of forward acceleration, is equal in magnitude to the draught force.

Research on the mechanics of animal traction has been mainly concerned with the measurement of the pull force, the draught angle and the forward speed which have then been related to the power output developed by the animal. Very little has been done on how the animal produces thrust and the contribution of each leg to this force.

In order to be able to study the individual leg forces developed during motion it was necessary to design an instrumentation system capable of measuring the forces generated at the feet, and a detailed testing procedure was developed (Ortiz-Laurel, 1992).

Animals develop power due to the forces of traction which arise from the interaction between the soil and the hooves. An animal's effort is applied on the ground at hoof level so the texture and level of compaction of the soil have an important influence on the available tractive effort (FAO, 1972).

3. OBJECTIVE

The principal objective of the present work was to study the tractive effort developed by individual feet of an animal in relation to the vertical load on each foot. In order to continuously monitor under sustained pull, sensing units were fitted to the animal's feet. All four feet were sensed at the same time but independently of each other.

4. EXPERIMENTAL PROCEDURE

The design of special foot dynamometers allowed simultaneous recording of the vertical and horizontal forces. The method of calibration and the practical application of the system, however, presuppose that the vertical force acts at right-angles to the ground and the horizontal force parallel to the ground. Therefore, it is an absolute requirement that the horse should be tested on a firm level surface in order to achieve sufficient accuracy during the recording of the forces. Tests on loose soil where the horse can press the toe of the shoe down into the surface makes accurate recording impossible, especially for horizontal forces.

In order to overcome these problems a carpet was utilized to provide a special flat test track. Some of the advantages of using the carpet as the test track were: 1) the horse obtained a firmer grip, 2) the horse was able to pull a bigger load, 3) the test-load sledge moved smoothly in a straight line, and 4) the carpet maintained a constant coefficient of friction for both the horseshoe and the sledge. The coefficient of friction between the steel runners and the carpet was found to be 0.305.

The choice of the data recording system was mainly influenced by the need to operate the unit in the field and to avoid any interference with the horse during the measurement phase. The solution was to use a lightweight, portable, battery-operated datalogger. The datalogger also supplied the excitation voltage for all the measuring instruments.

The cables from all foot dynamometers were arranged in such a way that they all emerged from the outside of the legs. Leggings were used to fix them to the lower part of each leg. From there the cables were connected to the datalogger strapped on the horse's back. Figure 2 shows the instrumented horse.

Figure 2. The horse used in the tests, equipped with foot instruments and recording equipment.

The recording time of each run was determined by the memory capacity of the logger. The time needed to fill out the memory for a recording frequency of 100 Hz was about 8 seconds. Three complete walking cycles were achieved by the horse in that time.

To provide the draught load a specially designed sledge which could be loaded with weights was used. For a given draught angle tests were carried out with 0, 392.4, 784.8, 1177.2, 1569.6 and 1962 N on the sledge. A strain gauge load cell was interposed between the swingletree and the sledge to measure the load in the traces. The angle of the traces was measured by a rotary potentiometer attached to the pivot of the load cell and the sledge. Four draught angles were set by changing the hake attachment point on the sledge. Forward speed was measured by a tachometer attached to the axle of a trailed bicycle wheel. The forward speed of operation was left to the will of the animal. Figure 3 shows these instruments connected to a second datalogger placed on the sledge.

Simultaneous measurement of all the parameters over one or more complete cycles enabled the working phases for individual legs to be determined - swing phase or support phase - as well as establishing the relative position of one leg with respect to another.

Data collected by the loggers was transferred to a portable microcomputer for storage. Subsequent analysis was carried out using a suitable software package for data manipulation.

Figure 3. Measuring instruments mounted on the sledge.

5. RESULTS

The weight of the animal at rest was approximately 410 kg. The proportion of it borne on the front legs was 57 percent and on the hind legs 43 percent. The horse's travel speed of operation was a fairly consistent at 1.0 m s^{-1}, throughout the series of tests, although the instantaneous variation was never constant, even for a small period of time. This in turn affected the power produced by each foot. Alternatively, the draught angles measured were approximately 9, 12, 13 and 18 degrees. The variations in the angle were found insignificant at a given load, thus the numerical differences between values were small.

The simplest case with which to start analysis of the forces produced by the legs is while the horse is walking at a steady rate. Results from the vertical and horizontal reactions acting on individual feet when pulling zero load are shown in Figure 4. For clarity only 3 seconds (one complete walking cycle) of test are plotted. These curves show the characteristic vertical and horizontal force profiles as described by Pratt and O'Connor (1976). Whereas the vertical force on a front leg rises to a clear peak, that on a rear leg shows a characteristic dip in the middle.

As far as horizontal force is concerned, during the first part of the step, the horizontal force produced by the frictional resistance between the horseshoe and the carpet was negative *i.e.* in a direction opposing the forward movement of the horse. As the body moved forward over a foot a backward push was exerted against the carpet, inducing a positive forward horizontal reaction. Therefore, areas above and below the 0 line represent positive and negative impulses respectively.

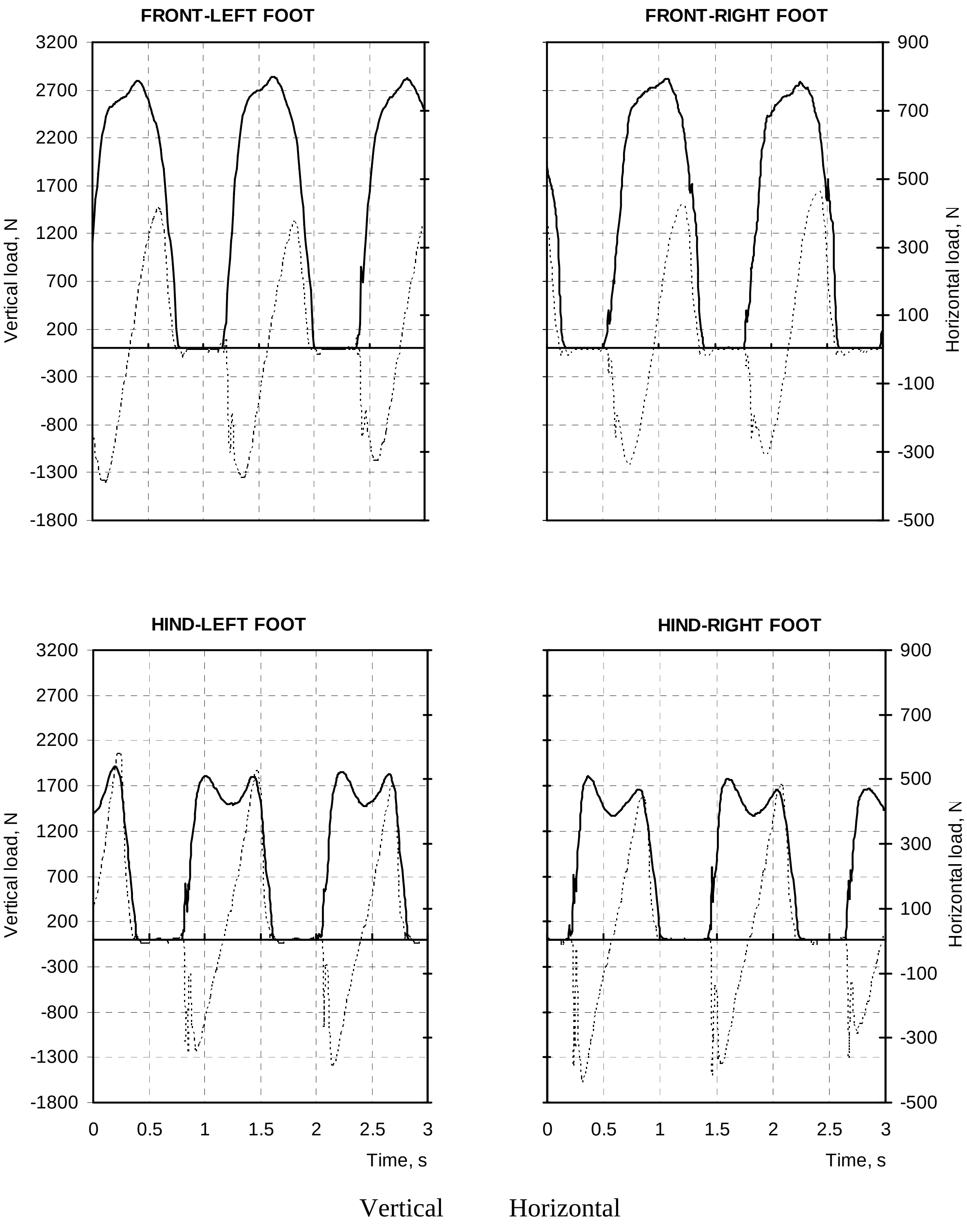

Figure 4. Indicator diagrams of vertical and horizontal reactions acting on individual feet when pulling zero draught load.

The horizontal force changed from braking mode to propulsion action when the vertical force in the foreleg was at its peak, while it changed from negative to positive near the lowest point of the dip in the hindleg-vertical force curve. However when a load was exerted the change from braking to propulsion occurred well before the maximum vertical force was reached.

However, it was noticed that the horse tended first to strike the ground with the hoof angled forward (toe first), but rapidly placed it flat on the ground, similarly the last contact was with the front of the hoof when the leg was being lifted. Since the foot-dynamometer was angled at this initial and final impact, force data in Figure 4 over the first and final 1/10 second are not true records and should be ignored; thereafter, this anomaly decreased markedly as the draught load was increased. The biggest entry angle observed (≈ 10 degrees) was in the walking phase; thereafter, it decreased sharply as the draught load was increased.

The effect of the pull force on the distribution of weight between both forelegs and both hindlegs is illustrated in Table 1. There was an initial increase on the front legs under no load, which it was presumed, came from the hind legs. This may be largely attributed to the horse adjusting its posture so that its centre of gravity was positioned nearer to the forelimbs than to the hind limbs. In addition, there was the dynamic effect of the head and neck oscillation. However, as the draught load was increased the vertical reaction on the forelimbs decreased whereas on the hind limbs it increased. Nevertheless, the greater proportion of the total weight; of the vertical component of pull and of the acceleration effects was borne on the forelegs.

Table 1. Changes in weight distribution.

Average Horizontal Draught (N)	Change of vertical forces from the static values * PAIRS OF LEGS	
	FRONT (N)	REAR (N)
0 (walking)	2453.4(+)	1568.6(-)
160	2345.2(+)	1721.0(-)
260	2334.8(+)	1737.1(+)
390	2319.5(+)	1755.6(+)
490	2286.9(-)	1826.4(+)
610	2274.8(-)	1888.7(+)
710	2198.8(-)	1997.3(+)

*static values: front = 2292 N; rear = 1729 N

Figure 5 shows the horizontal and vertical forces for the different legs for the maximum draught load of 710 N. It is shown that forces of forward and backward propulsion were generally larger in hindlimbs than in fore. Therefore, the forelegs contributed a smaller forward impulse to the body. This has implications for the efficiency with which the animal works. It is also suggested that the coefficient of traction (horizontal thrust/vertical reaction) was greater on the hind legs than on the front. It is also important to make a comparison between forward thrust through a whole walking sequence when the horse pulls at no-load (Figure 6) and the similar sequence at full load (Figure 7).

At zero load, the following could be observed:

1. Propulsion force came from a pair of legs that work in a sequential way, for example, the front-left and the hind-right and then the hind-left and the front-right. This pair of feet was the only one that developed positive power.
2. That sequence repeated itself in time.
3. The second leg of each pair started developing positive traction at a point close to the point of maximum peak positive traction force of the first leg of that pair.
4. At no time were there three feet generating positive propulsion force simultaneously.

At full load:

1. The sequence observed at zero load remains applicable; however, in this case there was a slight influence from the other pair of legs at the beginning and at the end of the sequence. During those small periods of time all legs contributed to develop draft power.
2. It was observed that rear-leg pull was larger at full load than at zero load.
3. Net power output for any leg became larger as the draught load increased (negative power decreased and positive power increased).
4. In variance with the pattern observed as point 3 for zero load (above), both legs of each pair developed positive traction nearly simultaneously.

Also, there was a slight difference in the time taken from the point that the first leg in a pair started developing power to the point that the second leg was lifted from the ground, i.e. at zero load test this time was 0.6 sec, while in the full load test this time was about 0.7 sec.

Similarly, the pull force generated by an animal varies considerably especially under normal tillage operations (O´Neill *et al*., 1987). Figure 8 shows the draught force as obtained by the tensile dynamometer. It was computed using the pull force in the traces and the draught angle. The observed variations in draught force were due mainly to the alternate forward thrust of the animal's legs. Also the variation in draught due to draught angle was insignificant at a given draught load since the numerical difference between the values was small. Analysis of the draught force for various load levels showed that the range of variation increased as the load being pulled increased.

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Figure 9 shows a comparison of power generated by the forelegs and the hindlegs. The power generated by the hindlegs was considerably greater than that produced by the forelegs at all draught loads. The positive power difference between the rear legs and the front legs increased as the draught load was increased, while the decline in negative power was equal for both fore and hind legs. The difference between the positive and negative power gives the net power available for pulling the load. The point at which the negative power fell to zero for all the limbs roughly corresponded to the point at which the draught load was equal to 15 per cent of the horse’s body weight.

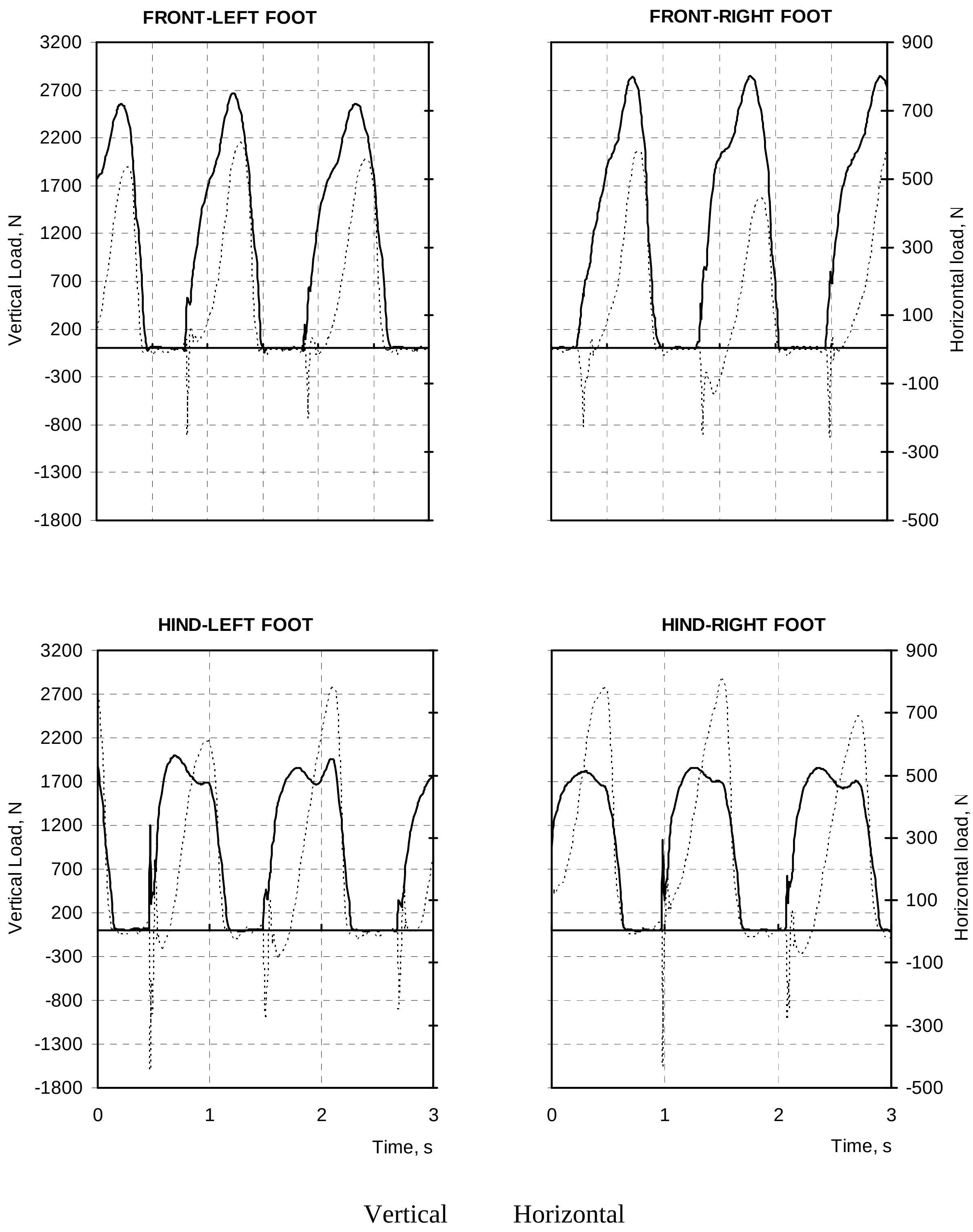

Figure 5. Indicator diagrams of vertical and horizontal reactions acting on individual feet when pulling a draught load of 710 N.

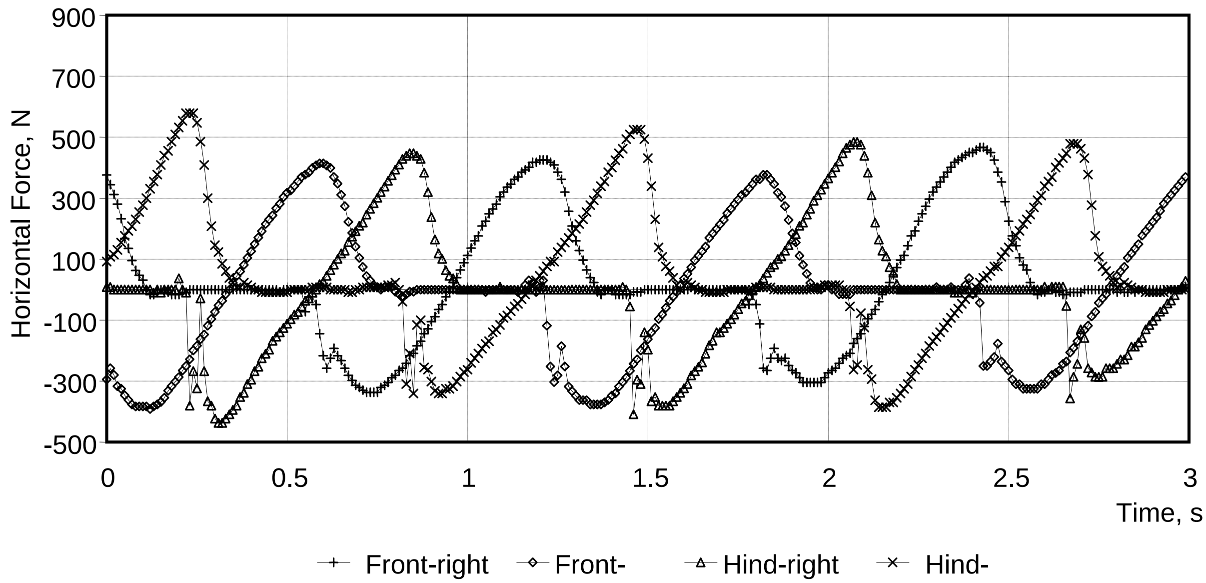

Figure 6. Indicator diagrams for propulsive thrust from all legs when pulling zero draught load.

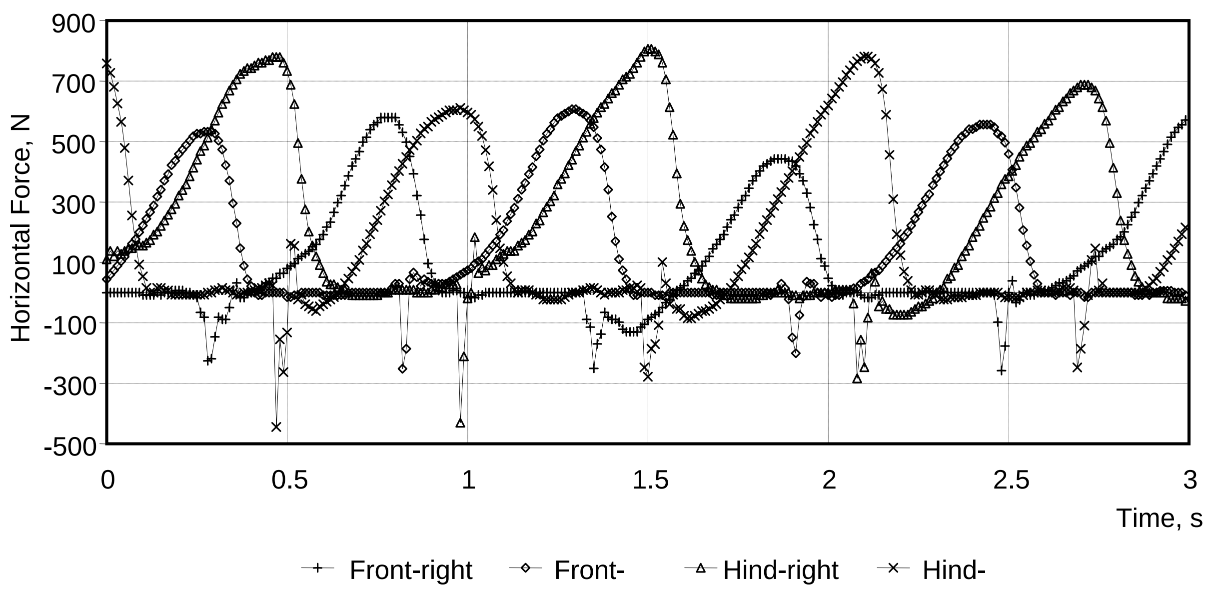

Figure 7. Indicator diagrams for propulsive thrust from all legs when pulling a draught of 710 N.

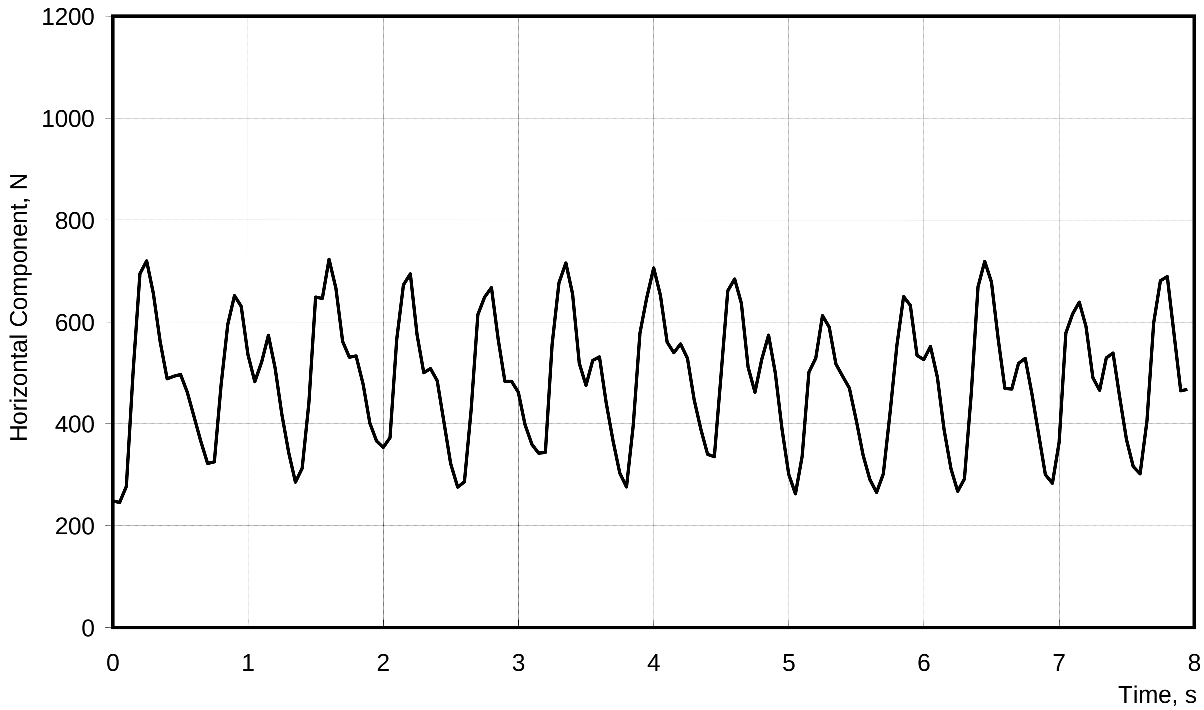

Figure 8. Horizontal component of the total draught force as measured by the tensile dynamometer during a test run with an average draught force of 490 N.

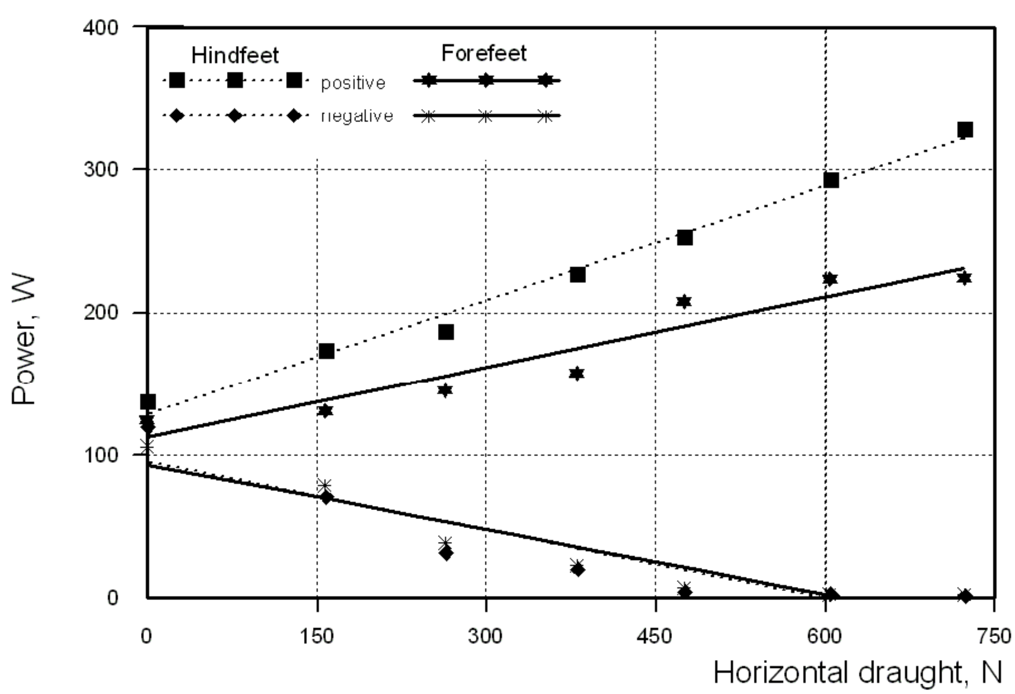

Figure 9. Effect of draught load on the power produced by both forelegs and both hindlegs with a forward velocity of 1 meter per second.

Out of all the tests the maximum tractive effort generated was 18% of the animal body's weight. This may be compared with the value of 10 percent of the body weight, which is frequently assumed to be a typical working pull for draught horses.

Data of the horizontal forces acting on the feet can be used to calculate the power generated. Comparison between net power generated by all limbs and that produced by the tension link showed not significant differences. Figure 10 illustrates how close is the relationship from power predicted from the foot dynamometers and that from pull measurements. It can be observed a close agreement as indicated by the coefficient determination.

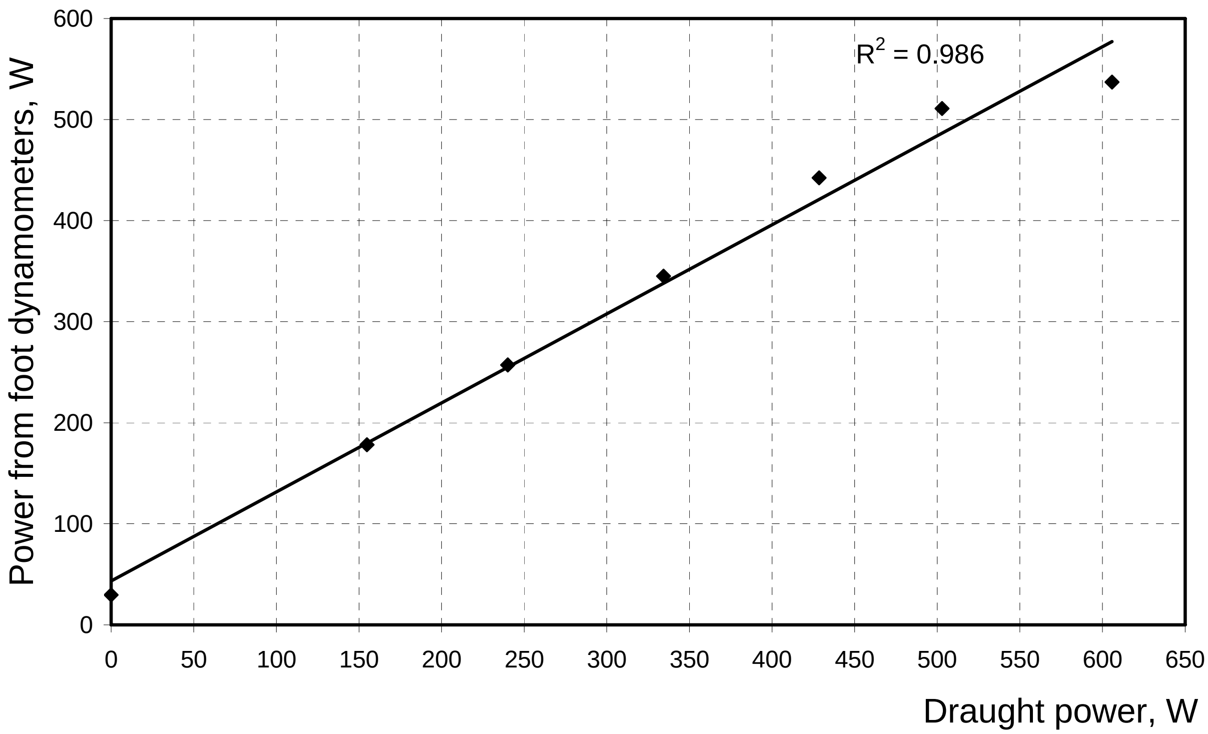

Figure 10. Curve indicator of relationship for power based on measurements by the foot dynamometers and power based on measurements with the tensile dynamometer.

6. CONCLUSIONS

- The draught angle had no significant effect on the average vertical and horizontal forces developed on the horse's feet at a given draught load. The power output was also not affected by draught angle.
- Comparison of the vertical forces on individual pairs of legs, indicated that at all draught load levels the forelegs carried the greater weight. The load carried on the front legs decreased and was transferred progressively to the hind legs as the draught load was increased.

- As the draught load was increased the traction force on any foot increased while the braking force was reduced. At draught loads below 300 N the forelegs and the hind legs made equal contribution to the propulsion force. At a draught load of 710 N the hind legs contributed 57 percent of the horizontal pull for this draught animal with a weight of 4022 N.
- Net power output for any leg became larger as the draught load increased. The hind legs developed more net power than the front legs, the difference between them growing as the draught load was increased.
- The curves of power produced as based on draught measured by the strain gauge load cell connected to the sledge and the power generated based on draught as measured by the foot dynamometers, were in close agreement.
- When walking both front and rear legs produce negative (backward) and positive (propulsive) power. As the draught load on the animal increases the negative power decreased and the positive power increased. The point at which the legs produced zero negative power corresponded to that at which the tractive effort was 15% of the body weight.

7. ACKNOWLEDGEMENTS

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