Impact during equine locomotion: Techniques for measurement and analysis

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Abstract

Impact is implicated in the development of several types of musculoskeletal injury in the horse. Characterisation of impact experienced during strenuous exercise is an important first step towards understanding the mechanism for injury. Measurement and analysis of large, short duration impacts is difficult. The measurement system must be able to record transient peaks and high frequencies accurately. The analysis technique must be able to characterise the impact signal in time and frequency. This paper presents a measurement system and analysis technique for the characterisation of large impacts.

A piezo-electric accelerometer was securely mounted on the dorsal surface of the horses hoof. Saddle mounted charge amplifiers and a 20 metre coaxial cable transferred these data to a PC based logging system. Data were down-loaded onto a UNIX workstation and analysed using a proprietary statistics package.

The values of parameters calculated from the time series data were comparable to those of other authors. A wavelet decomposition showed that the frequency profile of the signal changed with time. While most spectral energy was seen at impact, a significant amount of energy was contained in the signal immediately following impact. Over 99% of this energy was contained in frequencies less than 1,250Hz.

The sampling rate and the frequency response of a measurement system for recording impact should be chosen carefully to prevent loss or corruption of data. Time scale analysis using a wavelet decomposition is a powerful technique which can be used to characterise impact data. The use of contour plots provides a highly visual representation of the time and frequency localisation of power during impact.

1 Introduction

Horses experience impact during locomotion when the foot comes to the ground at the beginning of stance phase. There is evidence to suggest that impact can have both constructive and destructive effects on the musculoskeletal system. Increased dynamic loading will result in the bone remodelling to increase its strength. Chronic exposure to impact, however, has been linked to degeneration of articular cartilage and subchondral bone in sheep (Radin et al.1982) and the development of osteoarthrosis in humans (Radin 1983). Exposure to concussion is frequently implicated in the development of several types of musculoskeletal injury in horses (Stashak 1987). In apparent contradiction to this, it is believed that limited exposure to concussion during low intensity exercise is beneficial. Road work, for example, is widely used to strengthen musculoskeletal tissue during training for

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competition (Hodgson and Rose 1994).

Studies of impact in humans frequently measure force at impact using a force plate. Studies in horses have predominantly measured acceleration at impact using an accelerometer fixed to the hoof wall. These studies have shown that the time histories of force and acceleration at impact are similar in nature. Impact is first observed as a large magnitude transient peak (force or acceleration) which occurs in the first 50ms of stance (Nigg et al. 1987). This is immediately followed by vibrations which are quickly damped out during stance. It has been shown that an increase in the hardness of the foot/ground interface results in an increase in the magnitude and a decrease in duration of the initial peak, and an increase in the frequency of vibrations (Barrey et al. 1991, Benoit et al. 1993).

The difficulty of measurement and characterisation of impact is increased under conditions which produce complex time histories containing large magnitude transient peaks and high frequency vibrations. Careful attention must be paid to the design of the measurement system to ensure that transient peak values and the frequency of vibrations are measured accurately.

The frequency components contained in complex time histories are difficult to interpret in the time domain. Measures of predominant (mean) frequency or central (median) frequency have been successfully used to differentiate between types of ground surface (Barrey et al. 1991) although they are insensitive to changes in amplitude and distribution of frequencies. Recent development of the discrete wavelet transform has provided a powerful method for spectral analysis of complex time series data (Nason and Silverman 1994). This technique has been shown to provide a number of improvements over more traditional spectral techniques for the characterisation of impact in horses (Burn et al. 1996).

This paper describes a measurement system to record impact in horses, and demonstrates the application of time scale analysis using wavelets for the characterisation of impact data. Attention is drawn to aspects of the design of the measurement system upon which the accuracy of measurement is dependent.

2 Materials and Methods

2.1 Experimental Method

A single horse (thoroughbred, mass 450kg, 11 years) shod with steel shoes was used for the experiment. A piezo-electric accelerometer (Endevco[1] 7701-100) was bolted to a perspex mount which allowed the sensitive axis of the accelerometer to be set perpendicular to the ground surface. The mount was positioned in the saggital plane in line with the long axis of the limb, the mid-way between the coronet band and bottom of the front left hoof. The dorsal surface of the hoof was cleaned with ethanol and the mount secured using superglue and a plastic strap (RS[2]). A low noise cable (Endevco[1]), secured to the horse’s limb using a brushing boot, and adhesive tape around the antibrachium, was used to connect the accelerometer to a charge amplifier mounted on the horse’s back. The charge amplifier was fitted with an internal low pass filter with a cut-off frequency of 4.8KHz. A 20 metre long shielded cable was used to transfer the signal from the charge amplifier to a PC compatible microcomputer fitted with a data logging card (RTI-815A, Analog Devices[3]).

The response of the measurement system varied less than 0.4dB between 10Hz and 4.4kHz. The natural frequency of the accelerometer was 20kHz, and the mounting system did not resonate in the frequency range 10Hz - 5kHz.

Baseline data were logged before and after the experiment with the horse stood still.

A smooth level concrete runway was used to provide data for a hard foot/ground interface. The surface was swept before the experiment. The horse was lead in trot over the surface at a constant speed in a straight line. The mean speed for all the runs was 4m/s. Hoof acceleration data were logged at 10,000 samples /second for a 5 second period in the middle of each run. Five runs were recorded.

2.2 Data Analysis

Data were transferred to a UNIX workstation (SPARC 10, Sun Microsystems[4]). Analysis was done using a statistical package (S-PLUS version 3.2 MathSoft Inc.[5]).

The raw data were scaled to Acceleration. in ‘g’ (1g = 9.81m/s^2) using the accelerometer calibration data. A program was written in S-Plus to extract the impact acceleration for each stride. The beginning of impact was taken as the point during swing phase at which a large negative change in acceleration was first observed. The end of impact was taken as the point after the start of impact at which acceleration had returned to zero and vibrations had ceased. Time series plots of all impacts were produced for visual comparison.

Values for the peak initial impact deceleration (SHOCK), the duration of the initial deceleration (SHOCKDUR) the duration of vibrations (VIBDUR), and the mean frequency (MFREQ) were obtained for each impact using a second program. These parameters are defined in Barrey et al. 1991.

A discrete wavelet transform (DWT) was performed on the time series data for each impact using a wavelet from the family of ‘least asymmetric’ compactly supported wavelets (Daubechies 1988). A power spectrum was computed from the wavelet coefficients using the Wavethresh library (Nason and Silverman 1994) and plotted for each impact. Time is represented on the x axis of the power spectrum plot, and frequency, grouped into bands, is represented on the y axis. The power contribution from a single frequency band at a given time is represented by the magnitude of a vertical line plotted at the intersection of sample time and frequency.

3 Results

The baseline data confirmed that there was zero change in acceleration with the horse stood still.

Data for twenty eight strides were extracted from the five runs. A typical time series plot for an individual impact is shown in Figure 1. A large initial deceleration of 98g peak value was followed by vibrations which decayed over a period of 48ms. The vibrations were seen to contain several frequencies at different amplitudes.The initial deceleration is shown in Figure 2 with an expanded time scale and individual samples marked. Only ten samples occurred during the initial impact, corresponding to a period of 0.9ms.

Mean values and standard deviations of time series parameters were as follows: SHOCK was 96g, sd±23, and SHOCKDUR was 0.9ms ±0.3. VIBDUR was 49.0ms ±3.8 MFREQ was 618Hz ±75.

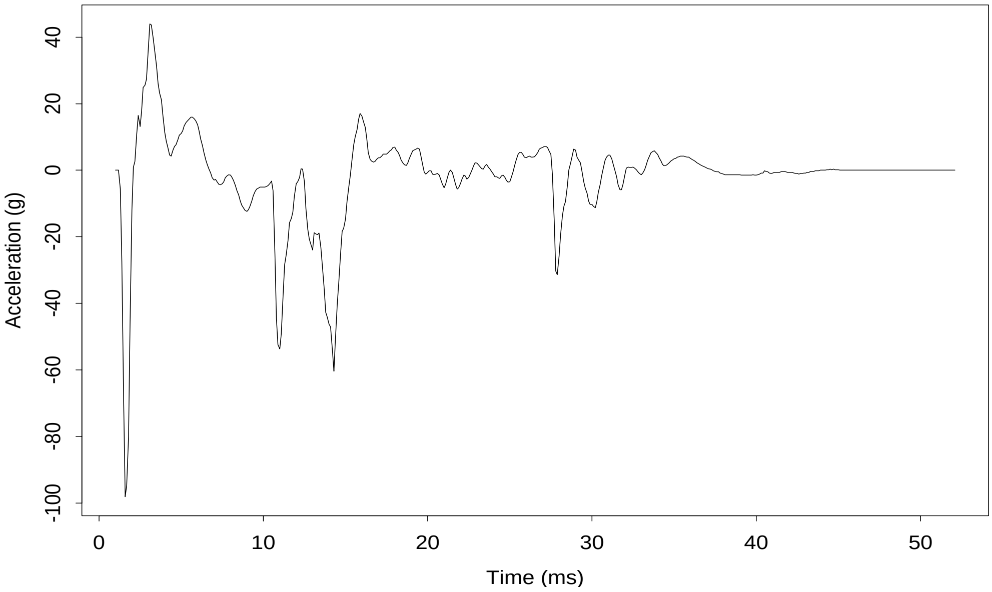

Figure 1: Time series for a typical hoof impact. on concrete.

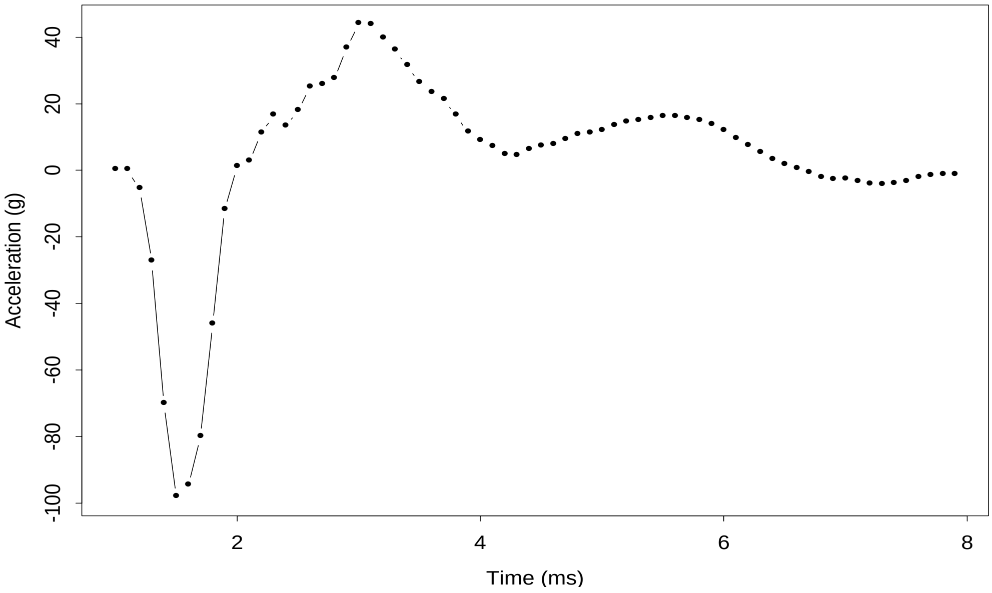

Figure 2: Time series for the initial deceleration at impact with sample points marked.

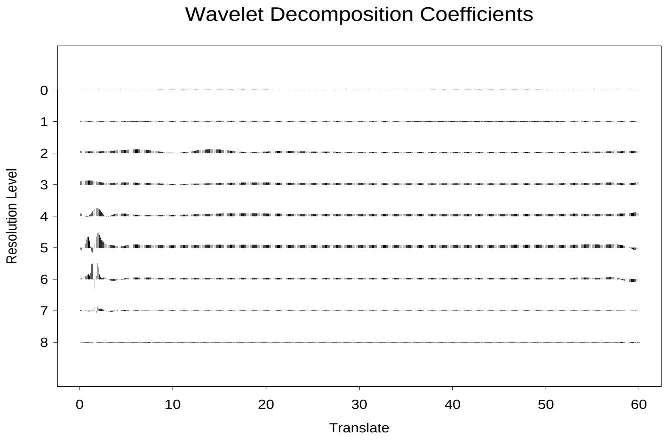

Figure 3: A stationary wavelet decomposition of the time series in Figure 2.

A wavelet power spectrum for the time series in Figure 1 is shown in Figure 3. The distribution of power between frequency bands, and the amount of power contained in the signal varied with time. Most energy (33.4%) was contained in the 39-78Hz band. 98.2% of the energy was contained in frequencies less than 625Hz. Less than 0.001% was contained in frequencies above 1,250Hz. Most energy was dissipated at the time of impact. Most of that energy was contained in the 313-625Hz band. Immediately after impact, there was a negligible amount of power contained above 78Hz for a period of 5-9ms. There was another bust of power in the 78 - 1250Hz band between 12ms and 20 ms after impact. A further bust of power in the 313-625Hz band was seen at around 33ms.

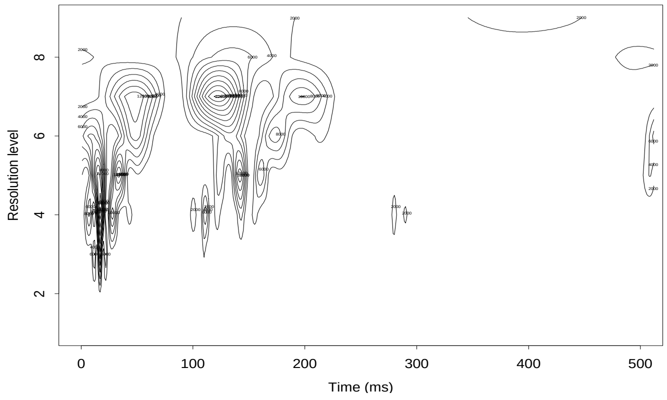

Figure 4: A contour plot of energy distribution localised intime and frequency.

A contour plot of the same data is shown in Figure 4. A transient burst of power was seen at impact followed by a lower frequency peak at approximately 13ms.

4 Discussion

The values obtained for SHOCK, SHOCKDUR, VIBDUR, and MFREQ are comparable with previous studies of impact in horses (Barrey et al. 1991). The value of SHOCK obtained from this experiment was larger than that obtained for asphalt in a similar study. This could reflect the greater hardness of concrete compared to asphalt although the differences in the orientation and mounting position of the accelerometer may also account for this. The variability of all parameters was less in this study than in previously published data. The may be due to the improvement in resolution gained from using a high sampling rate.

The sampling rate of the analogue/digital converter imposes an upper frequency limit on the bandwidth of the discrete data (Nyquist frequency) above which oscillations present in the analog signal will not be accurately recorded by the measurement system. Spectra calculated from those data will be distorted with frequencies above the Nyquist frequency in the analogue signal appearing as spurious frequencies below the Nyquist frequency in the sampled data. This phenomenon is known as aliasing. It is essential that the sampling rate is high enough to record all frequencies of interest, and that any frequencies above the Nyquist frequency are filtered out from the analogue signal before it is digitised. The Nyquist frequency for the measurement system described here was 5kHz. An analogue low pass filter was included to prevent frequencies above the Nyquist frequency being digitised. The wavelet power spectrum shows a negligible amount of energy contained in the highest frequency bands. It is reasonable to assume from this that the sampling rate was sufficiently high that no frequency in the analogue signal approached the Nyquist frequency. If a significant amount of power had been contained in the highest frequency bands of the spectrum, the sampling frequency would have had to be higher to prevent aliasing.

To record accurately the peak values of high frequency transients, the sampling rate must be several times higher than the Nyquist frequency. Less than 1% of the power was contained in frequencies above 1250Hz. If 1250Hz was taken as the Nyquist frequency, the minimum sampling rate would be 2500Hz. The mean value for SHOCKDUR was 0.9ms therefore at a sample rate of 2500 samples per second, only two points would be located in the peak. This would lead to large errors in the estimation of the peak value of deceleration. Even with the high sampling rate used in this experiment, only eleven points describe the initial impact peak (Figure 2).

The complex nature of the impact time series indicates that spectral analysis is an appropriate technique to characterise the signal. Although Spectral analysis has been used in the analysis of impact signals by a number of authors (Lafortune et al.1995) time-scale techniques have had limited application in gait analysis. Wavelets provide excellent resolution in time and frequency in comparison with more traditional techniques. The wavelet power spectrum of impact data provides information about the power distribution in time and frequency. As more is learned about the energy absorbing properties of the structures of the limb, this information will be important in understanding the aetiology of musculoskeletal injury.

The data presented here demonstrate that consideration of the high frequency element of impact must be undertaken before hoof ground interaction on hard surfaces may be understood. It is reasonable to assume that such impacts occur during strenuous sports activities such as racing, and their characterisation would be of use in future development of artificial riding surfaces, new types of horse shoe, and training regimes. Care must be taken when designing a measurement system to ensure transient peaks and high frequencies are recorded accurately. Time scale analysis using a wavelet decomposition is a powerful technique which can be applied to characterise impact data. Contour plots provide a highly visual representation of the time/frequency localisation of power in impact.

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6 Manufacturer's Addresses

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2 RS Components Limited, Birchington Road, Weldon, Corby, Northants. NN17 9RS UK
3 Analogue Devices Inc., Santa Clara, CA USA
4 Sun Microsystems Inc., 2550 Garcia Ave., Mtn. view, CA 94043-1100 USA
5 Mathsoft Inc., 1700 Westlake Ave. N., Suite 500, Seattle, WA 98109 USA

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