DETERMINING THE GROUND REACTION FORCE EXPERIENCED IN BEACH RUNNING

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INTRODUCTION: Running on the beach is a popular fitness activity, as well as a race component in the growth sport of ironman. The beach run in the ironman event involves athletes running in bare feet over terrain ranging from wet compacted sand to dry uncompacted sand, as the distance from the ocean surf line increases.

The dynamic loading response of sand surfaces at the extremes of this terrain range has been investigated recently by Barrett *et al*. The kinetic energies that typically occur in running were simulated by releasing four different masses from four different heights. The ground reaction force (GRF) acting on the drop masses was determined from their acceleration profiles, and a number of variables such as the peak impact force and the surface stiffness were calculated to characterize the sand surfaces.

In order to measure joint loading patterns in beach running via the method of inverse dynamics, it is necessary to know the GRF acting on the foot, as well as its point of application (centre of pressure). When running on conventional surfaces this information can be obtained using a force platform. However measurement of the GRF in beach running is problematic since the force measured via a force plate beneath the sand does not represent the force acting on the foot of the runner.

In this paper we demonstrate how to predict the time response of the GRF acting on the foot of the runner from the reaction force measured by a sand-covered force plate. Our approach uses a set of transfer functions determined from simulated impact experiments. This transfer function approach has been applied successfully by Lafortune *et al*. to quantify the relationship between the tibial axial acceleration and the GRF for runners on conventional surfaces.

METHODS: A piezoelectric force plate was covered by four different depths (D=0.1, 0.2, 0.3, 0.4m) of dry uncompacted sand and wet compacted sand. The vertical reaction force of the plate was recorded for the impact of four different masses (M=3.86, 7.24, 10.62, 14.00kg) released from four different heights (H=0.1, 0.2, 0.3, 0.4m). The values of the masses and the heights were identical to those used in the investigation of the dynamic loading response of sand surfaces by Barrett *et al*. The acceleration of the masses was also measured, and used to determine the GRF experienced by the drop masses during impact.

The output of the force plate, the reaction force x(t), is measured via a process which takes an input force, the ground reaction force y(t), and convolutes it with the instrument response p(t) of the sand-covered force plate. In the time domain this measurement process may be expressed as

$$x(t) = y(t) * p(t) ,$$

which is equivalent to $X(\omega) = Y(\omega)\ P(\omega)$ after transforming to the frequency domain. Thus in order to predict the GRF y(t) from a measured plate reaction force x(t), we need to apply the reverse process: a deconvolution of the plate reaction force using a previously calculated (complex) transfer function $P^{-1}(\omega)$,

$$Y(\omega) = X(\omega)\ P^{-1}(\omega)\ .$$

The transfer function $P^{-1}(\omega)$ corresponding to the force plate and a particular sand surface was determined *a priori* by „calibrating“ direct measurements of the GRF with corresponding plate force measurements, as shown in Figure 1. The GRF and the plate reaction force were filtered using a high-order Butterworth low-pass zero-lag filter with a cutoff frequency of 357Hz, which was determined from an analysis of residuals [Winter, 1990].

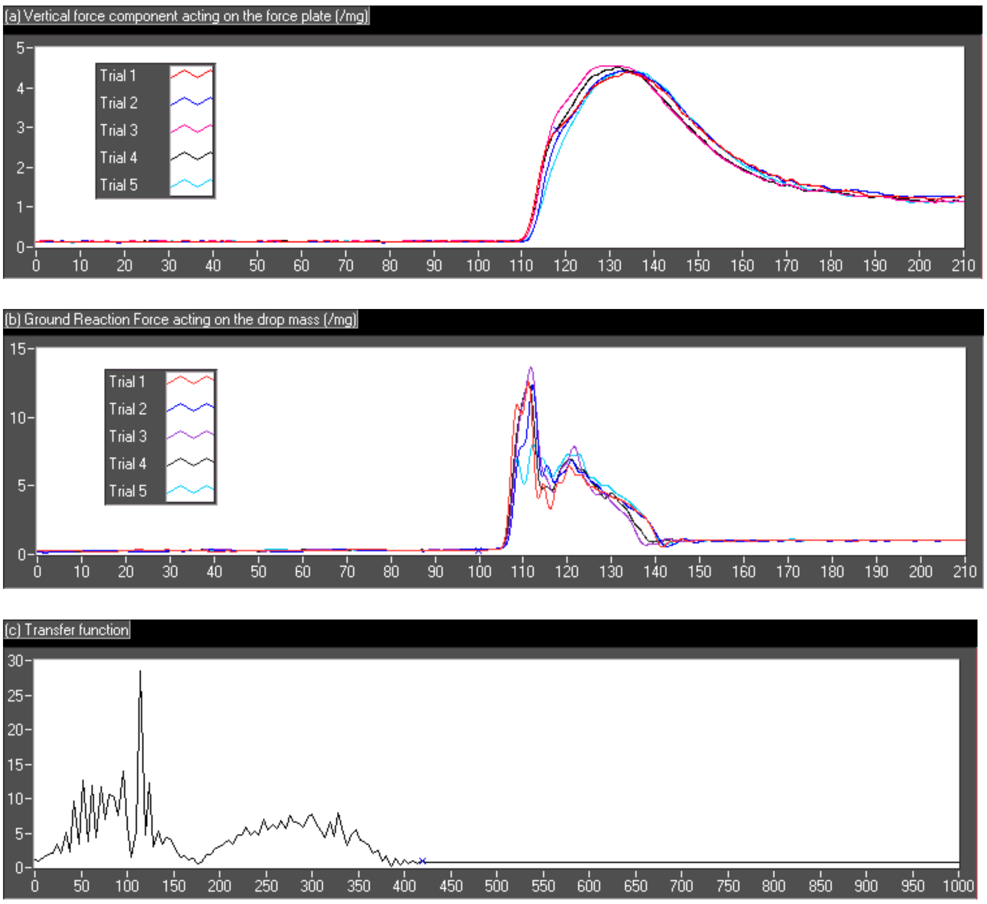

Figure 1. Calculating the transfer function $P^{-1}(\omega)=Y(\omega)X^{-1}(\omega)$ for a drop mass of 3.86kg, a release height of 0.1m, and a sand depth of 0.1m. (a) The normalized vertical reaction force measured by the force plate against time (ms). (b) The

normalized GRF acting on the drop mass against time (ms). (c) The magnitude of the transfer function against frequency (Hz), after averaging over five trials.

RESULTS: The transfer function of the force plate was found to depend on the effective depth of the sand, the drop mass, and the speed of the mass at the time of impact. The impact speed is directly proportional to the release height. In particular we observed that the transfer function was markedly different for trials using two different drop masses, which however, had the same impact energy or the same impact momentum. This implies that the transfer function does not depend solely on either the energy or the momentum of the mass at the time of impact.

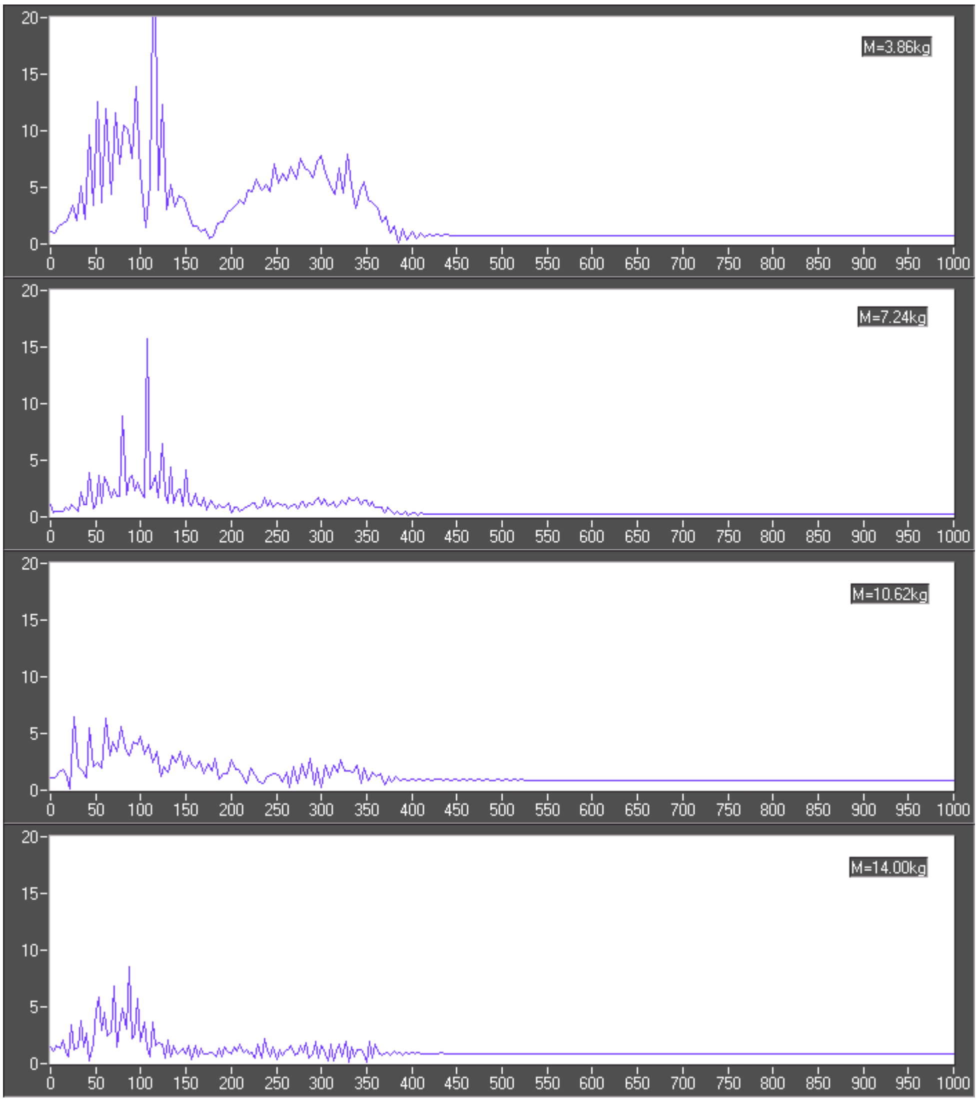

Figure 2. Average transfer functions against frequency (Hz), calculated for different drop masses M, which are released from a constant height of 0.1m. The sand covering the force plate is dry and uncompacted, and its depth is 0.1m in every case.

The general trends in the behaviour of the transfer function $P^{-1}(\omega)$ for the variables we have identified are summarized below:

- As the drop mass increased, the amplitude of the transfer function decreased, and the higher frequency components were attenuated; see the example shown in Figure 2.
- As the release height increased, the amplitude of the transfer function also increased.
- As the depth of sand covering the force plate increased, the higher frequency components of the transfer function were attenuated.

We tested our transfer function approach by predicting the GRF acting on a person running on dry uncompacted sand, from the experimental reaction force measured using a sand-covered force plate. The effective mass of the person was estimated to be ~10kg [Nigg, 1986], and the impact speed was ~1m/s, which is equivalent to a release height of ~5cm. The resulting GRF was in agreement with the expected result, despite the fact that we used the transfer function calculated for a release height of 10cm.

CONCLUSIONS: The transfer function approach presented here can be used to predict the time response of the ground reaction force experienced in beach running from a plate force measurement. Therefore, we only need to measure the reaction force from a force plate in order to calculate the GRF. The time response of the GRF can be used to estimate many physical quantities of interest e.g., the time of delay between the moment of impact and the trigger of the plate reaction force, or the peak GRF.

In future work, the transfer function needs to evaluated for a larger number of values of the drop mass and the release height. The transfer function can then be interpolated more accurately for any values of the effective mass and impact speed applicable to beach running.

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