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The mechanical properties of the human subcalcaneal fat pad in compression*

M. B. BENNETT† AND R. F. KER

Department of Pure and Applied Biology, The University, Leeds LS2 9JT, UK

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INTRODUCTION

When human beings walk or run, the plantar regions of the feet are subjected to considerable forces during the ground contact phase of every step. In many instances the heel is the first portion of the foot to strike the ground (Cavanagh & Lafortune, 1980) and large forces are generated by impact (Ker, Bennett, Alexander & Kester, 1989) irrespective of whether the subject is wearing footwear or not. A thick fat and connective tissue pad has developed on the ball of the heel, presumably to cushion the musculoskeletal system.

There have been a number of attempts to characterise the mechanical properties of the tissue beneath the heel. *In vivo* approaches have often utilised instrumented pendulums which have been impacted with the heel region of the foot to simulate the heel–ground contact (Nigg & Denoth, 1980; Denoth & Nigg, 1981; Cavanagh, Valiant & Misevich, 1984; Valiant & Cavanagh, 1984). Information from these impacts has suggested that most of the energy involved in the deformation of the heel pad is dissipated, with only small amounts of energy recovered in the subsequent elastic recoil.

Alexander, Bennett & Ker (1986) investigated the *in vitro* dynamic compressive properties of fat pads (metatarsal and metacarpal pads) of various non-human mammals. They suggested that pads might be composed in such a way as to eliminate the possibility of the paw, with its elastic pad, being set into oscillations that would result in the temporary loss of contact with the ground at the beginning of a step. The paw pads that were examined may be considered to be analogous with the heel pads of human beings. They were found to be highly resilient, returning about 70% of the energy used to deform them in their elastic recoil. The remaining energy was presumably lost as heat.

This paper examines the compressive properties of the isolated subcalcaneal fat pad of *Homo sapiens* by the method of Alexander *et al.* (1986). It attempts to determine whether or not the mechanical properties of the human heel pad differ from those of the analogous fat pads from other mammals and whether apparent differences are attributable to methodological variation. The structure of the heel pad is complex (Blechschmidt, 1934), with collagenous elements connecting the calcaneus to the skin and 'compartmentalising' the fat of the pad, restricting its displacements when subjected to compressive loading. In our experiments the integrity of the heel pad is maintained.

* Reprint requests to Dr R. F. Ker.

† Present address: Department of Anatomy, The University of Queensland, St. Lucia, Brisbane, Queensland, Australia.

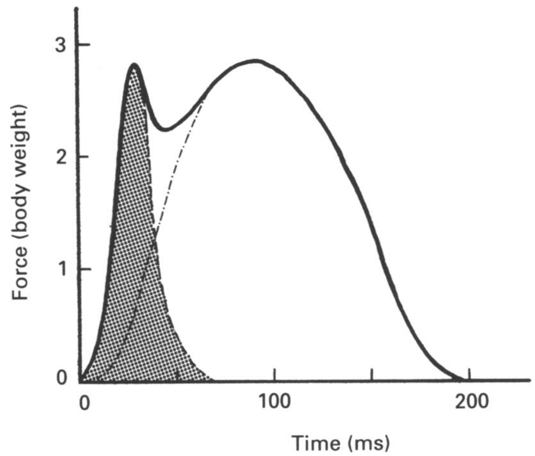

Fig. 1. Example of the ground reaction force (GRF) produced by a human subject running across a force plate at 6·5 m s^{-1}. The stippled area approximates to the proportion of the GRF that is due to the heel pad–ground contact, the later force peak is produced by more distal portions of the foot. (Derived, in part, from information in Munro *et al.* 1987.)

MATERIALS AND METHODS

Heel pads from 11 limbs, that were amputated for reasons of irreparable vascular disease, were used in this study. Patients were between 49 and 78 years (body masses, 46–76 kg).

Pads were tested in compression in an Instron 8031 servo-hydraulic materials testing machine, with the actuator moving sinusoidally, using the methods of Alexander *et al.* (1986). The rates of loading, unloading and the magnitude of the applied forces were varied over a range that included the values required to simulate the vertical ground reaction force of a running step (Munro, Miller & Fuglevand, 1987) (Fig. 1). Pads were used immediately or after thawing, having been stored at −20 °C wrapped in polythene until required. Radiographs taken of each foot were used to determine heel pad thickness and also to plan where a saw cut was to be made to remove most of the calcaneus (with the heel pad attached) from the rest of the foot. The plane of the saw cut determines the orientation of the heel in the machine and was chosen to reflect the position of the foot at a fairly early stage in the step (when the force on the heel is greatest – Figure 1). The calcaneal surface exposed by the saw cut was flat which simplified the mounting of the specimen in the machine; test specimens therefore consisted of most of the calcaneus and all of the heel pad, the latter still attached to its sides and lower surface (these are referred to as attached pads). A number of tests were made on heel pads that had been removed from the calcaneus by cutting the collagenous connections between the bone and the pad (these are referred to as isolated pads). Specimens were mounted in the Instron as shown in Figure 2 and subjected to compressive loads of up to −2 kN at frequencies of 0·1 to 70 hertz (Hz). The rollers shown in Figure 2 ensured that the applied force was always precisely aligned for measurement by the load cell. Each pad was also tested at a wide range of temperatures from about body temperature (37 °C) to about 0 °C. Pad temperatures above room temperature were achieved by immersing the pad (wrapped in a polythene bag) in a thermostatically controlled saline water bath. Pads were transferred to a similarly controlled chamber that encompassed the specimen and were subsequently

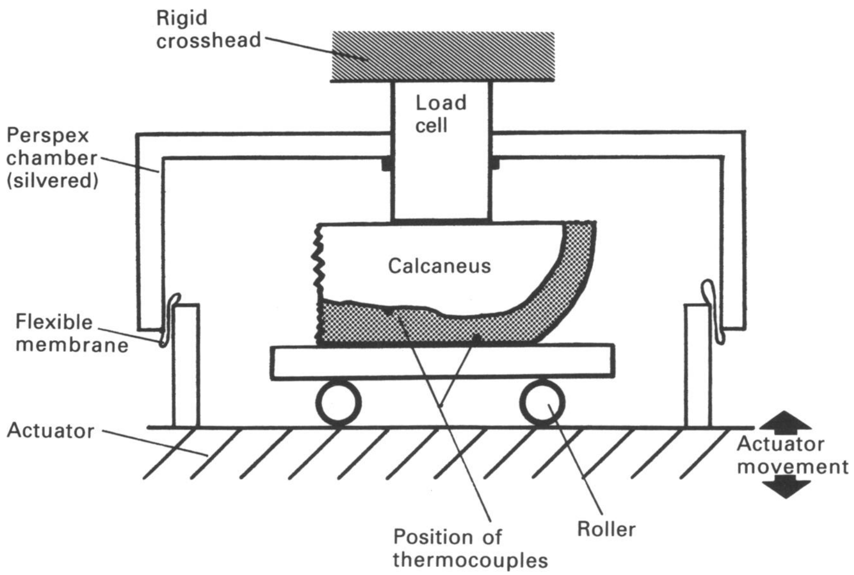

Fig. 2. The experimental arrangement with a heel pad mounted in the Instron materials testing machine. The air surrounding the specimen was constantly circulated and was temperature-controlled.

tested at known temperatures. These were monitored by two thermocouples (external diameter < 1 mm), one within and one beneath the pad. Pads were equilibrated at the required temperature before records were taken.

The heel pad stiffness and the energy dissipated during one loading–unloading cycle were calculated from *X–Y* plots of load *v* actuator displacement (Alexander *et al.* 1986).

Where results are presented as mean values they are followed by standard deviations.

RESULTS

All of the specimens tested demonstrated nonlinear stiffness, with the pads becoming stiffer as the applied load increased. A typical load-displacement record for one loading–unloading cycle is shown in Figure 3. Heel pad stiffness, measured at a load equal to body weight was -1160 ± 170 kN m^{-1} (mean and s.d., n = 5). Alteration of strain rate, produced by changing the frequency of the actuator movement, did not modify the stiffness of the pads (measured at body weight) in any consistent manner.

Radiographs were taken of heel pads in loaded and unloaded states. The example shown in Figure 4 demonstrates that under a compressive load of twice body weight, this pad was compressed by 4·7 mm. The mean compression produced by a load equivalent to body weight was $2{\cdot}07 \pm 0{\cdot}29$ mm (n = 5).

A small amount of fluid was observed to be extruded from the cut surfaces of the test specimens when subjected to compressive loads, but this did not appear to affect the results.

Energy dissipation

The area bounded by the rising and falling curves (Fig. 3) represents the energy lost during one loading–unloading cycle. The energy, or work done, in compressing the

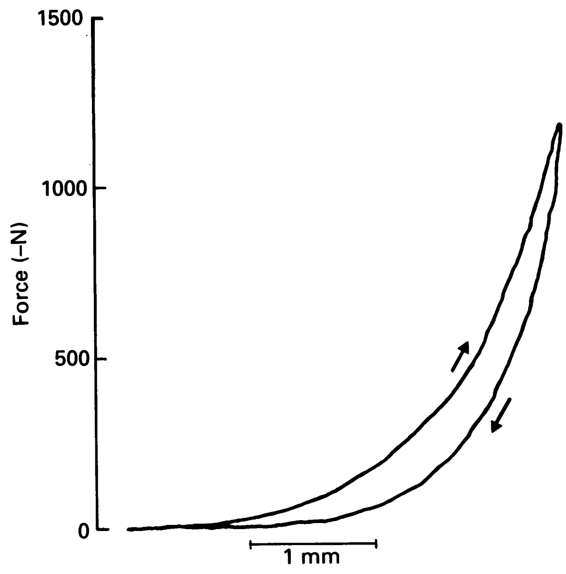

Fig. 3. Typical force-displacement record for one loading–unloading cycle of a heel pad. Sine wave displacement cycle at 2·2 Hz.

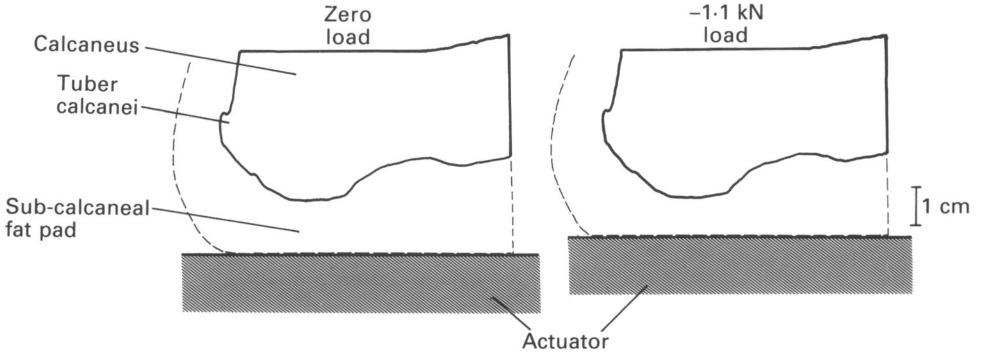

Fig. 4. Tracings from radiographs showing the deformation of a heel pad under zero load and at about twice body weight.

specimen is given by the area under the loading curve. Thus the percentage energy dissipation is given by:

$$(\text{Loop area}/\text{Area under loading curve}) \times 100\,\%.$$

Percentage energy dissipations for all tests ranged between 20·8 % and 44·7 %. Dissipations of $28{\cdot}6 \pm 6{\cdot}9$ % ($n = 7$) for pads attached to the calcaneus and $32{\cdot}3 \pm 5{\cdot}4$ % ($n = 6$) for isolated pads were found in tests conducted at 22 °C, using a peak load of -1 kN.

Frequency effects

The percentage energy dissipation did not alter greatly in experiments where different test frequencies, but the same peak loads, were used. With an order of magnitude increase in frequency, from 1·1 Hz to 11 Hz, there was a 5·3 % increase in the energy dissipation (from 29·2 to 34·5 %), but there was no significant difference in

Table 1. *The effect of test frequency on heel pad stiffness and energy dissipation*

Test frequency (Hz)	Stiffness (kN/mm)	Energy dissipation (%)
0·1	3·09	24
1	3·11	23
10	3·13	24
20	2·97	26
30	2·96	22
40	3·12	21
50	3·11	23
60	3·14	24
70	3·07	27

Stiffness was measured at a compressive load of −1 kN. Energy dissipation figures were calculated from tests where the peak load was −1·2±0·1 kN.

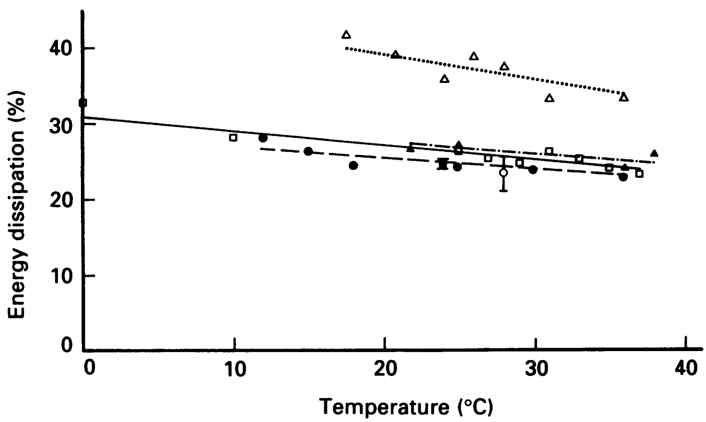

Fig. 5. Graph showing the effect of temperature on the percentage energy dissipation that occurs in heel pads that were attached to the calcaneus, during one loading–unloading cycle. In all cases the peak load was −1·1±0·05 kN; frequency = 2·2 Hz. Each heel pad is represented by a different symbol. The symbols with standard deviation bars refer to specimens that were only tested at the one temperature shown.

energy dissipation figures between 0·11 Hz and 1·1 Hz (Table 1). The observed stiffness at a given load and the percentage energy dissipation by the pads altered little over the complete range of frequencies examined (0·1 Hz to 70 Hz) (Table 1).

Temperature effects

Figure 5 shows that the percentage energy loss increases slightly with decreases in temperature from 37 °C to 10 °C. The slope of each of the regression lines for percentage energy dissipation versus pad temperature was significantly different ($P < 0·05$) from zero. This applies to the pad with markedly higher percentage energy dissipation (Fig. 5) as well as to the others. Results obtained from specimens which had been frozen and subsequently rewarmed before testing were indistinguishable from those obtained from heel pads that were tested immediately after amputation, i.e. they had not been allowed to cool before testing.

DISCUSSION

Although these subcalcaneal fat pads were tested *in vitro* (post-mortem in an artificial experimental situation) it is considered likely that the mechanical properties displayed are representative of those that would be found in the *in vivo* condition. This is supported by the results obtained from specimens that had been tested within one hour of amputation, compared with those that had been stored frozen prior to testing. No differences were observed between the shape of the curves, stiffnesses or energy dissipation. Furthermore, two pads that were tested immediately post-amputation yielded results that were indistinguishable from those obtained after freezing and thawing the same pads. These results suggest that no irreversible changes occur when the tissue is exposed to low temperatures. Similar observations have been made by other workers investigating the mechanical properties of various biological tissues (Ker, 1981; Ker *et al.* 1987; Woo *et al.* 1987).

One obvious difference from the *in vivo* condition is that in our tests any fluid that was extruded during compression drained away. This would possibly lead to a progressive reduction in the fluid within the specimen which may alter the mechanical properties in tests of long duration. Such fluid extrusion was very slight in our tests, but the possibility exists that it may have had some effect.

Changes in the pad temperature did not greatly alter its measured properties and although the effects on energy dissipation were statistically significant they seem too small to have biological importance. There have been numerous reports on the effects of temperature on various biological soft tissues and in many cases, although not all, a temperature-dependent effect was noted (Woo *et al.* 1987). The relatively small amount of temperature dependence was slightly surprising when one considers that the major portion of the heel pad consists of fat which may be expected to alter its properties at low temperatures. The foot pads of various mammals (e.g. the porcupine, *Erethizon dorsatum*) are known to fall to temperatures close to freezing when standing on snow (Irving, 1972). This is done in order to reduce the heat loss from the body to the ground. The production of foot pads where the mechanical properties are 'temperature insensitive' may be an adaptation linked to the possibility of encountering cold ground. Fat pads are presumably structured so that their properties are optimal at about body temperature (or slightly below body temperature because they are on an extremity, which tends to be somewhat cooler than core temperature). If the properties changed dramatically with cooling then the pads would have markedly sub-optimal properties, which may result in ineffective cushioning of the foot–ground impact.

Nakamura, Crowninshield & Cooper (1981), in their paper on finite element stress analysis of soft tissue loading of the foot, show a single load-displacement plot for a compressive test on a 30 × 30 × 15 mm section of a fresh cadaveric heel pad. Their test did not incorporate any of the calcaneus and was conducted at 0·125 Hz. No other information on their test procedure was provided. So far as can be assessed, their result does not differ from those obtained in this paper. De Clercq *et al.* (1989) recorded the *in vivo* deformation of heel pads using a high-speed 35 mm X-ray film method, but do not show any of their calculated force-deformation curves.

The results of *in vivo* experiments that have used ballistic pendulums (Nigg & Denoth, 1980; Denoth & Nigg, 1981; Cavanagh *et al.* 1984; Valiant & Cavanagh, 1984) have been quite different. These studies involved the impact of a pendulum with the heel region of the foot of a subject, whose flexed knee was braced against a wall. Accelerometers mounted on the pendulum and high speed cine film were used to calculate load-displacement information. An example of one of these plots is given in Cavanagh *et al.* (1984). The major difference between results obtained from pendulum studies and those on *in vitro* heel pads is that the energy dissipations in the latter are very much smaller. Our tests showed that about 30% of the energy used in deforming the pad was dissipated, whereas between 85% and 95% of the energy was absorbed (dissipated) in the pendulum studies. An energy dissipation of about 30% was found in compressive tests conducted with analogous fat pads of a wide range of other mammals – badger, fox, cat, dog, wallaby, camel (Alexander *et al.* 1986). It is considered likely that our tests represent the properties of the fat pads, with respect to energy dissipation in particular, whereas the pendulum impact results may be descriptive of the properties of the lower leg as a whole. Cavanagh *et al.* (1984) mention the possibility that energy may be partitioned, in an unknown manner, between the heel/foot/leg system. With the whole limb intact there are many levels at which energy can be absorbed, for example, within the pad, the cartilage of the talo-calcaneal and talo-tibial articulations, the ligaments limiting joint movements and at the point of contact between the knee with the wall. The pendulum experiments do not appear to mimic the conditions that occur during running, as subjects found that forces in excess of about body weight were painful, whereas force plate records show that peak forces of up to about three times body weight occur at heel strike (Munro *et al.* 1987).

Subcalcaneal fat pads do provide a degree of 'cushioning', which will always tend to reduce the peak force at the instant of heel strike (Ker *et al.* 1989), but because of the rapid stiffening upon compression (Fig. 3) it can only provide a limited amount of protection. To avoid severe jarring that would accompany the bottoming out of the pad if it were subjected to high loads, the body may adjust limb-joint flexion/extension actively at the time around impact in order to reduce the peak force of impact (see Frederick, 1986). This may involve a change in the portion of the foot that first contacts the ground, thus removing the heel impact phenomenon. The effects of heel pad confinement on the mechanical characteristics (Jørgensen & Ekstrand, 1988) were not investigated in this study.

SUMMARY

The subcalcaneal fat pads of *Homo sapiens* were subjected to cyclic compressive loading in a materials testing machine. Rates of loading and the absolute loads to which pads were subjected were chosen to simulate the pattern of forces that the pad would be exposed to during the ground contact phase of the running step. Heel pads were found to be resilient, returning approximately 70% of the energy used to deform them. This was modified little by changes in loading frequency. A reduction of temperature from 37 °C to 10 °C produced a small, but significant, increase in the percentage energy dissipation.

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