Foot strike and the properties of the human heel pad

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Many force-plate records of human locomotion show an impulse (the foot strike) shortly after ground contact. The authors' hypothesis is that this results from the rapid deceleration of a mass (the 'effective foot') under forces which compress the heel pad. The quantitative implications are investigated through an illustrative calculation. The observations used are (a) the peak force reached in foot strike (b) the vertical velocity of the foot immediately before ground contact and (c) the properties of the heel pad in compression. Data for (a) and (b) are available in the literature; measurements for (c) are presented here. The deductions are: (a) the time taken to reach peak force is about 5.4 ms, which agrees with published measurements; (b) the mass of the effective foot is about 3.6 kg. The effective foot thus includes a substantial portion of the leg: this seems reasonable. The models used for the calculations clarify the relationship between the foot strike and the shock wave, which it generates.

1 INTRODUCTION

The purpose of this paper is to relate the foot strike in human locomotion to the mechanical properties of the heel pad. The force–time plot from a force-plate investigation often shows a sharp peak shortly after the foot has first touched the ground. Figure 1, after a figure in **(1)**, shows such an impulse in the vertical force record for barefoot running and an example for walking is to be found in **(2)**. Many other records have been published, mostly for subjects wearing shoes with which we are less concerned here. All the records of a substantial force soon after ground-contact are for 'rearfoot strikers': the phenomenon is less significant for 'midfoot strikers'. Rearfoot strikers contact the ground initially with the heel; midfoot strikers with more anterior parts of the foot **(3)**.

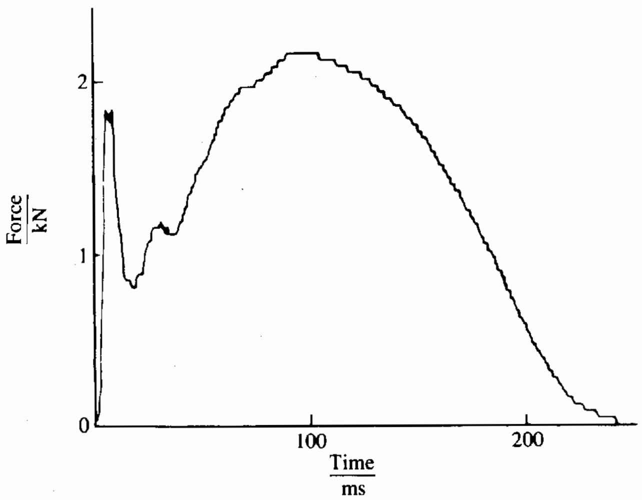

Fig. 1 Force-plate record (vertical) of a barefoot subject running at about 4.6 m/s [after Dickinson, Cook and Leinhardt **(1)**, copyright Pergamon Press 1985]

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The following three papers are concerned with the mechanical properties of the human heel pad in compression. Nigg and Denoth **(4)** and Cavanagh, Valiant and Misevich **(5)**, describe *in vivo* measurements, in which, because the rest of the leg was attached, the extent of the system being investigated is rather uncertain: in both cases, it seems likely to be more than just the heel pad. Nakamura, Crowninshield and Cooper **(6)** made *in vitro* measurements in connection with a study, by finite element analysis, of the loading of the foot in standing. They give a plot of compressive force versus displacement to a maximum load of 600 N. Alexander, Bennett and Ker **(7)** measured the compressive properties of isolated paw pads from some (non-human) mammals. The same methods are used here.

In an impact, the magnitude of the peak force depends sharply on the velocity of the foot immediately prior to contact. The measurements of Cavanagh *et al.* **(5)** will be used. With ten subjects running in shoes at 3.6 m/s, they found the average downward vertical velocity at foot contact to be 0.7 m/s with a range from 0.16 to 1.2 m/s. In the context of human locomotion 0.7 m/s is a small velocity: it is that of a body which has fallen 25 mm under gravity. The velocity of the foot prior to contact with the ground depends on the way the leg muscles have been used: considerable variation is to be expected.

If the foot has a horizontal component to its velocity immediately before ground contact, an impact peak is also to be expected in the horizontal ground forces. Force-plate records seem rather inconsistent. Nigg **(8)** gives horizontal records for running (in shoes) which have no discernible impact peak. In walking, Landshammar and Strandberg **(9)** observed a reversed horizontal impact force which they interpreted as due to reversal of the direction of movement of the heel just prior to ground contact. Similar records are shown by Alexander and Jayes **(10)**. In contrast, Cavanagh *et al.* **(5)** observed the average forward velocity of the foot (in running) to be 0.9 m/s at the moment of initial contact.

This will not be considered further here; this paper will concentrate on the vertical impact which can be treated separately from any horizontal components. [In contrast to humans, Alexander and Vernon (**11**) observed a large horizontal impact and negligible vertical impact in a hopping wallaby.]

2 COMPRESSION OF THE HUMAN HEEL PAD

2.1 Materials

The feet used had been amputated because of irreparable vascular failure. The skin of the heel appeared normal. The mean thickness of five pads, by measurement on X-ray photographs, was 16.3 mm (standard deviation 2.7 mm). Steinbach and Russell (**12**) give the mean thickness as 17.8 mm (standard deviation 2.0 mm), so the pads used appear to be of normal thickness.

The specimens were stored when necessary at $-20°C$. Some were tested without ever having been frozen.

2.2 Methods

The calcaneus was divided by sawing to leave a distal portion with the heel pad still attached. This was inserted into an Instron 8031 dynamic testing machine as part of a sandwich between two horizontal metal plates. The lower plate pressed against the plantar skin of the heel and the upper plate against the sawn surface of the calcaneus. Alexander *et al.* (**7**) used a similar method for tests on isolated mammalian paw pads.

The actuator of the testing machine was displaced sinusoidally (under position control) with the mean position and range of movement adjusted to give compressive loads from near zero to a maximum of about 2 kN. This fully covers the range of impact forces; this work is concerned mainly with tests having a maximum compressive load of about 1.1 kN. Most tests were at frequencies between 0.22 and 5.5 Hz; some ranged up to 77 Hz.

The pad was subsequently cut away from the calcaneus and tested again directly between metal plates.

Most tests were at room temperature but higher temperatures were also used—to about 36°C.

2.3 Results

Figure 2 shows a load–compression plot. The area (A + B) under the upper line represents the energy required to compress the pad and the area under the lower line (B) is the energy returned in the second half of each cycle. The area of the loop (A) represents the energy dissipated as heat in one cycle. This loop is similar to those obtained with mammalian paw pads (**7**).

The relevant energy in relation to foot strike is the energy to compress the pad. In the calculations below (Section 3), a peak force of 1.1 kN will be considered. With five heel pads the mean energy required to compress the pad, area (A + B), to this load was 0.75 J with a standard deviation of 0.16 J.

Altering the test conditions, as described in Section 2.2 above, produced no marked changes in the results. The response of the pad to compression is much the same when it is isolated as when it is still attached to the calcaneus. It changes very little with temperature (between room temperature and 36°C) and frequency (0.22–77 Hz).

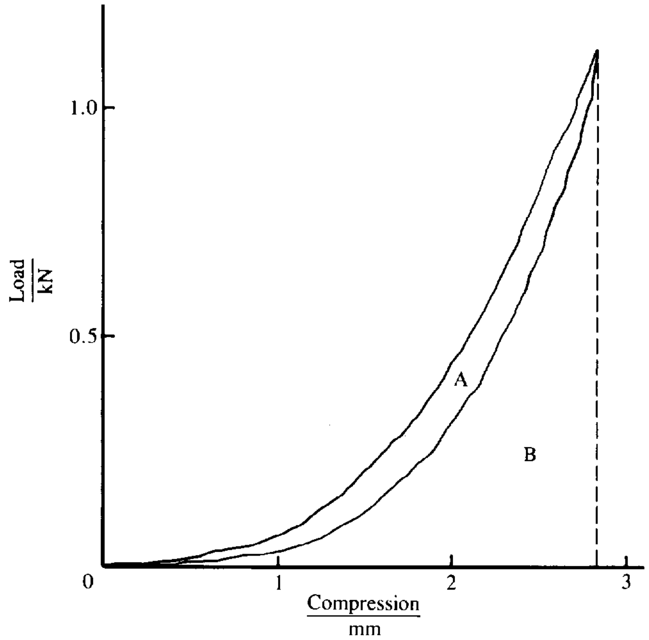


Fig. 2 Load–compression plot for a human heel pad. The upper curve is for loading (increasing compressive force) and the lower curve for unloading. A is the area of the loop and B is the area under the unloading curve. (Frequency 0.22 Hz; room temperature; pad attached to calcaneus; pad thickness 14.5 mm)

3 A MECHANICAL MODEL OF FOOT STRIKE

3.1 Developing a model

In running, the leg behaves as a spring (**13**). Figure 3a shows a simple model for running. The body is represented by a rigid mass, M, and a leg by a weightless spring. Figure 3b is a model for foot strike, formed by adding a rigid 'foot' of mass m and a second spring representing the foot pad. Alexander *et al.* (**7**) analyse this model to consider the appropriate mechanical properties for the material of the pad.

Figure 3c is a free-body diagram for the 'foot' of Fig. 3b showing the vertical forces acting on the foot during ground contact: (i) its weight, mg, (ii) F_l, the force from the body transmitted through the leg spring and (iii) F_p, the force from the ground transmitted through the pad. The net force is $(F_p - F_l - mg)$ and the equation of motion is

$$F_p - F_l - mg = ma \tag{1}$$

where a is the acceleration of the foot.

Before ground contact, with the springs unstrained, $F_p = F_l = 0$ (and, therefore, $a = -g$). After the foot hits the ground, the forces build up rapidly reaching over 1 kN (Fig. 1). With these relatively large forces, the weight of the foot can be neglected. Thus, omitting mg and rearranging, equation (1) becomes

$$F_p = ma + F_l \tag{2}$$

With a weightless pad, F_p is equal and opposite to the force of the pad on the ground measured by a forceplate. In the light of equation (2), the plot of Fig. 1 can

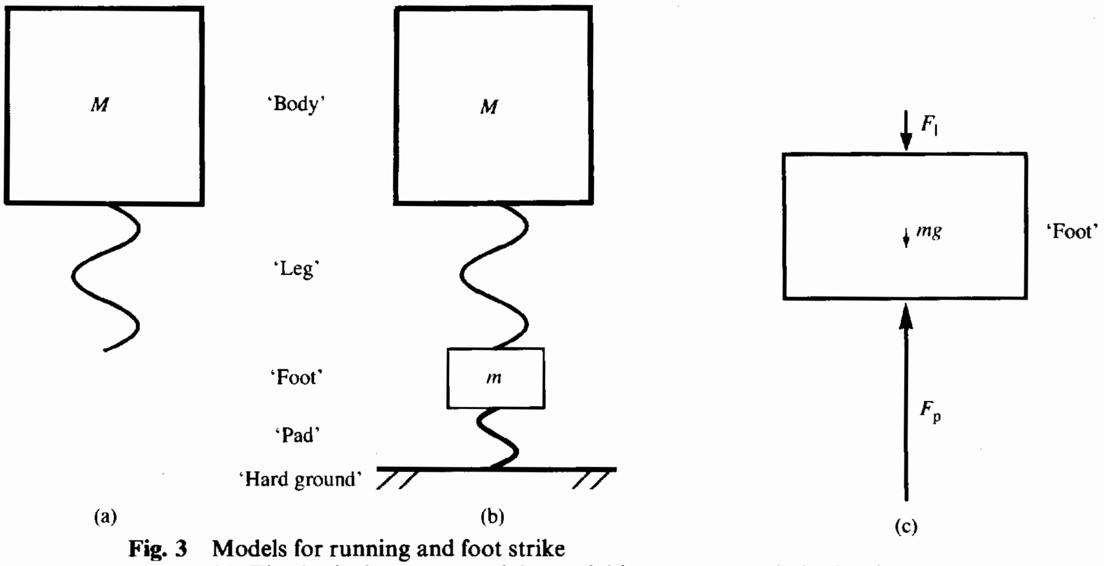


Fig. 3 Models for running and foot strike
(a) The body is represented by a rigid mass, M, and the leg by a weightless spring
(b) As (a), but with the addition of a second mass, m, (the 'foot') and a second spring (the 'pad') [after Alexander, Bennett and Ker (7) copyright The Zoological Society of London 1986]
(c) A free-body diagram showing the forces on the 'foot': F_p is the force from the ground transmitted through the pad; F_l is the force from the body transmitted through the leg; mg is the weight of the foot

be considered as the superposition of the plots for (i) the force required to accelerate the foot, ma, and (ii) the force of the leg on the foot, F_l.

When the heel strikes the ground oscillatory motions start. The period of oscillation of the mass M on the leg is very much longer than of mass m on the pad, because M is very much greater than m and the leg is much more compliant than the pad. Forces in the leg build up relatively slowly: the maximum value is at the midpoint of the step and is represented in Fig. 1 by the main peak at 100 ms. By this stage oscillations of the foot have died down and a is zero. For the impact immediately following ground contact, ma is much greater than F_l: the initial impulse is largely due to decelerating the foot.

At this point it is appropriate to introduce a sign convention for vertical displacements: the positive direction will be taken as upwards. The net force on the foot throughout the relevant period is always upwards and therefore the foot has positive acceleration. The vertical velocity, v, is initially negative and becomes less negative. The displacement, y, will be taken to be zero at the instant of ground contact and thereafter is negative.

Following Cavanagh *et al.* (5), the initial vertical velocity will be assumed to be -0.7 m/s when the running speed is 3.6 m/s (see Section 1). The runner who caused the force-plate record of Fig. 1 was going faster (4.6 m/s). Dr Alison Cutts (personal communication) found a peak impact force of 1.25 kN for a barefoot runner going somewhat slower than 3.6 m/s. In the case being considered the peak force during the impact will be taken to be 1.4 kN. To assess how much of this should be attributed to F_l, it is useful to compare force platform records of a runner when barefoot and when wearing soft shoes, which reduces and delays the impact peak. Dickinson *et al.* (**1**) provide such a pair of records. The authors estimate the force from the leg contributes about 0.3 kN to a peak ground force of 1.4 kN. The peak force accelerating the foot is then 1.1 kN.

Figure 4 is a direct (smoothed) copy of the loading curve of Figure 2: it is a plot of force against $-y$. The maximum force shown in Fig. 4 is 1.1 kN, which is the maximum force accelerating the foot. It will be assumed for the purposes of illustrative calculation that the rest of the plot also represents the net force (that is, that accelerating the foot). This is an approximation. Strictly, F_l (to a value of 0.3 kN downwards) should be found as a function of y and subtracted, according to equation (1), from the plot for F_p (taken to a value of 1.4 kN). This would involve further assumptions and a more detailed analysis than intended. The error, on these

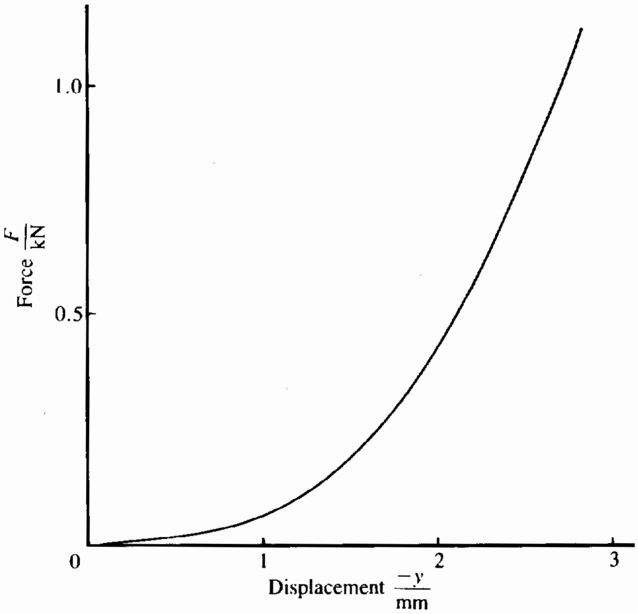


Fig. 4 Force, F, on the foot against its displacement, y, during impact via the heel pad

grounds, cannot be large and is certainly less than that of the alternative assumption of entirely disregarding the force from the legs during foot strike.

In this model, when the force accelerating the foot is at its maximum (1.1 kN), the velocity is zero and the displacement, from Fig. 4, is −2.8 mm.

3.2 Effective mass of the foot

The area under the graph of Fig. 4 is 0.87 J and represents the kinetic energy removed from the foot. If V is the velocity at foot contact,

$$\tfrac{1}{2}mV^2 = 0.87 \text{ J} \quad (3)$$

With $V = -0.7$ m/s, m is found to be 3.6 kg for this particular force–displacement record.

This will be called the *effective mass* of the 'foot'—as far as the impact is concerned. It clearly includes more than the anatomical foot alone. This is not surprising as the leg is not massless, in contrast to the models of Fig. 3. Thus segments above the anatomical foot will also be involved in the impact, though their accelerations will be less because of the rotations allowed by the joints. [This aspect of 'effective mass' has been considered by Denoth (**14**).] With rotations, the concept of effective mass remains valid, but the magnitude of 3.6 kg understates the portion of the body involved in the impact: as well as the distal portion of the limb to a mass of 3.6 kg, higher portions of the body will also make some contribution. The 'foot' of Fig. 3 is henceforth to be replaced by an 'effective foot' of mass equal to the effective mass for impact.

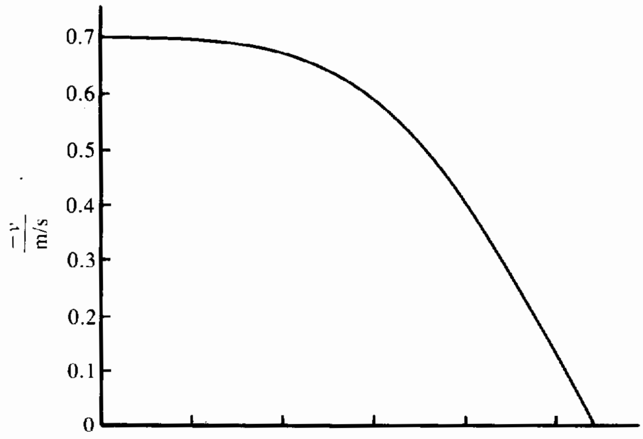
Zatsiorsky and Seluyanov (**15**) give the average mass of the leg below the knee of an adult man as 4.2 kg, within which the mass of the foot is 1 kg.

3.3 Time

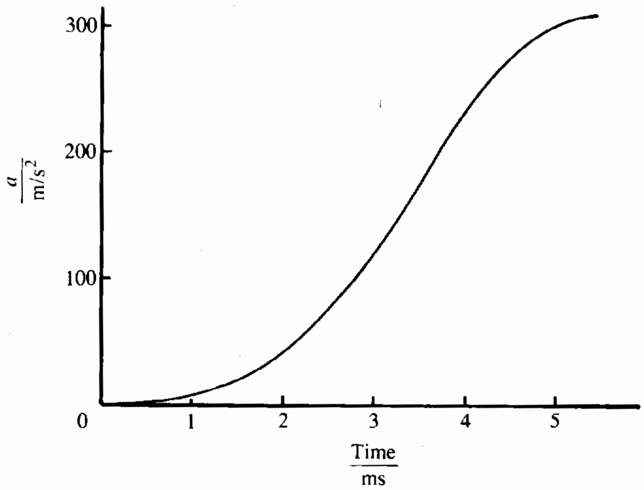
Let $F = F_p - F_l$. Then equation (2) becomes $F = ma$. According to the approximations of the preceding subsection, F is represented as a function of y by Fig. 4.

To find a numerical solution, the graph of Fig. 4 was replaced by a version with 47 steps, using equal y intervals. If F_n is the force at the beginning of the nth interval, the approximating step was set at a constant force of $(F_{n+1} + F_n)/2$. The subsequent procedure is as follows.

1. Find m for the stepped function using equation (3). The area under the stepped function is equal to the area obtained for the original curve by the trapezoidal rule. It is a very slight overestimate. But for consistency in the mathematics it is necessary to use the value of m for the stepped function.
2. For each step, find the acceleration $a_n = (F_{n+1} + F_n)/2m$.
3. If v_n is the velocity at the beginning of the nth step, v_{n+1} is found by the standard formula for uniform acceleration: $v_{n+1}^2 = v_n^2 + 2a_n s$, where $s = (y_{n+1} - y_n)$. The initial conditions are known ($v = -0.7$ m/s; $y = 0$), so this can be followed through step by step. A check on the correctness of the mathematics arises since $v = 0$ when $y = -2.8$ mm.
4. The time intervals, t_n, are given by $(v_n - v_{n+1})/a_n$, since the acceleration is uniform. This gives a set of time values corresponding to the already known values of displacement, velocity and acceleration.



(a) Velocity versus time



(b) Acceleration versus time

Fig. 5 Time plots for impact of the foot of the model represented by Fig. 3c

Figures 5a and b show the time plots thus obtained for v and a respectively. The time until the velocity is zero is 5.4 ms and the displacement and acceleration are then at their extreme values (−2.8 mm and 1100/3.6 m/s^2 respectively). The equivalent calculations were also carried out using an approximation to the curve of Fig. 4 having linear segments rather than steps. The results are very similar.

The interval from zero to maximum force corresponds to one-quarter of a full oscillation. The rates of change involved are therefore similar to those in an oscillation at a frequency of 1000/(5.4 × 4) Hz, that is 46 Hz. This is within the range of the tests on the pads (0.22–77 Hz).

From force-plate measurements on six male barefoot runners, Dickinson *et al.* (**1**) found the average time to peak impact force to be 4.8 ms (standard deviation 1.6 ms).

Since $F = ma$, the graph in Fig. 5b is proportional to the force–time plot. Such a plot is provided by a force-plate (if allowance is made for the contribution from F_l). The effective mass can equivalently be assessed by equating the area under the force–time plot (the impulse) to the change of momentum, mV. Alexander and Vernon (**11**) did this for the horizontal impact record provided by a wallaby.

4 DISCUSSION

4.1 Validity of the model

The acceptability of the results for the effective mass of the 'foot' and for the time of impact supports the hypothesis implicit in the model of Fig. 3: that is the impact at heel strike is due to the acceleration (upwards) of the effective foot as the heel pad is compressed. However, the calculations are dependent on imprecise, indeed variable, data: the area under the load–compression curve for the heel pad depends sharply on the peak force; for a given energy, the mass calculated depends on the square of the initial vertical velocity. The velocity of the foot prior to ground contact can be changed by using the muscles differently. Using muscles to minimize the strike might well require energy, thus offsetting the energy saving from avoiding the impact. The energy to distort the heel pad under impact approaches 1 J, which is about 1 per cent of the energy exchange in a running step (**16**). The heel pad can return most of this energy, but it is nonetheless hard to see how that energy can be fed back into the running system.

The model fails to explain two negative observations: (i) the lack of a substantial horizontal impact and (ii) the very limited impact with midfoot strikers. The explanations must depend on (a) control of the relevant velocities, (b) a relatively low effective mass subjected to acceleration and/or (c) a mechanism to increase the time of impact thus delivering a given impulse with a lower peak force.

The model is intended to be as simplified as possible to give an idea of the overall mechanism. One of the simplifications is the assumption that, apart from the heel pad, the foot is composed of rigid materials (with jointed segments being allowable—see Section 3.2). Thoroughly compliant materials within the effective foot would lead to internal modes of vibration of long periods. This would increase the time over which the impact was spread: not all the foot would accelerate simultaneously. However, the agreement between the calculated and the observed time to peak force indicates reasonable rigidity (for impacts on the heel). The implication is that forces are distributed through the effective foot in a time which is substantially less than 5 ms (see Section 4.3 below).

4.2 Mechanical properties of the heel pad

The peak force at heel strike, for a 'foot' of given effective mass and initial velocity, depends only on the loading curve of the load–compression plot of the heel pad; the fate of the energy in the pad (that is the relative proportions stored as strain energy and lost as heat) is irrelevant. What happens after the impact peak depends very much on the loss characteristics of the material. With high hysteresis, in which most of the energy is dissipated within the material, vibrations are rapidly damped out (**7**). In the same way, a running shoe with a high hysteresis material in the heel is no better at restricting the impact peak than an equally compliant heel of more resilient material.

4.3 Shock wave

The distinction between the foot strike impulse and the shock wave it can generate is clearly demonstrated by the model of Fig. 3b. This model gives an impulse but no shock wave. With real materials, having properties both of compliance and inertia, the distinction is less sharp. The forces required by the impact are carried through the effective foot by waves and, in addition, a shock wave is generated which can travel out beyond the effective foot.

The involvement of waves introduces a time-scale. Parts of the body which cannot be reached by a compression wave during the time of the impulse must be considered to be outside the effective foot. Light, McLellan and Klenerman (**17**) observed transient accelerations with a barefoot subject at the proximal end of the tibia and at the teeth. The vibrations at the teeth were delayed relative to those at the tibia by about 10 ms indicating a wave velocity (for 1.2 m) of about 120 m/s. Alexander (**18**) has shown this to be consistent with a wave travelling through cancellous bone. Thus the head cannot contribute to the initial impact in which the heel becomes stationary in about 5 ms. On the other hand, Smeathers (**19**) has shown the wave velocity in the tibia to be much higher ($\sim$600 m/s) and therefore the bony parts, at least, of the lower leg could respond within 1 ms. An effective foot of mass 3.6 kg is consistent with these times.

The shock wave as it travels through the body will inevitably be attenuated. The authors' finding of an extensive effective foot makes the attenuation difficult to assess. An accelerometer within the effective foot will superimpose the accelerations of the impulse and the shock wave. For example, comparing the magnitudes of the transient accelerations at the tibia and the teeth gives little information about the attenuation of the shock wave because the acceleration at the tibia includes a contribution from the impulse. Alexander (**18**) made cautious comments relating to attenuation on the basis of the results of Light *et al.* (**17**). He would have been even more cautious had he realized the extent of the effective foot.

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