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

G Robert Colborne <sup>a,\*</sup>, Liqiong Tang <sup>b</sup>, Brooke R Adams <sup>a</sup>, Brooke I Gordon <sup>a</sup>, Bridie E McCabe <sup>a</sup>, Christopher B Riley <sup>a</sup>

<sup>a</sup> School of Veterinary Science, Massey University, Palmerston North 4410, New Zealand

<sup>b</sup> School of Engineering and Advanced Technology, Massey University, Palmerston North 4410, New Zealand

Corresponding author:

G Robert Colborne  
School of Veterinary Science  
Massey University  
Private Bag 11 222  
Palmerston North 4410  
New Zealand  
Email address: [G.R.Colborne@massey.ac.nz](mailto:G.R.Colborne@massey.ac.nz)  
Phone: +64 6 356 9099 Ext 85185

31 Abstract

32

33 During transport, horses are subjected to acceleration in three dimensions, rapid braking, turning,  
34 noise and other stressors. The animal's ability to make postural corrections may be insufficient to  
35 prevent injury or distress, and so knowledge of the compensatory motion patterns of the horse in the  
36 trailer is a necessary precondition for smart design of transport systems. A custom two-horse trailer  
37 was built for this project. It had a horse compartment 1.85 m wide by 3.95 m long, with adjustable  
38 bulkheads and a centre divider separating the horses. The floor was instrumented with 24 shearbeam  
39 load cells to measure the vertical load imposed by each horse and its horizontal motion. Two horses  
40 were driven on a 56km trip on both rural and urban roads. Load data were collected at 100 Hz for the  
41 58-minute trip and were filtered with a cut-off frequency of 5 Hz using a Butterworth low-pass filter  
42 and then vertical acceleration computed. A pivot table counted sign reversals in the vertical  
43 acceleration signal, and vertical displacement was calculated using the fundamental frequency of the  
44 resulting acceleration data. Total vertical motion was calculated by making the negative  
45 displacements absolute and summing these with the positive displacements, and vertical work done  
46 was calculated by multiplying the force by the displacement measures. Horizontal motion was  
47 calculated by averaging the transverse and cranio-caudal position of the centre of pressure every  
48 second and adding the resultant displacements. Absolute vertical displacement of the two horses was  
49 69.55 m and 97.56 m. In addition to the work done by standing, vertical work done in response to  
50 vibration was 322.4 kJ and 443.2 kJ. Horizontal excursion was 227.1 m and 243.0 m. This is a first  
51 effort to quantify the additional workload imposed on animals during transport, which will aid in the  
52 design of smart transport vehicles that will minimise the stress to horses.

53

54 Key words:

55

56 Horse

57 Forces

58 Horse trailer

59 Load

60 Mechanical energy cost

61 Vibration

62

## 63 **1. Introduction**

64 Animals are frequently transported to provide us with food and for reasons related to work,  
65 recreation and companionship [1]. In New Zealand alone, more than 43 million animals (including  
66 horses) are transported at least once in their life, and many are transported more frequently [2]. Globally,  
67 up to half of the 5 million horses transported to slaughter arrive injured [3]. These statistics are echoed  
68 for cattle, sheep, and other transported livestock species [4]. Horses transported by road in non-  
69 commercial, low capacity trailers (floats) for recreational purposes face similar risks with more than  
70 108 million journeys made in North America alone [5,6]. The potential for compromised behavioural  
71 and physical welfare during transport is associated with driver behaviour, the inability of livestock to  
72 cope with unanticipated vehicle movements, and a lack of welfare-oriented trailer or truck design [6-  
73 8]. During transport, animals are in a dynamic environment and are subjected to acceleration in three  
74 dimensions, rapid braking, turning, noise and other stressors. These arise as a result of vehicle dynamics  
75 that are influenced by driver skill and behaviour, road conditions, weather and other factors experienced  
76 in transit [5]. The animal's postural corrections may be insufficient to prevent injury or distress, either  
77 because they exceed its physical abilities, or because of the varying behavioural (i.e. emotional)  
78 responses of individual animals (and species) to these stressors. A key challenge is to determine which  
79 of these animal responses (behavioural, kinematic, biomechanical or a combination thereof) to transport  
80 dynamics are the most indicative and earliest indicators of adverse welfare, so that real-time feedback  
81 can be implemented in smart vehicle design and initiate operator responses before injury or distress  
82 occurs. Whereas various approaches have been used previously to evaluate energetics during equine  
83 gait [9,10] there has been a lack of development of tools that facilitate the real-time measurement of  
84 animal movement and the dynamic loads experienced by them during road transport. Earlier studies  
85 have reported on gross movements of horses in transport using video. Untethered single horses in a 4-  
86 horse trailer left free to choose their own orientation spent significantly more time facing rearward than  
87 in any other orientation during a 32km trip on country roads [11]. Total forward and rearward motion  
88 was measured in horses confined to a compartment and travelling facing forward or rearward during  
89 a 14.4km trip around a track with turns and stops. Facing forward, total cranio-caudal motion was  
90 12.95m and facing rearward was 16.99m, although the range of movements across 12 horses was highly  
91 variable and so not significant [12]. In both of the studies cited above, the investigators concluded that  
92 individual horse effects were stronger than the effects due to orientation alone and neither provided a  
93 basis on which to determine comparative workload of different transport orientations.

94 To facilitate a multidisciplinary approach to the problem of understanding the biomechanical  
95 environment and its impacts upon animal behaviour and dynamic movement during transport, we  
96 have assembled a team of researchers with expertise in livestock health, behaviour, transport welfare,  
97 kinematics, mechatronics and data modelling. Anecdotally, horses are variably reported to prefer  
98 transport facing forward, backward or on an angle, and a suitably designed research platform is a step  
99 toward putting objective evidence to evaluate these beliefs. The objective of this paper is to describe a

100 custom-built horse trailer with load cells in the floor as a research platform for the estimation of  
101 vertical and horizontal motions of the horse, and its mechanical vertical work output during road  
102 transport based upon displacement of its centre of mass.

103

## 104 **2. Materials and Methods**

105

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

108

### 109 *2.1 Trailer*

110

111 A custom dual-axle two-horse trailer <sup>1</sup> measuring 2 m wide x 5 m long (excluding the drawbar)  
112 was designed by the authors and constructed for the project. The inside dimensions of the horse  
113 compartment measure 1.85 m wide x 3.95 m long, with adjustable bulkheads and a centre partition for  
114 positioning a horse either side. The trailer has a progressive electric braking system with wireless  
115 control that is automatically run from the towing vehicle, and an airbag suspension system with  
116 onboard air compressor and 12V deep-cycle battery. There are two roof vents forward and a small  
117 rectangular sliding window on each side at the rear for ventilation. There is no front window. The  
118 trailer has an enclosed forward compartment for batteries and the measuring equipment.

119 The floor of the horse compartment consists of four independent sensing panels, each measuring  
120 0.92 m x 1.15 m and constructed of 32 mm plywood with a 3 mm steel plate on its undersurface and  
121 covered with an 8 mm high density non-skid rubber top surface. When positioned facing forward or  
122 backward on either side of the centre partition, the front feet of the horse were on one panel, and the  
123 hind feet on the other panel. Each floor panel is supported on six anodised aluminum shearbeam load  
124 cells <sup>2</sup>, one under each corner and one under the midpoint of each long edge. The wires from each  
125 load cell are led to the front compartment of the trailer, through the floor and connected to six 3-  
126 channel National Instruments (NI) 9923 modules plugged into an NI c-RIO 9066 chassis (8-slots,  
127 integrated 667MHz integrated dual-core controller) <sup>3</sup>. A triaxial accelerometer <sup>4</sup> is interfaced to the NI  
128 c-RIO chassis with a 3-channel NI 9230 module and attached to the front bulkhead of the trailer to  
129 record accelerations of the trailer in the vertical, side-to-side and front-to-back directions during  
130 motion.

131

### 132 *2.2 Software*

133

134 A data acquisition program was developed using NI LabView to collect the dynamic signals from  
135 each load cell and from the accelerometer. Data were collected at 100 Hz directly to a laptop  
136 computer, which was started and stopped manually at the beginning and end of each trip. Prior to

137 loading the horses, offset values were collected for 1 second to zero the transducer signals. The  
138 horizontal (X= transverse, Y= fore-aft) location of each load cell and the load (kg) on it was used to  
139 calculate the X-Y location of the centre of pressure of each horse between all four feet. This location  
140 was recorded to disk at 100 Hz. The total vertical load (kg) generated by the horse on its two panels  
141 was recorded from the 12 load cells and likewise stored to disk at 100 Hz. All data were stored in .csv  
142 format so they could be post-processed in Microsoft Excel <sup>5</sup>.

143

### 144 *2.3 Horses*

145

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

151

### 152 *2.4 Transport details*

153

154 The trailer was pulled by a Toyota Hilux 2.8L diesel utility vehicle <sup>6</sup> driven by an experienced  
155 driver. The round trip of 56 km included both rural and city roads, with some gentle hills, stoplights  
156 and sharp turns. The maximum speed limits (80-100 km/h in the rural area and 50 km/h in the city)  
157 were followed at all times, and the trip took about 58 minutes from start to end, which was the same  
158 location.

159

### 160 *2.5 Data processing*

161

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

171

172 Consequently, the raw total vertical load data (measured in kg) from the horse transport trial,  
173 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

174 by  $g$  (acceleration due to gravity,  $9.81 \text{ m/s}^2$ ) to obtain force ( $F$ ) in Newtons and then vertical  
175 acceleration ( $a$ ) was calculated from the following equation [Equation 1] using mass of the horse ( $m$ )  
176 and  $g$ :

$$177 \quad a = (F/m) - g \quad \text{[Equation 1]}$$

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

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

$$187 \quad D_{vert} = (2\pi f)^2 \times a \quad \text{[Equation 2]}$$

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

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

$$194 \quad F = m \times (a + g) \quad \text{[Equation 3]}$$

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

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

203

### 204 3. Results

205

206 The FFT on the combined signals from the six load cells under one panel bearing the steel bench  
207 were a mix of true load plus higher frequency vibrations from the road surface. Most of the power in  
208 the signal was contained below 5 Hz (Fig. 1a) and peak magnitude was at about 2 - 2.5 Hz. The FFT  
209 on the accelerometer signal (Fig. 1b) indicates a broader range of frequencies with a less clear  
210 dominant power, and reflects the vibration measured by the accelerometer due to the road surface.

211 The FFT from the load cells bearing one of the horses in its compartment (Fig. 1c) likewise indicates  
212 that most of the signal was below 5 Hz and the peak amplitude was below 2Hz. At the sampling  
213 frequency of 100 Hz, the horse transport trip generated a data stream of 346,916 samples (57.8  
214 minutes).

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

224 The horizontal excursion of the centre of pressure was calculated to be 227.1 m for Horse 1, and  
225 243.0 m for Horse 2. Figure 3 illustrates the excursion for Horse 1, and excluding extreme outliers,  
226 the range of excursion transversely was about 0.32 m and cranio-caudally about 0.30 m.

227

#### 228 4. Discussion

229

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

238 Calculation of the vertical displacement of the centre of mass between changes in sign of the  
239 vertical acceleration using Equation 2 outlined above depends on knowledge of the fundamental  
240 frequency of the acceleration signal generated from the loads recorded by the floor transducers. The  
241 FFT of the raw load signal per horse indicated a peak amplitude below 2 Hz, and estimation of the  
242 fundamental frequency of the signal by dividing half the number of reversals in the acceleration signal  
243 by the total number of samples yielded fundamental frequencies of 1.94 Hz and 1.65 Hz for the two  
244 horses, which roughly corresponds to the frequency of the peak amplitude in the FFT. The output  
245 from that process would assume roughly even numbers of raw samples contributing to the averaged  
246 positive and negative acceleration values, and although this is not likely per reversal, it is reasonable  
247 to assume roughly even numbers across the entire trial. Given the trip started and ended in the exact

248 same place, and that the sum of all the actual calculated positive and negative displacements worked  
249 out to -0.001 m and -0.002 m for the two horses, our findings suggest that this method of calculating  
250 displacement is valid. The difference in calculated vertical displacement between the two horses is  
251 accounted for by the difference in their fundamental frequencies. Theoretically, a stiffer horse will  
252 have a higher vibrational frequency, whereas a horse that is better able to accommodate the vibrations  
253 through its limbs will demonstrate reduced frequency and larger vertical displacement and mechanical  
254 work as a result. The characterization of the differences may provide the means to quantify individual  
255 mechanical responses to transport that have been reported previously [11,12].

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

275 It is not possible to calculate the mechanical work done against gravity in a static, standing animal  
276 because there is no vertical displacement, aside from the very small changes in centre of mass position  
277 caused by breathing. Calculating mechanical work from the vertical displacement of the centre of  
278 mass requires a non-zero value for displacement, and so the negative displacements were made  
279 absolute such that all the positive and negative changes contributed to a total displacement value that  
280 was positive. However, the metabolic demand of positive work is greater than for negative work by at  
281 least a factor of two [16,17] in humans performing gross cyclic motions like going up and down stairs  
282 and cycle ergometry and the discrepancy increases with increasing speed. Whether this holds true for  
283 small and transient alternating positive and negative vertical displacements caused by perturbations or  
284 vibrations would be difficult to test using physiological methods. Burdett et al. [14] found good

285 correlation between increases in mechanical and metabolic energy cost at five gait speeds in humans  
286 but did not investigate standing. Minetti et al. [15] determined that the rate of energy consumption of  
287 standing horses was 1.94 ml O<sub>2</sub> kg<sup>-1</sup> min<sup>-1</sup> and assumed that 1 ml of O<sub>2</sub> is equivalent to 20.1 J for  
288 conversion of metabolic into mechanical units during locomotion [18]. If that is the case, then the  
289 mechanical cost of standing for Horse 1 in our study, over the course of 58 minutes would be  
290 calculated at 1045 kJ, and the additional cost of 322.4 kJ accommodating the vibrations would be  
291 additive. However, we simply added the absolute displacement values together without accounting for  
292 the theoretically lower metabolic cost of the negative work. Also, the work done during these small  
293 amplitude movements by series and parallel elastic elements in the muscles with little metabolic cost  
294 would be impossible to quantify.

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

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

309

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311

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318 with loading and unloading.

319

## 320 **Footnotes**

321

- 322 1. Paul-Douglas Floats, Angove Engineering Ltd., 17 Mangahao Road, Pahiatua 4910, New Zealand  
323 2. Model ASB-250, PT Global Ltd, Auckland, New Zealand  
324 3. National Instruments New Zealand Ltd., PO Box 147801, Ponsonby, Auckland 1021, New  
325 Zealand  
326 4. Model 356A32, PCB Piezoelectronics, ThermoFisher Scientific, 4 Talavera Rd, North Ryde NSW  
327 2113, Australia  
328 5. Microsoft Office 365 ProPlus, Microsoft Corporation.  
329 6. 2019 Hilux SR5 2.8L 4WD Automatic, Toyota New Zealand.

330

331 **Author contributions:** C.B.R. and G.R.C designed the trailer and the experiment; C.B.R, G.R.C.,  
332 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  
333 data. C.B.R. and G.R.C. wrote the article. All the authors reviewed the manuscript.

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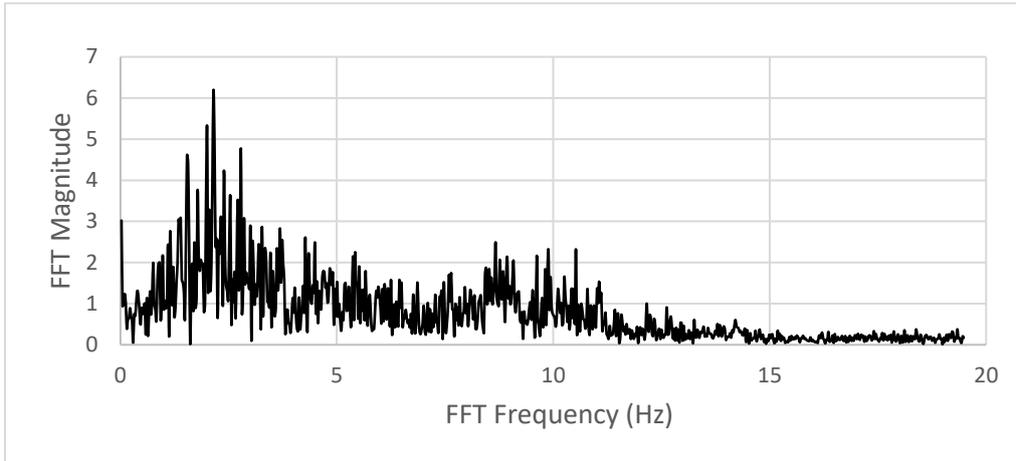
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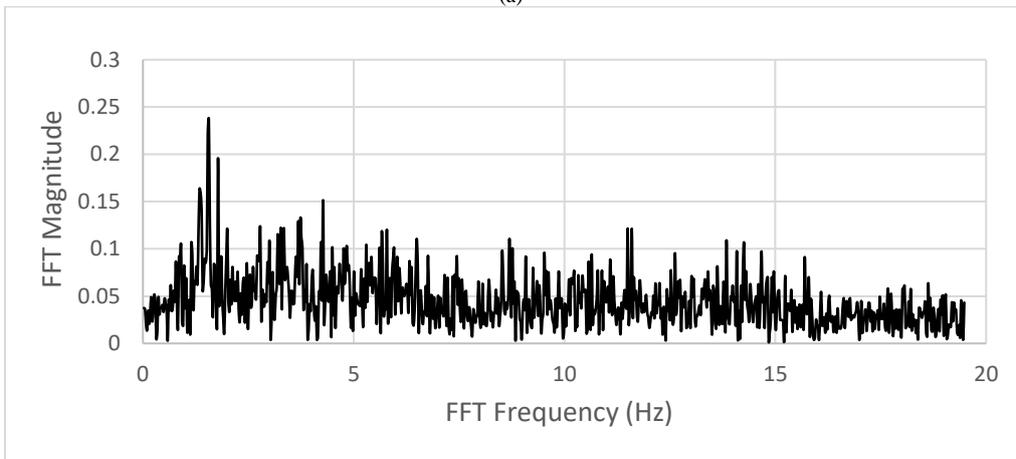
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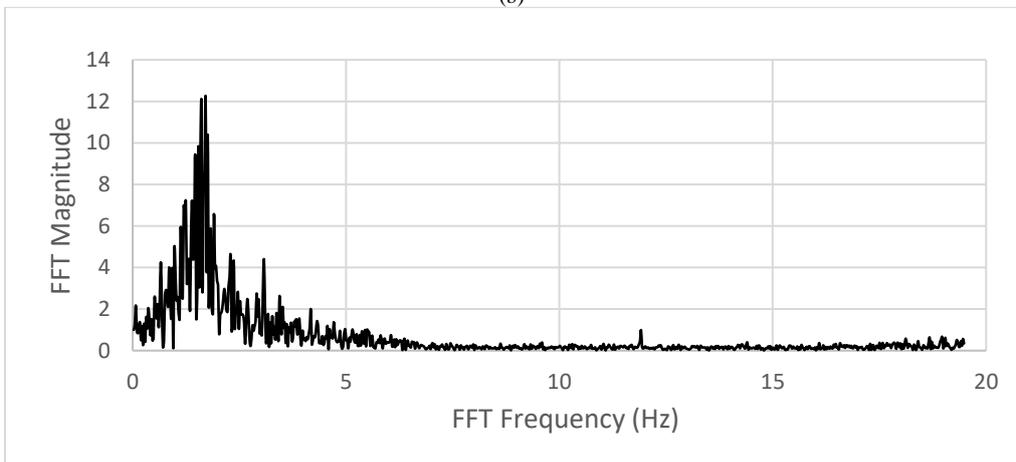
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(a)



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(b)

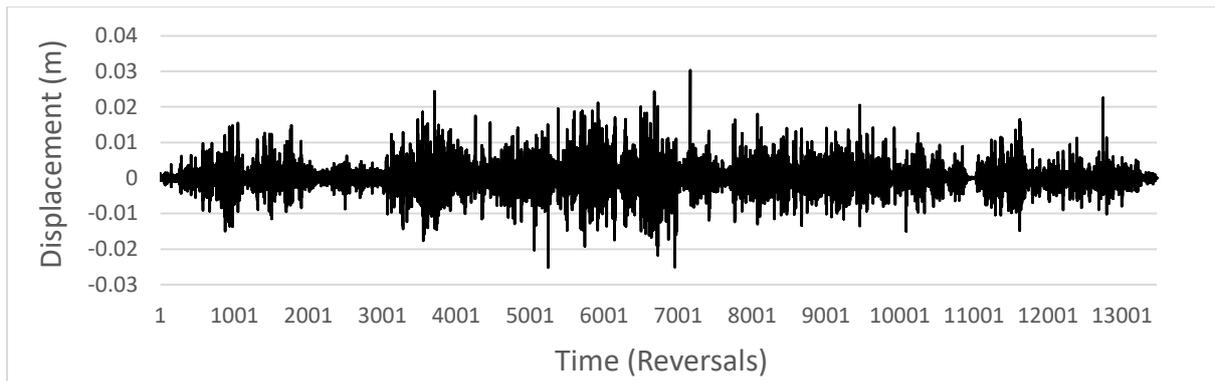


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(c)

391 Fig. 1. Fast Fourier Transform (FFT) on (a) the load data collected from the steel bench transport  
392 trial, on (b) the vertical acceleration data collected from the bulkhead-mounted accelerometer and on  
393 (c) the load data collected from a horse transport trial.

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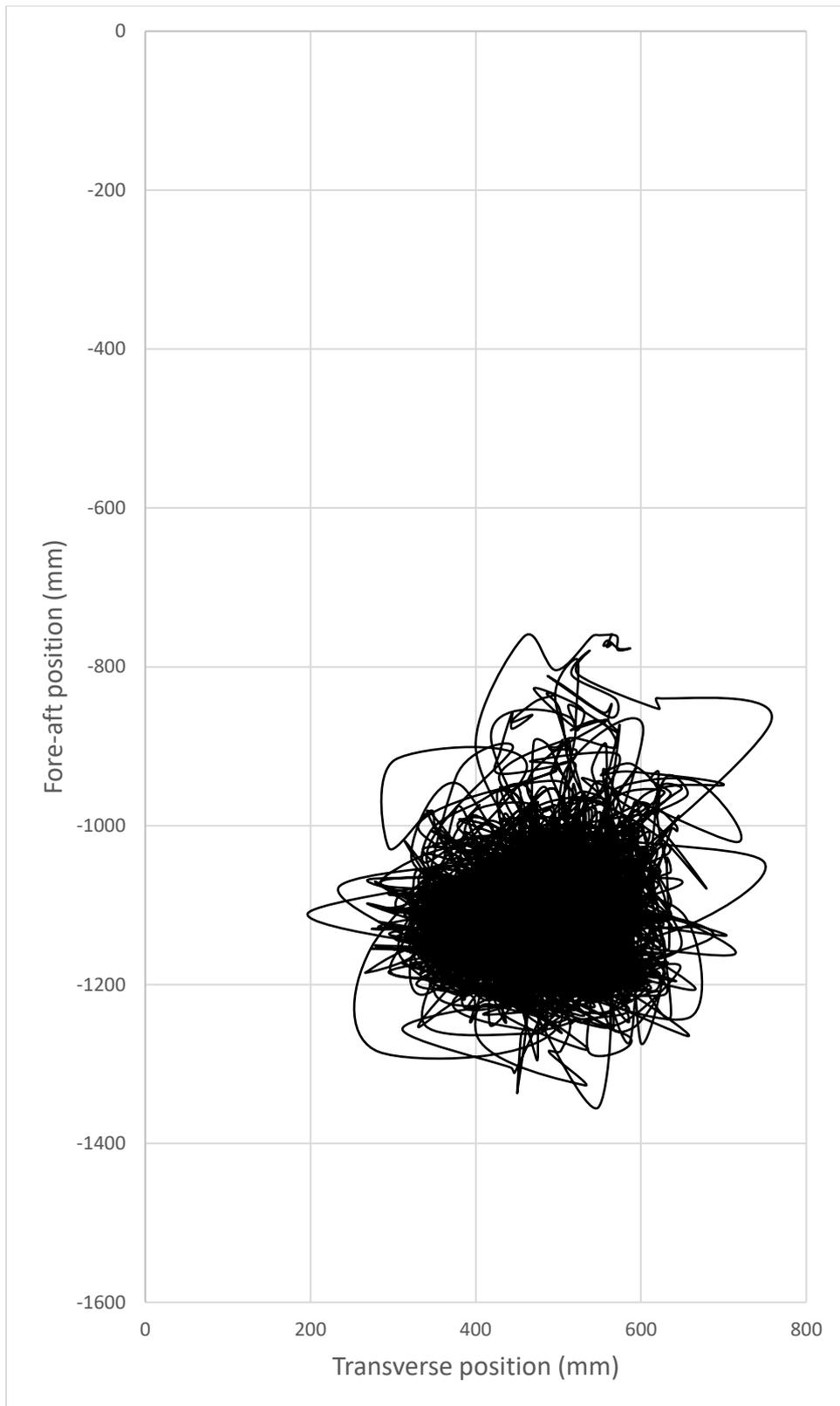
397 Fig. 2. Vertical displacement of the horse's centre of mass, calculated from the acceleration data.

398 Load data were collected at 100Hz, filtered with a low-pass Butterworth filter at a cut-off frequency

399 of 5Hz and then the number of reversals in sign of the acceleration signal determined with a pivot

400 table. In this case, the number of reversals in sign was 13,478 from 346,916 samples at 100Hz.

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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.