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THE TIME-DEPENDENT MECHANICAL PROPERTIES OF THE HUMAN HEEL PAD IN THE CONTEXT OF LOCOMOTION

ROBERT F. KER
Department of Biology, The University, Leeds LS2 9JT, UK

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Summary

Previous measurements of the mechanical properties of the heel pad, especially of the energy loss during a cycle of compressive loading and unloading, have given contrasting values according to whether the investigators used isolated single impacts (e.g. pendulum tests; energy loss approximately 48 %) or continuous oscillations (energy loss approximately 30 %). To investigate this discrepancy, rest periods were inserted between single compressive cycles, giving intermittent loading as in locomotion. The energy loss, measured as the percentage area of the hysteresis loop, was found to change linearly with the logarithm of the rest time. It was approximately 33 % when the rest time was 1 s. Each 10-fold increase in the rest time added approximately 3.7 % to the energy loss. Thus, with rest times appropriate to locomotion, the pad is far from fully relaxed. The springy heel pad may help to reposition the foot during the transfer of load from the heel to the forefoot. Information is also included on the load–deformation curves for the heel pad and the way in which these change with rest time. This is presented as equations which may be useful in future models relating the mechanical properties of the heel to either its structure or its function.

Key words: heel pad, hysteresis, time-dependent, mechanical properties, locomotion.

Introduction

Aerts *et al.* (1995) noted variations in the properties of the human heel pad in compression during a sequence of tests. The purpose of the present paper is to investigate these variations in the context of the pattern of loading experienced during locomotion.

Aerts *et al.* (1995) compared two test methods: (i) impact by an instrumented pendulum and (ii) forced oscillations from a dynamic tensile testing machine, an Instron 8031. This approach directed attention to the first cycle of loading and unloading in an Instron test, since only one impact is available for each pendulum test. The mechanical properties displayed during the first cycle were found to be significantly different from those during subsequent cycles. The change is greatest between the first and second cycles and thereafter becomes less and less, with essentially constant properties after only five or six cycles. Bennett and Ker (1990) reported on the mechanical properties of heel pads using hysteresis loops recorded after a sufficient number of cycles for change to have ceased. Aerts *et al.* (1995) refer to these as '*n*th loops'. Fig. 1 shows first and *n*th hysteresis loops from Aerts *et al.* (1995). These loops were recorded for different purposes from the comparison being made here, were from test sessions several months apart and have somewhat different peak loads. None the less, they serve to illustrate the main difference between first and *n*th loops, which is in the loading curve, with the unloading curve being much less changed. The shift in the loading curve changes the area of the hysteresis loop. Aerts *et al.* (1995) give mean values for the percentage of energy dissipation, at a frequency of 11 Hz, of 48 % for first loops and 31 % for *n*th loops. Furthermore, *n*th loops are frequency-insensitive, but the percentage energy dissipation of first loops increases with frequency (i.e. as frequency increases, the loading curve shifts further from the unloading curve).

Several authors have used measurements based on a single impact when considering the consequences of heel-to-ground contact in locomotion; e.g. Cavanagh *et al.* (1984), Denoth (1986), Aerts and De Clercq (1993), Noe *et al.* (1993) and Gerritsen *et al.* (1995). However, Alexander *et al.* (1986), for the paw pads of various mammals, and Ker *et al.* (1989), for the human heel pad, used measurements obtained during continuous sinusoidal oscillations. The observation of substantially different loops in these two situations makes it seem likely that neither is entirely appropriate for locomotion, when the loading of the heel pad is neither a single impact nor a continuous sine wave. For the first step each morning, first-loop properties may well apply, but the situation is likely to be different once the pattern of locomotion has been established for more than a few steps. During locomotion, the heel has a 'rest period' in each stride while it is off the ground. Cavanagh and Lafortune (1980) give data for a man running at a velocity

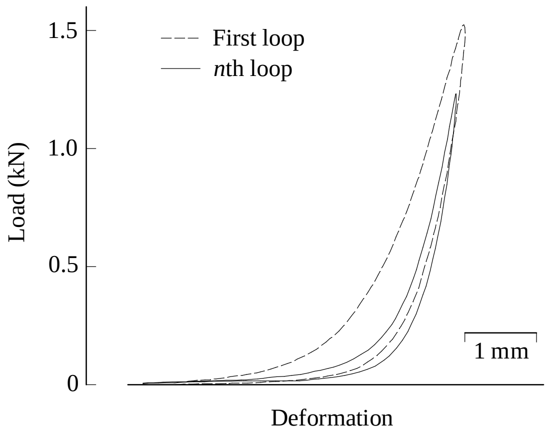

Fig. 1. Hysteresis loops from Aerts *et al.* (1995), where they appear in Fig. 2A (dashed line) and Fig. 2D (continuous line). Both are for heel pad IV of that paper and are 'half-cycle tests'; i.e. the actuator was moving sinusoidally, but contact was maintained for only half of its cycle, so that peak velocity is at the moment of contact. The dashed line is the first loop of a new test period: the solid line is an '*n*th loop'; i.e. the record was made after sufficient oscillations for changes to the loop to have ceased. The upper line of each loop is the 'loading curve' and is for the quarter-cycle when the pad is being compressed: the lower line is the 'unloading curve', for the next quarter-cycle. Percentage energy dissipation, *D*, is '100 times the ratio of the area of the loop to the area under the loading curve': the values here are 49 % for the first loop and 30 % for the *n*th loop. Average values are given in the text. Frequency, 11 Hz. Room temperature (approximately 20 °C).

of 4.5 m s^{-1}. The time of foot contact is approximately 0.18 s, but, even for a rear-foot striker, the heel is only under load for part of this time, with the load being fully transferred to the forefoot at about midstep, after, say, 0.09 s. The stride time is about 0.68 s (Cavanagh and Kram, 1987). Is the rest time, in this case 0.59 s, sufficient to affect the form of the hysteresis loop?

Thus, the immediate aim of this paper is to provide data at timings relevant to locomotion. The investigation was widened to include a greater range of rest times and, as will be seen below, a regular pattern emerges. This aspect of the work is an investigation in materials science involving the relaxation behaviour of the pad. 'Conditioning' is a technique of preparing biological materials for mechanical testing by applying a sequence of stresses until unchanging results are obtained. Alexander *et al.* (1986) used this technique with paw pads (although they did not designate it as such). The present study investigates the changes more closely. A similar approach may prove instructive with other tissues.

Stiffness on the loading curve is crucial to the function of the pad as a cushion during heel-strike (Ker *et al.* 1989). Values of stiffness at body weight have been previously published. A curve-fitting process, described below, was used to extract comparable data over the range of rest times. The resulting equations and their parameters provide a concise mathematical description of the load–deformation curves for the heel pad and of the changes with rest time, which I hope will be of use to any reader involved in modelling the mechanical properties of the pad in relation either to its function or its structure.

Table 1. *Donors of the heel pad specimens*

Designation of pad	Sex	Age (years)	Mass (kg)
A	Female	80	56
B	Male	66	74
C	Male	73	58

Materials and methods

Specimens and test set-up

One of the reasons for using human heel pads for this work is the convenient way in which they are attached to the single calcaneal bone. The properties of the paw pads of other mammals (Alexander *et al.* 1986) are likely to be similar, but they are less conveniently mounted.

The specimens used in this study were from three feet amputated because of irreparable vascular failure. Details of the donors are given in Table 1. Feet from fit, young people would have been preferable, but were not available. However, Aerts *et al.* (1995, 1996) included two feet which had been amputated for reasons other than vascular failure and were from younger donors. These feet gave results which matched those from their other specimens, whose donors were similar to those in Table 1.

Feet A and B (Table 1) were stored at a temperature of –20 °C until required and the pads were tested at room temperature (approximately 20 °C). Foot C was obtained immediately after amputation and the heel pad was tested while still warm. Further tests, at room temperature, were carried out after a period of frozen storage. Bennett and Ker (1990) found, for *n*th loops, that testing when fresh and warm gives the same results as testing at room temperature after frozen storage.

For testing, the pads remained attached to the lower surface of the calcaneus. Each specimen was isolated from the rest of its foot by making two cuts: (i) above the pad, through the calcaneus, on a plane horizontal with the foot in its usual orientation for standing, and (ii) a vertical cut anterior to the pad. The thickness of the whole specimen (i.e. the distance from the plane of the horizontal cut to the skin surface) was about 45 mm, measured with the pad uncompressed. Aerts *et al.* (1996) showed that cutting through the soft tissues in this way does not affect the measured mechanical properties of the pad. Tests were carried out with the specimen mounted between horizontal metal plates in an Instron 8031 dynamic tensile testing machine (Fig. 2). The arrangement is the same as that used for Instron tests by Aerts *et al.* (1995). Bennett and Ker (1990) included rollers in the rig to ensure that the force was purely compressive, without shear. While this is appropriate in principle, I have not observed any difference between results obtained with or without rollers. Rollers could not be included in the present tests, nor those of Aerts *et al.*

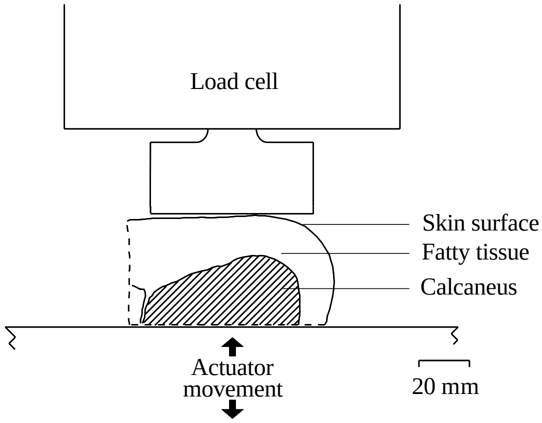

Fig. 2. Test rig with the actuator at its mean position, where contact was just made. The surfaces cut when isolating the heel pad from the foot are indicated by dashed lines. The pad was covered by plastic clingfilm, to avoid risk of drying. The volar skin of the heel impacts against a horizontal circular plate of 64 mm diameter. This was introduced by Aerts *et al.* (1995) to correspond to the impacting surface of their instrumented pendulum. Its area is sufficient to compress virtually the whole pad and the results are the same with a plate of larger area. The cut surface of the calcaneus is glued to the plate on the actuator.

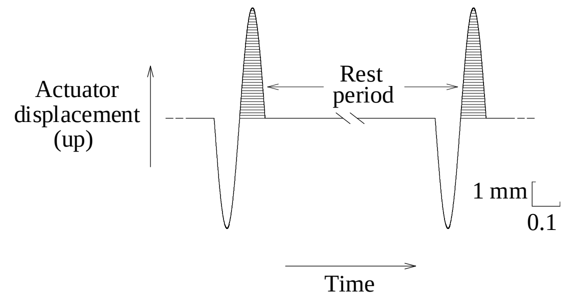

Fig. 3. Movement of the actuator. The hatched portions represent the times when the pad was under load. The sine wave was at a frequency of 5.5 Hz and its amplitude was adjusted to give a maximum load of approximately 1.4 kN. The 'rest time' was variable, with a minimum of 0.09 s.

(1995), because the load was entirely removed for part of each test. Bennett and Ker (1990) maintained some compressive load at all times, which served to keep the rollers in place.

Isolating and mounting the pad in this way provides the firm support that is essential for proper measurements. Aerts *et al.* (1995) found by hard experience just how firm a support is required. They started, for pendulum tests, with the calcaneus mounted against a brick wall, but this proved inadequate and they had to change to a concrete wall. With direct contact between the flat cut surface of the calcaneus and a flat steel plate, the orientation of the pad is fixed. This is an appropriate design for investigating material properties. However, it does not match the loading pattern in locomotion, which starts on the posterior part of the pad and moves anteriorly to reach the test position. However, I assume the pad has reasonably uniform material properties as it looks and feels similar throughout.

Operation of the dynamic testing machine

The machine was operated in position control with the mean level set at the point where contact was just made. When oscillating sinusoidally, the actuator starts by moving downwards, so the pad is not under load for the first half oscillation and contact is made, as the actuator comes up, at maximum velocity. Aerts *et al.* (1995) call this a 'half-cycle test' and used it to mimic a pendulum test, in which the impact starts at maximum velocity. It also seems a reasonable way of mimicking the impact of the heel on the ground in locomotion. Bennett and Ker (1990) used 'full-cycle tests', in which contact was maintained throughout, with the minimum load at zero velocity. In practice, the distinction seems of little importance: Aerts *et al.* (1995) showed that the results of full-cycle and half-cycle *n*th-loop tests are not significantly different. The frequency used for all tests to be reported here was 5.5 Hz and, therefore, the time under load was approximately 0.091 s [=1/(2×5.5) s]. The amplitude was set to give a peak load for all tests of about 1.4 kN. A variable rest time was introduced by keeping the actuator stationary at the mean level for a set time after each full cycle of the sine wave. Fig. 3 shows the movement of the actuator as a function of time with the periods for which the pad was compressed indicated by hatching. The rest time, corresponding to a set stationary time, was measured by timing a full cycle, and subtracting 0.091 s. The set and measured times differ slightly, not only because of the 0.091 s of non-contact oscillation, which is part of the rest time, but also because the Instron 8031 requires about 0.035 s to switch between program blocks. The minimum rest time of 0.091 s was achieved with a continuous sinusoidal oscillation. This equates to the half-cycle test of Aerts *et al.* (1995).

Hysteresis loops as in Fig. 1 were plotted *via* a digital recorder with two separate channels, for load and actuator displacement. The aim of the experiment was to observe changes in the hysteresis loop as a function of rest time and, therefore, peak compressive load and contact time were not varied. For each rest time, the hysteresis loop was recorded after at least 10 cycles so that the loop was no longer changing with time: these are *n*th loops. Thus, the results apply for steady locomotion and not for the first few steps. After recording a hysteresis loop, the machine was stopped with the pad unloaded and the next test run was started after a standard interval of 10 min. In practice, the length of the interval between tests is not critical for *n*th loops. The following checks were used to ensure that the properties of the pad did not change during a session of tests: (i) the sequence of rest times was selected at random, (ii) a few rest times used early in a sequence were repeated later and (iii) some 'first loops' were recorded, as well as *n*th loops. (Note: these 'first loops' are not first loops in the strictest sense, but only 'first loops after a 10 min rest'. Hereafter they will be called '10 min' loops.)

Tests were carried out at room temperature, except, as mentioned above, for the first session of tests on pad C, which were designed as a check on whether a fresh, warm specimen might give substantially different results. For these tests, the pad, glued by its cut calcaneal surface to an additional steel plate, was placed in a water-tight plastic bag and submerged in a water bath at 37 °C until required. Transfer to the Instron was rapid and a test sequence was carried out quickly. The pad was returned to the water bath during its 10 min pause. The temperature was monitored by a thermocouple inserted through the skin of the heel into the fatty tissue and did not drop below 30 °C.

Energy dissipation: statistical methods

Areas on the hysteresis plots were measured to obtain values for the dissipation of energy (see legend to Fig. 1). I aimed throughout at a constant peak load, but this was not achieved very reliably, since the actuator was operating under position rather than load control (load control was not feasible for these experiments because contact was lost during each cycle). Multiple regression was used to adjust the results to a common peak load. The peak load chosen was 1.34 kN, which was the mean for all 35 *n*th loops used.

In the regression analysis, percentage energy dissipation, D, is the dependent variable and rest time, T, and peak load, F, are the independent variables (T and F are clearly physically independent since they are set entirely separately). The multiple regression equation used is:

$$D = A + b\log_{10}T + cF\,. \tag{1}$$

The analysis gives, for each pad, the best-fit values of the constants A, b and c. In particular, b, the partial regression coefficient of D on $\log_{10}T$, represents the change in D for a unit change in $\log_{10}T$ when F is constant. With F=1.34 kN, equation 1 may be rewritten as:

$$D = D_1 + b\log_{10}T\,, \tag{2}$$

where D_1=A+1.34c. With T in seconds, D_1 is the percentage energy dissipation when the rest time is 1 s, which is the order of magnitude appropriate for locomotion.

Multiple regression was carried out using SigmaStat for Windows from Jandel Scientific.

In the Results, some means are given with S.D. and some with S.E.M. values. The choice depends on whether the intention is to give an idea of the spread of values (S.D.) or of the significance of a mean (S.E.M.).

Stiffness

The initial aim was to measure the slopes of the tangents to the loading curves at body weight (i.e. full weight on one pad). This evolved into a broader examination of the shapes of the load–deformation curves and the way in which these change with rest time.

Each of the 35 hysteresis loops was digitised, with the greatest density of points where the changes in slope were most rapid. Local stiffness was calculated for each load–deformation point by averaging the slope to its immediate neighbours, assuming linearity over these small displacements. These data were fitted to equations of the form:

$$1/S = g + h/F\,, \tag{3}$$

where S is the stiffness, F is the load (or force) and g and h are parameters obtained by the least-squares method. Note the following three points. (1) A non-linear regression of S on F was used, rather than a linear regression of $1/S$ on $1/F$, to avoid giving excessive weight to small values of S and F, which have little physical significance. (2) The region near the maximum displacement was omitted since equation 3 cannot fit there. This is not a major impediment in describing the material properties of the pad, as the turn-round in deformation has more to do with the cyclic nature of the test than with the material. (3) Separate fits were carried out for the loading and unloading curves.

The relationship between deformation (or displacement), d, and F is obtained by integrating equation 3:

$$d = gF + h\ln F + \text{constant}\,. \tag{4}$$

The zero of deformation cannot be defined because of the extreme softness of the pad at low loads and the progressive change in contact as the actuator leaves or approaches the pad. This is reflected by the arbitrary additive constant in equation 4 and is the main reason for using stiffness, rather than displacement, when curve-fitting. The additive constant in equation 4 is arbitrary for both loading and unloading curves and, therefore, equation 4 gives no information about the area of the loop. In this sense, the information available complements that given by D.

Curve-fitting was carried out using SigmaPlot for Windows from Jandel Scientific. Use of equation 3 was suggested by TableCurve for Windows from Jandel Scientific.

Results

Fig. 4 is a hysteresis loop from a test with a rest time, 0.76 s, appropriate for running. As the rest time increases, the loading curve moves further from the unloading curve. The change is quantified by measuring the relative area of the loop, i.e. the percentage energy dissipation, D; see legend to Fig. 1.

Part of the displacement is due to compliance of the machine and rig. To check on this, a steel block was placed in the position of the pad and a test was carried out. The displacement at a compressive load of 1.4 kN was 0.018 mm. As this is only about 0.5 % of the displacement in tests with pads, no correction for machine compliance was made in arriving at the deformation plotted in Fig. 4. The effect on the hysteresis loop will be even smaller because the percentage energy dissipation for the machine loop is an order of magnitude smaller than that for the pad.

Fig. 5 shows, for pad A, percentage energy dissipation, D, plotted against the rest time, T, using a logarithmic scale. Each value of D has been adjusted to a peak load of 1.34 kN by subtracting $c(F-1.43)$, as required by equation 1. The linear regression line shown in Fig. 5 therefore corresponds

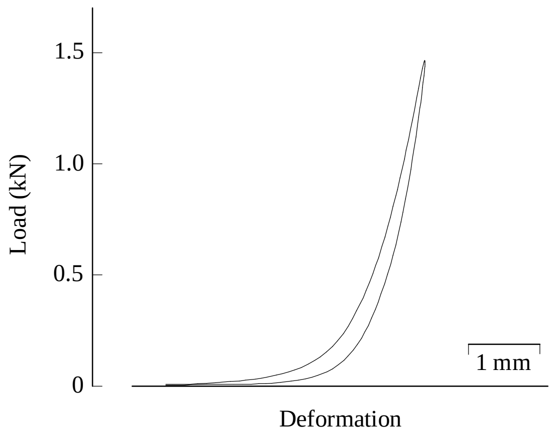

Fig. 4. A hysteresis loop with a rest time of 0.76 s, which is appropriate for locomotion. The energy dissipation is 30 %. Result is from pad A.

to equation 2. The rest times shown may be compared with those of locomotion. An assessment of a typical rest time for running was given above (see Introduction) as 0.59 s. Speed changes are accomplished more by changing stride length than stride time (Cavanagh and Kram, 1987) and therefore result in fairly small changes in rest time. Walking gives a greater range. The rest time starts during foot contact as the weight is transferred to the forefoot. Measurements of the pressure distribution under the foot cited by Nigg (1986) show that the heel is unloaded for somewhat less than half of the foot contact time. Assuming this fraction is 0.4, the rest time, *T*, is given by 0.4(stride time) + 0.6(swing time). Grieve

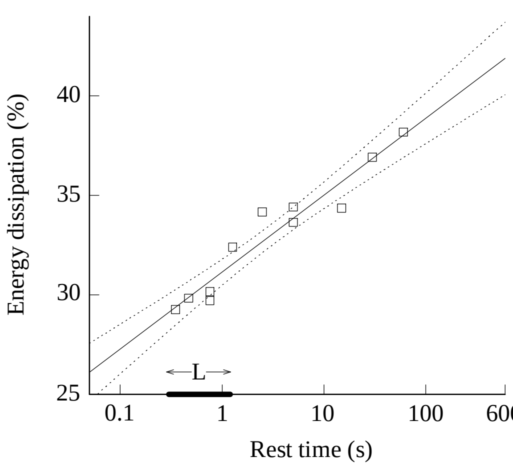

Fig. 5. The linear regression of percentage energy dissipation against $\log_{10}$(rest time) (s) is shown by the continuous line. The dotted lines are the 95 % confidence limits. The points have been adjusted to a constant peak load of 1.34 kN (see Materials and methods). The thickened region of the abscissa, marked L, indicates the rest times relevant to locomotion (0.3–1.2 s). Extrapolation to a rest time of 600 s gives an energy dissipation of 41.9 %, which does not differ significantly from the mean value of 42.3 % measured for first loops after 600 s of recovery (‘10 min’ loops). Results are from pad A.

and Gear (1966) give full details of stride times and foot contact times at various walking speeds. Using their data, *T* ranges between about 0.49 s (fast walking) and 1.2 s (very slow) for adults. For children, the rest times are somewhat shorter. The range of times marked L on the abscissa of Fig. 5 is from 0.3 to 1.2 s and is intended to cover most of human locomotion.

During locomotion, the heel contact time varies substantially, and variation of the frequency of oscillation from approximately 2 to 10 Hz would be required to cover the full range. However, I preferred to keep to a single frequency (5.5 Hz) to focus attention on changes with rest time alone. The change in energy loss with frequency is likely to be small (Bennett and Ker, 1990).

This paper is mainly concerned with *n*th loops. However ‘10 min’ loops (i.e. first loops after the 10 min of recovery time) give additional information. They were recorded at intervals during each test session and therefore provide a check that the properties of the pad did not change. ‘10 min’ loops are illustrated here by data from pad A; pads B and C gave entirely comparable results. For pad A, five ‘10 min’ loops were measured and numbered according to the order in which they were recorded. A Pearson product-moment correlation analysis showed no significant relationship between the order number and the energy dissipation (r^2=0.21, P=0.44). This gives confidence that the pad did not change significantly during the test session. The mean percentage energy dissipation for these loops, adjusted to a peak load of 1.34 kN with *c* as for the *n*th loops, was 42.3±0.79 (95 % confidence limits). (Note: 95 % confidence limits are given here for comparison with the limit lines in Fig. 5.) Extrapolation of the regression line and its 95 % confidence limits in Fig. 5 gives the percentage energy dissipation for a rest time of 600 s as 41.9±1.92. Thus, the first loops after a 10 min recovery period seem to be equivalent to *n*th loops with a 10 min rest time.

Results from all three pads are shown in Fig. 6, and corresponding data, including values for D_1 and *b*, are in Table 2. D_1 relates to a rest time of 1 s, which is near the upper end for normal locomotion. However, the change in *D* in taking a middle value of, say, 0.75 s is small and it is convenient to use D_1 as representative of energy loss in locomotion. In energy loss, pad B differs significantly from pads A and C. The reason for this is unclear, but note that pads with unusually high energy losses, similar to pad B, were also found by Aerts *et al.* (1995) and Bennett and Ker (1990). The average of the three values of D_1 is 33±4.1 % (S.D.). As is clear from Table 2, the values of *b* are not significantly different. It is therefore appropriate to calculate the standard error of the overall mean as $\sqrt{[(\text{S.E.M.}_A)^2+(\text{S.E.M.}_B)^2+(\text{S.E.M.}_C)^2]}/3$. This gives b=3.7±0.29. Thus, when the rest time increases by a factor of 10, the percentage energy dissipation increases by 3.7 %. Such a 10-fold change, or less, is involved in switching from continuous oscillations (half-cycle, 5.5 Hz and therefore a rest-time of 0.091 s) to the conditions of locomotion. The further change in going to first loops, with fully relaxed pads, is much greater.

Table 2. *Results of the tests on the three pads*

Pad	Peak load mean ± S.D.	D_1 (%) mean ± S.E.M.	b mean ± S.E.M.	S at body weight when T = 1 s	N
A	1.4±0.1	31.1±0.31	3.9±0.35	0.96±0.013	11
B	1.2±0.1	37.5±0.49*	3.9±0.50	0.98±0.020	10
C	1.4±0.1	29.8±0.60	3.4±0.64	0.91±0.024	14

The quantities D_1 and b are defined in equation 2.
Stiffness, S, is the slope of the loading curve.
Units: time (s), force (kN), stiffness (kN mm^{-1}).
*Denotes a value where one pad differs significantly from the other two.
Note: the second column gives the peak loads recorded during the tests. The D_1 values stated are after adjustment to a common peak load of 1.34 kN, as described under Materials and methods.

Table 2 includes values of stiffness, for T=1 s, measured as the slope of the loading curve at body weight. Stiffness, on the loading curve at a given force, decreases as rest time increases. For example, for pad A at body weight, when T=0.1 s, S=1.02 kN mm^{-1}; when T=1 s (Table 2), S=0.96 kN mm^{-1}; when T=100 s, S=0.86 kN mm^{-1}. These values were obtained from equation 3 using parameter values given in the Discussion below (see Table 3).

To check that equations 3 and 4 provide a good fit to the data, I plotted each fitted curve together with its data points. The match was visually good. This was confirmed by calculating the coefficient of determination, r^2, for each of the 70 non-linear regressions of stiffness on load (35 loading and 35 unloading). In each case, $r^2 \geqslant 0.99$: the average value for the loading curves was 0.996 and for the unloading curves was 0.997.

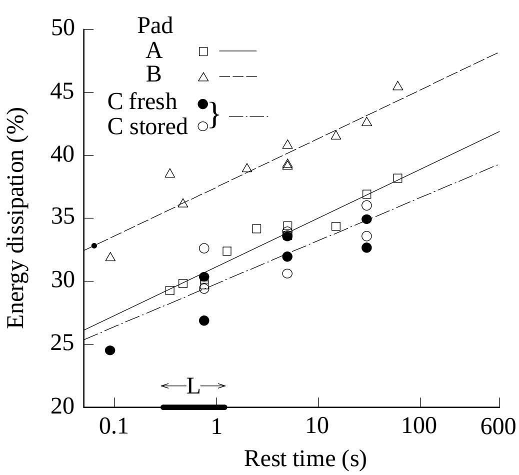

Fig. 6. Linear regression of percentage energy dissipation against $\log_{10}$(rest time) (s) for all three pads. The confidence limits for the regression lines have been omitted for clarity. The values for pad C are shown separately for (i) when fresh and warm (filled circles), and (ii) at room temperature after storage (open circles). The regression lines for these two sets did not differ significantly and all the points were used to calculate the regression line shown. Values for the gradients and intercepts for these lines are included in Table 2.

Discussion

Fig. 6 demonstrates a linear relationship between the percentage energy loss and the logarithm of the rest time. However, this linearity must have limits. At the lower end, the concept of rest time ceases to be clear when it is less than the period of oscillatory loading. Two observations which suggest that the values in Fig. 6 approach the minimum for energy dissipation are as follows: (i) continuous sinusoidal loading, with the actuator never out of contact (full-cycle loading), gives comparable results to half-cycle loading (Aerts *et al.* 1995) and (ii) energy loss with continuous sinusoidal loading shows little change with frequency (Bennett and Ker, 1990). The upper limit suggested by the first-loop measurements of Aerts *et al.* (1995) was approximately 48 %. These first-loop measurements were more erratic than the *n*th-loop measurements, which perhaps reflects the vagaries of achieving 'complete rest'. Note that *in vivo* tests give losses which are much greater than 48 %. This is a consequence of the presence of other structures (Aerts *et al.* 1995) and is not a time-dependent effect such as that investigated here.

Combining the results from Bennett and Ker (1990) and Aerts *et al.* (1995) with those above gives the average energy loss in a steady oscillatory test as 30±4.5 % (S.D.; N=20, with 14 different pads). In arriving at this average, I have assumed that full-cycle and half-cycle tests give essentially the same values and I have subtracted 3.7 % from the D_1 values in Table 2. With this subtraction, the average for the present results alone is 29±4.1 % (S.D.), which is in line with all the other comparable values. Introducing a rest time of 1 s, as in locomotion, gives an average energy loss for the 14 pads of 33 %.

This lower energy loss compared with single-impact tests (energy loss=48 %) implies a bouncier heel. Alexander *et al.* (1986) introduced the term 'chatter' to describe the possibility that the pad might bounce clear of the ground after its initial impact and long before the due time for lift-off. They found some difficulty in reconciling their theory with the lack of chatter in actual locomotion. Alexander *et al.* (1986) found an average energy loss of 30 % at a frequency of 11 Hz in continuous oscillation for the paw pads of seven different mammals. Except for a camel, the mammals were smaller than humans with, presumably, rest times too short to lead to much increase in energy loss, so the present results do not resolve this question. Had the single-strike value been found to be appropriate to locomotion, the difficulty would have been lessened.

Having a springy heel pad may help in positioning the foot during the step phase of locomotion. The energy required to compress the pad (i.e. the area under the loading curve to maximum force) is of the order of 1 J, which is small compared with the energy exchanges during locomotion. In running, the energy lost during the first half of each step may be about 100 J (Ker *et al.* 1987), so plenty of energy is available for compressing the pad and the pad is subjected to a forced oscillation much like that provide by the Instron. With 67 % of the 1 J returnable, the calcaneus will receive a substantial force, as it begins to lift away from the ground, over a distance approaching 2 mm (see Fig. 4). This transfer of energy back to the calcaneus could have a significant effect in positioning the foot during the part of the step when load is being transferred from the heel to the forefoot.

For stiffness at body weight, Bennett and Ker (1990) give a value of 1.16±0.170 kN mm^{-1} (five pads) and Aerts *et al.* (1995) give a value of 1.45±0.105 kN mm^{-1} (S.D.; *N*=9, with four different pads), but measured in a slightly different way that might have led to a marginally higher value. These values are for continuous half-cycle tests, which at 5.5 Hz means a rest time of 0.091 s. The corresponding value from the present results is 1.03±0.056 kN mm^{-1}. This is slightly larger than appears in Table 2 because the latter allows for a rest time of the order of 1 s. The average of these three values, weighted by the number of pads in each set, is 1.2 kN mm^{-1}. The deviations from this average may have more to do with variations in body weight than with the properties of the pad.

To summarise, the best values to use in models of locomotion are approximately 33 % for energy loss and 1.2 kN mm^{-1} for stiffness on the loading curve at body weight. Use of mechanical properties derived from tests with steady oscillations, as was done by Alexander *et al.* (1986) and Ker *et al.* (1989), will not be likely to introduce substantial errors.

These mechanical results provide some indications about the mechanism of deformation in the material of the pad. The results for pad C, in Fig. 6, show that the recovery process is the same when the pad is fresh and warm as when it is at room temperature after storage. This corresponds to a similar observation reported by Bennett and Ker (1990) for energy dissipation, but is, at first sight, perhaps even more unexpected. The consistency of the fatty material of the pad appears very different when fresh and warm from that at room temperature after storage. This indicates that the consistency of the fat is not critical to either process: whether fresh or at room temperature, it acts simply as a liquid filler. The fat is held in collagenous pockets (Blechschmidt, 1934). Presumably, there is no bulk flow between pockets, which would be bound to vary with the consistency of the fat, but only a change of shape within each pocket, which can happen easily with little reliance on consistency. Lack of bulk flow would seem to be a proper structural design for long-term integrity, and in this respect the same pad preparation can be used for innumerable tests, so long as it is stored frozen between test sessions.

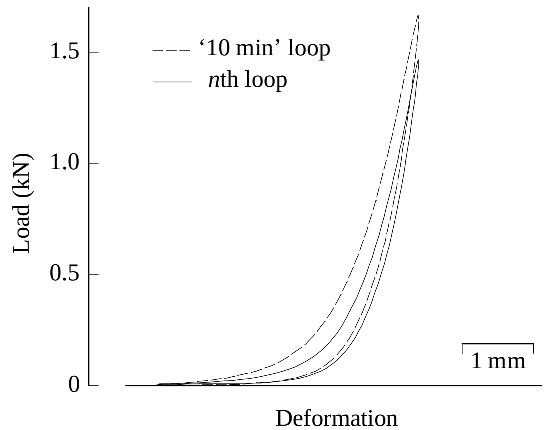

Fig. 7. Comparison between a first and *n*th loop of the same preparation. The dashed line is a first loop after a 10 min recovery period. The solid line (same results as in Fig. 4) is an *n*th loop recorded later during the same set of measurements with the deformation range and mean position unaltered. Results are from pad A.

Fig. 7 is included to allow direct comparison between a '10 min' and an *n*th loop. The loops in Fig. 7, in contrast to those in Fig. 1, are taken from the same sequence of tests with the set-up unchanged. In addition to the differences in the loading curves, to which attention has already been drawn, for the *n*th loop, the pad is in effect slightly thinner than for the '10 min' loop. The unloading curve for the *n*th loop is displaced from that for the '10 min' loop by about 0.07 mm; otherwise they are very little different. Because of the steepness of the plot at high loads, this small shift in position results in a very noticeable drop in the peak force. This is a procedural inconvenience and complicates the comparison of the two curves. However, such a small reduction in thickness is irrelevant to biological function. Creep when under load is a familiar phenomenon. The slight creep in the pad, noted here, is reversible and is not associated with damage.

The changes in loop area with rest time imply changes in the shape of the curves and hence in the parameters *g* and *h* of equation 3. Which of the parameters vary with log*T* and by how much? This question was investigated by linear regression and the statistical results are given in Table 3. The parameters for the loading and unloading curves are distinguished by the subscripts L and U respectively. Of the four parameters, only h_L showed a statistically significant correlation with rest time. For h_L, the relationship is $h_L=p+q\log_{10}T$, where *p* and *q* are additional parameters, values for which are given in Table 3. In particular, the unloading curves show no statistically significant change with rest time. This is consistent with the observation noted above that the two unloading curves in Fig. 7 are very similar.

Table 3. *Results of linear regression of the parameters* g *and* h *from equation 3 on log$_{10}$*T

Pad	Parameter	p ± S.E.M. (P value)	q ± S.E.M. (P value)
A (N =11)	g_L	0.206±0.0064 (<0.0001)	−0.0089±0.0075 (0.91)
	h_L	0.459±0.0046 (<0.0001)	0.0325±0.0053 (0.0002)
	g_U	0.071±0.0088 (<0.0001)	0.017±0.010 (0.13)
	h_U	0.399±0.0076 (<0.0001)	−0.005±0.009 (0.13)
B (N =10)	g_L	0.096±0.0101 (<0.0001)	−0.023±0.010 (0.057)
	h_L	0.671±0.0077 (<0.0001)	0.072±0.0079 (<0.0001)
	g_U	−0.004±0.0075 (0.91)	0.017±0.012 (0.19)
	h_U	0.478±0.0072 (<0.0001)	−0.0041±0.0073 (0.059)
C (N =14)	g_L	0.236±0.0147 (<0.0001)	−0.012±0.016 (0.47)
	h_L	0.493±0.0083 (<0.0001)	0.042±0.0089 (0.0005)
	g_U	0.081±0.0104 (<0.0001)	−0.0031±0.011 (0.79)
	h_U	0.446±0.0083 (<0.0001)	0.0064±0.0089 (0.48)

The equation is: h or $g = p + q\log_{10}T$.

p gives the magnitude of the parameter and q describes its variation with $\log_{10}T$.

Subscript L refers to the loading curve and U to the unloading curve.

Units: time (s), force (kN), stiffness (kN mm^{-1}).

At the P=0.05 level, of the four parameters, only h_L varies significantly with log$T$.

The stiffness values stated in Table 2 were obtained using the best-fit parameters for each individual pad as given in Table 3. Where a more general idea of the properties of an adult pad is sufficient, I suggest the use of the following: g_U=0, h_U=0.5, g_L=0.2, p=0.5 and q=0.03 with deformation in mm, time in s and force in kN. These ‘round numbers’ were chosen to give curves which are plausible in the light of the previously published data referred to above as well as the present results. With g_U=0, equation 4 shows, for unloading, an exponential dependence of force on deformation. The loading curve is a little more complicated. In general, at any given load, the slope of the unloading curve is greater than that of the loading curve. As rest time increases, the difference between the slopes increases. This model of the material properties, including changes with rest time, may be useful in future investigations of the relationship between the structure of the pad and its properties or between these properties and its function.

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