A novel load cell-supported research platform to measure vertical and horizontal motion of a horse’s centre of mass during trailer transport

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Abstract

During transport, horses are subjected to acceleration in three dimensions, rapid braking, turning, noise and other stressors. The animal’s ability to make postural corrections may be insufficient to prevent injury or distress, and so knowledge of the compensatory motion patterns of the horse in the trailer is a necessary precondition for smart design of transport systems. A custom two-horse trailer was built for this project. It had a horse compartment 1.85 m wide by 3.95 m long, with adjustable bulkheads and a centre divider separating the horses. The floor was instrumented with 24 shearbeam load cells to measure the vertical load imposed by each horse and its horizontal motion. Two horses were driven on a 56km trip on both rural and urban roads. Load data were collected at 100 Hz for the 58-minute trip and were filtered with a cut-off frequency of 5 Hz using a Butterworth low-pass filter and then vertical acceleration computed. A pivot table counted sign reversals in the vertical acceleration signal, and vertical displacement was calculated using the fundamental frequency of the resulting acceleration data. Total vertical motion was calculated by making the negative displacements absolute and summing these with the positive displacements, and vertical work done was calculated by multiplying the force by the displacement measures. Horizontal motion was calculated by averaging the transverse and cranio-caudal position of the centre of pressure every second and adding the resultant displacements. Absolute vertical displacement of the two horses was 69.55 m and 97.56 m. In addition to the work done by standing, vertical work done in response to vibration was 322.4 kJ and 443.2 kJ. Horizontal excursion was 227.1 m and 243.0 m. This is a first effort to quantify the additional workload imposed on animals during transport, which will aid in the design of smart transport vehicles that will minimise the stress to horses.

Key words:

Horse
Forces
Horse trailer
Load
Mechanical energy cost
Vibration
1. Introduction

Animals are frequently transported to provide us with food and for reasons related to work, recreation and companionship [1]. In New Zealand alone, more than 43 million animals (including horses) are transported at least once in their life, and many are transported more frequently [2]. Globally, up to half of the 5 million horses transported to slaughter arrive injured [3]. These statistics are echoed for cattle, sheep, and other transported livestock species [4]. Horses transported by road in non-commercial, low capacity trailers (floats) for recreational purposes face similar risks with more than 108 million journeys made in North America alone [5,6]. The potential for compromised behavioural and physical welfare during transport is associated with driver behaviour, the inability of livestock to cope with unanticipated vehicle movements, and a lack of welfare-oriented trailer or truck design [6-8]. During transport, animals are in a dynamic environment and are subjected to acceleration in three dimensions, rapid braking, turning, noise and other stressors. These arise as a result of vehicle dynamics that are influenced by driver skill and behaviour, road conditions, weather and other factors experienced in transit [5]. The animal’s postural corrections may be insufficient to prevent injury or distress, either because they exceed its physical abilities, or because of the varying behavioural (i.e. emotional) responses of individual animals (and species) to these stressors. A key challenge is to determine which of these animal responses (behavioural, kinematic, biomechanical or a combination thereof) to transport dynamics are the most indicative and earliest indicators of adverse welfare, so that real-time feedback can be implemented in smart vehicle design and initiate operator responses before injury or distress occurs. Whereas various approaches have been used previously to evaluate energetics during equine gait [9,10] there has been a lack of development of tools that facilitate the real-time measurement of animal movement and the dynamic loads experienced by them during road transport. Earlier studies have reported on gross movements of horses in transport using video. Untethered single horses in a 4-horse trailer left free to choose their own orientation spent significantly more time facing rearward than in any other orientation during a 32km trip on country roads [11]. Total forward and rearward motion was measured in horses confined to a compartment and travelling facing frontward or rearward during a 14.4km trip around a track with turns and stops. Facing frontward, total cranio-caudal motion was 12.95m and facing rearward was 16.99m, although the range of movements across 12 horses was highly variable and so not significant [12]. In both of the studies cited above, the investigators concluded that individual horse effects were stronger than the effects due to orientation alone and neither provided a basis on which to determine comparative workload of different transport orientations. To facilitate a multidisciplinary approach to the problem of understanding the biomechanical environment and its impacts upon animal behaviour and dynamic movement during transport, we have assembled a team of researchers with expertise in livestock health, behaviour, transport welfare, kinematics, mechatronics and data modelling. Anecdotally, horses are variably reported to prefer transport facing forward, backward or on an angle, and a suitably designed research platform is a step toward putting objective evidence to evaluate these beliefs. The objective of this paper is to describe a
custom-built horse trailer with load cells in the floor as a research platform for the estimation of vertical and horizontal motions of the horse, and its mechanical vertical work output during road transport based upon displacement of its centre of mass.

2. Materials and Methods

Ethics approval was granted by Massey University Animal Ethics Committee prior to commencement of the project (MUAEC No. 17/97).

2.1 Trailer

A custom dual-axle two-horse trailer measuring 2 m wide x 5 m long (excluding the drawbar) was designed by the authors and constructed for the project. The inside dimensions of the horse compartment measure 1.85 m wide x 3.95 m long, with adjustable bulkheads and a centre partition for positioning a horse either side. The trailer has a progressive electric braking system with wireless control that is automatically run from the towing vehicle, and an airbag suspension system with onboard air compressor and 12V deep-cycle battery. There are two roof vents forward and a small rectangular sliding window on each side at the rear for ventilation. There is no front window. The trailer has an enclosed forward compartment for batteries and the measuring equipment.

The floor of the horse compartment consists of four independent sensing panels, each measuring 0.92 m x 1.15 m and constructed of 32 mm plywood with a 3 mm steel plate on its undersurface and covered with an 8 mm high density non-skid rubber top surface. When positioned facing forward or backward on either side of the centre partition, the front feet of the horse were on one panel, and the hind feet on the other panel. Each floor panel is supported on six anodised aluminum shearbeam load cells, one under each corner and one under the midpoint of each long edge. The wires from each load cell are led to the front compartment of the trailer, through the floor and connected to six 3-channel National Instruments (NI) 9923 modules plugged into an NI c-RIO 9066 chassis (8-slots, integrated 667MHz integrated dual-core controller). A triaxial accelerometer is interfaced to the NI c-RIO chassis with a 3-channel NI 9230 module and attached to the front bulkhead of the trailer to record accelerations of the trailer in the vertical, side-to-side and front-to-back directions during motion.

2.2 Software

A data acquisition program was developed using NI LabView to collect the dynamic signals from each load cell and from the accelerometer. Data were collected at 100 Hz directly to a laptop computer, which was started and stopped manually at the beginning and end of each trip. Prior to
loading the horses, offset values were collected for 1 second to zero the transducer signals. The horizontal (X= transverse, Y= fore-aft) location of each load cell and the load (kg) on it was used to calculate the X-Y location of the centre of pressure of each horse between all four feet. This location was recorded to disk at 100 Hz. The total vertical load (kg) generated by the horse on its two panels was recorded from the 12 load cells and likewise stored to disk at 100 Hz. All data were stored in .csv format so they could be post-processed in Microsoft Excel.

2.3 Horses

Two horses (both mares) belonging to the veterinary teaching herd at Massey University were used. They were accustomed to forward-facing trailer transport but had not been recently moved by trailer. Their masses were 462 kg and 471 kg. They were transported side by side facing forward in the trailer and aside from being constrained within their compartments by the centre divider and their fore and aft bulkheads, they had no other restraints.

2.4 Transport details

The trailer was pulled by a Toyota Hilux 2.8L diesel utility vehicle driven by an experienced driver. The round trip of 56 km included both rural and city roads, with some gentle hills, stoplights and sharp turns. The maximum speed limits (80-100 km/h in the rural area and 50 km/h in the city) were followed at all times, and the trip took about 58 minutes from start to end, which was the same location.

2.5 Data processing

To establish the frequency range of the data recorded by the load cells using a rigid, passive load, a four-legged steel bench weighing 223 kg was positioned on one floor panel and driven around a shorter version of the normal trip (without horses) at the same speed. A Fast Fourier Transform (FFT) was run on 4096 samples of the load data, collected at 100 Hz, to determine the frequency range containing the most signal power. This was compared to the data from the accelerometer on the forward bulkhead, also collected at 100 Hz at the same time. Figure 1 shows that the output from the FFT on the load cell data under the steel bench indicated that most of the signal power was below 5 Hz. Subsequently, an FFT was run on the raw load cell data generated by a horse in transport, and that likewise indicated that most of the signal power was below 5 Hz (Fig. 1).

Consequently, the raw total vertical load data (measured in kg) from the horse transport trial, calculated as the sum of the individual loads from all the load cells under each panel, was put through a low-pass Butterworth filter with a cut-off frequency of 5 Hz. This filtered load data was multiplied
by $g$ (acceleration due to gravity, 9.81 m/s$^2$) to obtain force ($F$) in Newtons and then vertical
acceleration ($a$) was calculated from the following equation [Equation 1] using mass of the horse ($m$) and $g$:

$$a = \frac{F}{m} - g$$  \hspace{1cm} [Equation 1]

This generated a long series of positive and negative acceleration values. These data were then put through a pivot table in MS Excel to record the number of sign changes in the data, and to calculate average acceleration values within each sign change. The fundamental frequency ($f$) of the data series was determined as half the number of sign changes divided by the total number of samples in the original data and the acceleration data was expressed as the alternating positive and negative average values generated by the pivot table.

The instantaneous vertical displacement ($D_{vert}$) of the horse’s centre of mass was calculated [13] from the following equation [Equation 2] using the fundamental frequency ($f$) previously calculated and the acceleration values ($a$) calculated in Equation 1:

$$D_{vert} = (2\pi f)^2 \times a$$  \hspace{1cm} [Equation 2]

This equation generated a series of positive and negative vertical displacements, the overall sum of which was close to 0. The negative values were converted to positive, and then all values were summed to represent the total vertical motion of the horse’s centre of mass during the transport trip.

To calculate the vertical work done by the horse, it was necessary to re-calculate vertical force from the average acceleration values yielded by the pivot table. Vertical force ($F$) was calculated according to the Equation 3:

$$F = m \times (a + g)$$  \hspace{1cm} [Equation 3]

Work was then calculated by multiplying $F$ by the absolute vertical displacement at each interval in the pivot table and summing all the values to generate a total value.

The raw X (transverse) and Y (forward-backward) positions of the centre of pressure under the horse, collected at 100 Hz, were likewise filtered using a Butterworth filter at a cut-off frequency of 5 Hz. Then, the average of every 100 samples was calculated, and the resultant horizontal displacement of the centre of pressure calculated every second using Pythagorean theorem, generating a map of the horizontal excursion of the centre of pressure during the trip. The resultant X-Y displacement from one second to the next was summed for a measure of total horizontal excursion during the trailer trip.

3. Results

The FFT on the combined signals from the six load cells under one panel bearing the steel bench were a mix of true load plus higher frequency vibrations from the road surface. Most of the power in the signal was contained below 5 Hz (Fig. 1a) and peak magnitude was at about 2 - 2.5 Hz. The FFT on the accelerometer signal (Fig. 1b) indicates a broader range of frequencies with a less clear dominant power, and reflects the vibration measured by the accelerometer due to the road surface.
The FFT from the load cells bearing one of the horses in its compartment (Fig. 1c) likewise indicates that most of the signal was below 5 Hz and the peak amplitude was below 2 Hz. At the sampling frequency of 100 Hz, the horse transport trip generated a data stream of 346,916 samples (57.8 minutes).

After putting the acceleration data through the pivot table, and counting the sign reversals, the fundamental frequency of the vertical load data was determined to be 1.94 Hz for Horse 1 (in the left compartment) and this is likewise evident in the peak of the Fourier transform from that same horse (Figure 1c). Figure 2 illustrates the vertical motion of the horse between reversals in acceleration. The total (absolute) vertical displacement of the horse’s centre of mass was calculated to be 69.55 m over the course of the trip. The fundamental frequency of the data generated by Horse 2 (in the right compartment) was 1.65 Hz and its absolute vertical displacement was calculated to be 97.56 m. The vertical work done was 322.4 kJ for Horse 1, and 443.2 kJ for Horse 2 during the trip, reflecting the difference measured in total vertical displacement between the two horses.

The horizontal excursion of the centre of pressure was calculated to be 227.1 m for Horse 1, and 243.0 m for Horse 2. Figure 3 illustrates the excursion for Horse 1, and excluding extreme outliers, the range of excursion transversely was about 0.32 m and cranio-caudally about 0.30 m.

4. Discussion

According to the Fourier transforms illustrated in Figure 1, the majority of the signal power from the load transducers was below 5 Hz for both the trial using the weighted steel bench, and the trial with the two horses, and this justifies the cut-off frequency of 5 Hz in the low-pass Butterworth filter used to filter the data. The damping effect of the compliant limbs of the horse resulted in the peak amplitude of the FFT frequency spectrum being slightly lower than the non-compliant steel bench, and for the reduction of some of the higher frequency noise. Previously collected video recordings of the limbs of the horse in a pilot study indicate substantial high-frequency joint motion as the limbs attenuate vibrations caused by the road surface (unpublished data).

Calculation of the vertical displacement of the centre of mass between changes in sign of the vertical acceleration using Equation 2 outlined above depends on knowledge of the fundamental frequency of the acceleration signal generated from the loads recorded by the floor transducers. The FFT of the raw load signal per horse indicated a peak amplitude below 2 Hz, and estimation of the fundamental frequency of the signal by dividing half the number of reversals in the acceleration signal by the total number of samples yielded fundamental frequencies of 1.94 Hz and 1.65 Hz for the two horses, which roughly corresponds to the frequency of the peak amplitude in the FFT. The output from that process would assume roughly even numbers of raw samples contributing to the averaged positive and negative acceleration values, and although this is not likely per reversal, it is reasonable to assume roughly even numbers across the entire trial. Given the trip started and ended in the exact
same place, and that the sum of all the actual calculated positive and negative displacements worked out to -0.001 m and -0.002 m for the two horses, our findings suggest that this method of calculating displacement is valid. The difference in calculated vertical displacement between the two horses is accounted for by the difference in their fundamental frequencies. Theoretically, a stiffer horse will have a higher vibrational frequency, whereas a horse that is better able to accommodate the vibrations through its limbs will demonstrate reduced frequency and larger vertical displacement and mechanical work as a result. The characterization of the differences may provide the means to quantify individual mechanical responses to transport that have been reported previously [11,12].

The method outlined here is proposed as a starting point for estimating the work done (ie. as a proxy for energy expenditure) by the horse and other livestock during transport. In its simplest form, Work = force x displacement. Working backwards from the average positive and negative acceleration values generated by the pivot table, force (N) oscillates about the value for (mass of the horse x gravity) and vertical displacement is calculated from the acceleration values per sign change. Multiplying these average force values by the absolute vertical displacement values as the horse bounces up and down in response to perturbations by the road surface yielded work values of 322.4 kJ for Horse 1 and 443.2 kJ for Horse 2 over the course of the 58-minute trip. It is important to note that this is a calculation for mechanical work, and there is not a 1:1 relationship with metabolic work, although the two are linearly related during medium speeds of locomotion [14,15]. In real terms, there is also mechanical work done by the horse making postural adjustments in the horizontal plane, and these horizontal excursions were 227.1 m and 243.0 m respectively. The external horizontal forces were not measured by our floor transducers, and so calculation of the horizontal work done is not possible with this method. Work is done by the hip abductors and adductors to control movement in the transverse direction, and also by the adductors of the forelimb. The flexors and extensors of the proximal limb joints control motion in the cranio-caudal direction. Work done by these muscle groups in controlling the transverse and sagittal motion of the trunk’s centre of mass would need to be calculated from the horizontal forces against the floor, or by a musculoskeletal model with knowledge of the moment arms and muscle forces.

It is not possible to calculate the mechanical work done against gravity in a static, standing animal because there is no vertical displacement, aside from the very small changes in centre of mass position caused by breathing. Calculating mechanical work from the vertical displacement of the centre of mass requires a non-zero value for displacement, and so the negative displacements were made absolute such that all the positive and negative changes contributed to a total displacement value that was positive. However, the metabolic demand of positive work is greater than for negative work by at least a factor of two [16,17] in humans performing gross cyclic motions like going up and down stairs and cycle ergometry and the discrepancy increases with increasing speed. Whether this holds true for small and transient alternating positive and negative vertical displacements caused by perturbations or vibrations would be difficult to test using physiological methods. Burdett et al. [14] found good
correlation between increases in mechanical and metabolic energy cost at five gait speeds in humans but did not investigate standing. Minetti et al. [15] determined that the rate of energy consumption of standing horses was 1.94 ml O\textsubscript{2} kg\textsuperscript{-1} min\textsuperscript{-1} and assumed that 1 ml of O\textsubscript{2} is equivalent to 20.1 J for conversion of metabolic into mechanical units during locomotion [18]. If that is the case, then the mechanical cost of standing for Horse 1 in our study, over the course of 58 minutes would be calculated at 1045 kJ, and the additional cost of 322.4 kJ accommodating the vibrations would be additive. However, we simply added the absolute displacement values together without accounting for the theoretically lower metabolic cost of the negative work. Also, the work done during these small amplitude movements by series and parallel elastic elements in the muscles with little metabolic cost would be impossible to quantify.

There are drawbacks to using a centre of mass approach for calculating work. The floor transducers only measured the overall effect of all the sources of positive and negative muscle work on the vertical displacement of the centre of mass as it moved in response to perturbations in the road surface. It is likely that it would underestimate the metabolic effects of co-contraction by muscles in near-isometric stabilisation of the limbs, and the simultaneous positive and negative work done by muscles at different joints [19]. Work can also be calculated from changes in kinetic energy of the centre of mass, but as we calculated vertical displacement from variable numbers of points in the raw acceleration data, it would be difficult to calculate velocity with reasonable accuracy, and this is also true of attempting to get velocity by integration of the acceleration curve.

Other factors influencing the energy cost of transport would be heart rate, and increased metabolic rate caused by stress. This is a first effort to quantify the additional mechanical load caused by adjustments the horse needs to make in response to perturbations caused by changes in direction, speed and road surface. We will use it in future to evaluate the effects of the horse’s position in the trailer (facing front, back, angled), along with other modalities like heart rate monitors and video.

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Footnotes
Author contributions: C.B.R. and G.R.C designed the trailer and the experiment; C.B.R, G.R.C., B.R.A, B.I.G. and B.E.M. collected the data. C.B.R., G.R.C. and L.T. analyzed and interpreted the data. C.B.R. and G.R.C. wrote the article. All the authors reviewed the manuscript.

References


Fig. 1. Fast Fourier Transform (FFT) on (a) the load data collected from the steel bench transport trial, on (b) the vertical acceleration data collected from the bulkhead-mounted accelerometer and on (c) the load data collected from a horse transport trial.
Fig. 2. Vertical displacement of the horse’s centre of mass, calculated from the acceleration data. Load data were collected at 100Hz, filtered with a low-pass Butterworth filter at a cut-off frequency of 5Hz and then the number of reversals in sign of the acceleration signal determined with a pivot table. In this case, the number of reversals in sign was 13,478 from 346,916 samples at 100Hz.
Fig. 3. Horizontal excursion of the horse’s centre of pressure during transport. Raw data collected at 100Hz were filtered using a low-pass Butterworth filter at a cut-off frequency of 5Hz and then every 100 frames were averaged to yield one point per second.
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