J. Anat. (1996) **188**, pp. 417–423, with 4 figures Printed in Great Britain

The effects of isolation on the mechanics of the human heel pad

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(*Accepted 26 September 1995*)

ABSTRACT

In previous studies on the mechanical properties of the human heel pad (Bennett & Ker, 1990; Aerts et al. 1995) the fat pad and part of the calcaneus was removed from amputated test specimens. The present study tested whether this procedure influences the mechanical behaviour of the sample. Intact amputated feet were therefore mounted on steel rods driven through the calcaneus and placed in a mechanical test situation (pendulum or servohydraulic material tester). The mechanical properties of the pad were determined for a series of experiments in which the pad was gradually freed from the foot in the way done by Bennett & Ker (1990) and Aerts et al. (1995). The results showed no observable differences in the mechanics of the pad by isolating it from the rest of the foot. Thus, in relation to human locomotion, the load-deformation relation of heel pads as described by Aerts et al. (1995) is the most appropriate to date.

Key words: Biomechanics; foot.

INTRODUCTION

When walking or running, a shock wave propagates through the body at each foot fall (Light et al. 1980; Volochin et al. 1981; Dickinson et al. 1985). The intensity of these waves depends upon the mechanical characteristics of the materials involved in the impact at heel strike. This interaction manifests itself in 2 possible but complementary ways: (1) an increase of the compliance at the level of the contact surface reduces the peak forces occurring at impact (i.e. shock reduction), and (2) mechanical energy can dissipate as heat during the heel strike (i.e. damping). Such functions can be compared with the suspension springs and the shock absorbers of a car, respectively (see also Alexander, 1988).

The human heel pad (i.e. the fatty tissue cushion underneath the calcaneus) is assumed to perform such a role, and its mechanical properties have been investigated in this context (e.g. Cavanagh et al. 1984; Nigg et al. 1984; Valiant, 1984; Jørgensen & Bojsen-Møller, 1989; Ker et al. 1989; Bennett & Ker, 1990; Kinoshita et al. 1992, 1993; Aerts & De Clercq, 1993; Noe et al. 1993). Different studies seemed to show very different mechanical properties (see De Clercq et al. 1994; Aerts et al. 1995). This is especially true for tests giving a complete description of the load-deformation transients at heel impact: in vivo impact tests (Cavanagh et al. 1984; Valiant, 1984; Kinoshita et al. 1992, 1993; Aerts & De Clercq, 1993), on the one hand, and measurements performed by means of a servohydraulic material testing machine on isolated heel pads (Bennett & Ker, 1990), on the other. The in vivo results showed strong damping (up to 95% energy dissipation) and a relatively high compliance, whereas the in vitro INSTRON tests revealed energy losses of merely 30% and compliances about one magnitude below those from in vivo tests (see Aerts et al. 1995). Elucidating this conflict is of crucial importance when experimental data are to be used in further pure (biomodelling) or applied (e.g. orthopaedics, footwear) research (see Aerts et al. 1995).

According to Bennett & Ker (1990) the divergent results from the lower leg inevitably present in the in vivo test situation: the test person is placed with the knee against a fixed external support (e.g. the wall; cf. fig. 1 in Aerts & De Clercq, 1993; or the floor, cf. fig. 1

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in Kinoshita et al. 1993) with the lower leg in line with the impacting mass. In this way, the compliance of the entire lower leg is assessed, instead of that of the calcaneal fat pad alone.

Aerts et al. (1995) showed for isolated heel pads that, when carefully executed, the results from pendulum impact tests do not differ from the output of the servohydraulic testing machine. This supports the above theory on the influence of the lower leg. However, one feature that might bias the in vitro tests remains to be examined. The pad is made of collagen reinforced chambers filled with fatty tissue (Blechschmidt, 1982; Miller, 1982) and functions as an assembly of hydrostats. It is not inconceivable that skin tension, tension from the plantar ligaments, or any other interaction with surrounding structures are essential in maintaining the in vivo configuration of the construction. In that case, cutting the surrounding soft tissues during detachment of the pad for in vitro testing might seriously affect the mechanics of the heel pad. This could, for instance, allow bottoming out more readily (and thus cause an apparent increase of stiffness) when the pad is mechanically tested.

This paper aims to assess this last uncertainty in the controversy between in vivo and in vitro mechanics of heel pads by testing the above hypothesis. Therefore in vitro experiments need to be performed on foot specimens for which the soft tissues around the heel pad have been cut to the minimal possible extent. In addition, it is necessary to fix the specimen in the apparatus by means of the calcaneal bone in order to exclude any possible effects of skeletal movements, mainly in the ankle joint (lower leg effect). The compromise by which we sought to satisfy these somewhat contradictory requirements is described under Materials and Methods. Thereafter, load-deformation loops are recorded in a series of tests in which the heel pad is progressively freed from the rest of the foot. The cuts to be made mimic those of Aerts et al. (1995). Comparison of the resulting hysteresis loops will allow the effect of isolation of the heel pad to be assessed. In that way, the reliability for further use in scientific research of data on heel pad mechanics published to date can be evaluated.

MATERIALS AND METHODS

Two lower limbs were available for these tests. One (i.e. FOOT I) was amputated for reasons of irreparable vascular disease (female aged 77 y; weight 44 kg). The second (i.e. FOOT II) was a healthy lower leg, lost in an accident (male aged 24 y; weight 78 kg). These lower limbs had been stored at −20 °C. Bennett & Ker (1990) showed that freezing did not effect the mechanical properties of the pads.

The feet were mounted in solid oak frames (25 mm boards) by means of 2 steel rods ($\phi = 8$ mm; with screw-thread), transversely driven through the calcaneus above the plane where the pads were cut in the previous experiments (Bennett & Ker, 1990; Aerts et al. 1995; see Fig. 1*A*, *B*). Holes were drilled slightly narrower than the bar diameter, so that the rods had to be screwed through the bone, thus ensuring good anchoring of the specimen. A 100 mm wood-screw ($\phi = 5.7$ mm) was driven sagittally through the calcaneus in the posteroanterior direction. The screw was located below the transverse bars and projected about 1.5–2 cm beyond the posterior surface of the foot (Fig. 1*B*). Two different but equivalent experimental approaches were applied, each on one foot.

FOOT I was tested in the pendulum experimental setup also used by Aerts & De Clercq (1993) and Aerts et al. (1995). This has been shown to give a reliable output concerning the mechanics of isolated pads (see Aerts et al. 1995). The supporting frame was firmly attached by means of stout metal braces to a heavy steel girder (1 cm I-profile) pinned to a solid concrete outer wall (Fig. 1*A*). The wood screw was supported by tightly squeezing an 18 mm oak board between its free end and the steel girder (see Fig. 1*A*). The heel was impacted by means of an instrumented mass of 11.615 kg. (For an extended description of the entire pendulum setup, refer to Aerts & De Clercq, 1993 and Aerts et al. 1995.) All impact velocities equalled 0.35 m s^{-1}. From records of deceleration–acceleration against time, load-deformation loops of the pendulum strikes could be deduced. To assess the compliance of the frame, a linear steel spring (stiffness: 147 kN m^{-1}) was mounted on an artificial oak heel in the frame (mounted in essentially the same manner as the actual specimens). If the frame were insufficiently stiff, or if energy losses occurred in it, load-deformation loops derived from impact tests on the steel spring would show a lower stiffness than the known stiffness of the spring and/or a clear hysteresis. All pendulum impacts on FOOT I were videotaped in lateral view at 400 frames s^{-1} (NAC 400).

FOOT II was tested in a servohydraulic material testing machine (INSTRON 8031). In this case, the frame could be made shorter compared with the one shown in Figure 1*A*, and was placed directly, in a vertical position, on the actuator of the INSTRON. The load cell first touched the sample halfway through the deformation cycle (i.e. half cycle tests; cf. Aerts et al. 1995), thus mimicking a running impact. Deformation was preset at 4.5 mm and tests were carried

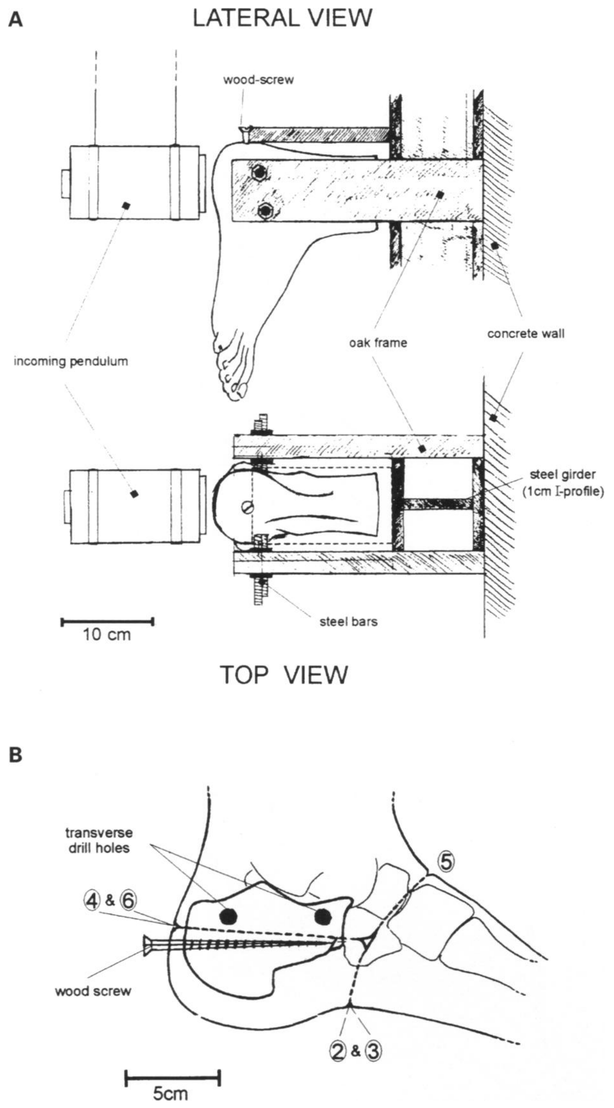

Fig. 1. (*A*) Lateral and top views of the mounting procedure of a test specimen for the pendulum test (see text). (*B*) Schematic representation of part of FOOT II (based on a radiograph). The numbers and dashed lines refer to the successive cuts for isolating the heel pad (see text). The positions of the transverse steel rods and the wood screw are indicated.

out at 11 Hz. Records were taken after many consecutive cycles, because such records are consistent from test to test (cf. Bennett & Ker, 1990) and therefore provide clear comparison when the specimen is altered by cutting. (Note that the pendulum is restricted to a single impact analogous to the 1st cycle of an INSTRON test. First cycle records differ from those made later in a test run because heel pads are to some extent sensitive to mechanical setting of the material (Aerts et al. 1995). Stiffness of, and energy loss through, the frame could directly be measured by means of the INSTRON (tested at 2.2 Hz).

A series of in situ operations gradually freed the pads from the rest of the feet, finally resulting in isolated heel pad samples as used in previous investigations (Bennett & Ker, 1990; Aerts et al. 1995). At each stage, mechanical impact tests were carried out. These stages were: (1) foot intact; (2) plantar aponeurosis cut; (3) all ventral muscles cut (reaching the tarsal bones); (4) circumferential cut at the level of the next saw plane (reaching the calcaneus); (5) removal of the entire forefoot; (6) sawing of the calcaneus (the numbers refer to Fig. 1 *B*). For the tests at stage 6, on the isolated pads, the sawn surface of the calcaneus was glued to a flat plate. The pad of FOOT I was mounted on the artificial heel used in the spring tests (see above; impact velocity = 0.380 m s^{-1}). The pad of FOOT II was mounted on a steel plate and tested in the INSTRON as described by Aerts et al. (1995).

In a preliminary experiment, a 3rd lower leg (FOOT III) was tested by means of the pendulum setup (amputation due to malignant muscle tumour; male aged 37 y, weight unknown). For this foot, however, the successive operative stages to free the pad were not performed. After testing of the intact foot (impact velocity = 0.536 m s^{-1}), the calcaneus was immediately sawn (cf. stage 6 of FOOT I and FOOT II) and the pad was tested separately (impact velocity = 0.514 m s^{-1}).

The isolated heel pads of FOOT I and FOOT III were also used for the experiments described in Aerts et al. (1995), where they are described as PADS V and III respectively.

RESULTS

Panels *A* and *B* of Figure 2 show the superimposed load-deformation loops from stage 1 (intact foot) up to stage 5 (forefoot removed) for FOOT I and FOOT II respectively. Despite the difference in mechanical behaviour (due to the difference in the cycle number (see Materials and Methods) and the variations between specimens), the results are consistent: skin tension, tension from the plantar aponeurosis or any other mechanical stress from surrounding tissues on the heel do not affect the dynamic behaviour of the fat pad. All loops are basically on top of each other. This is further demonstrated by the small deviations of stiffness (linear measurement over the 200–400 N range of the loading phase; FOOT I: 198.4 kN $m^{-1} \pm 4.8$ kN m^{-1} S.D.; FOOT II: 504.2 kN $m^{-1} \pm 19.99$ kN m^{-1} S.D.), work spent in deformation (FOOT I: 0.71 J $\pm$ 0.00 J S.D.; FOOT II: 0.58 J $\pm$ 0.02 J S.D.) and percentage of energy dissipation (FOOT I: 89.2% $\pm$ 1.33% S.D.; FOOT II: 34.6% $\pm$ 2.06% S.D.). Within the resolution of the

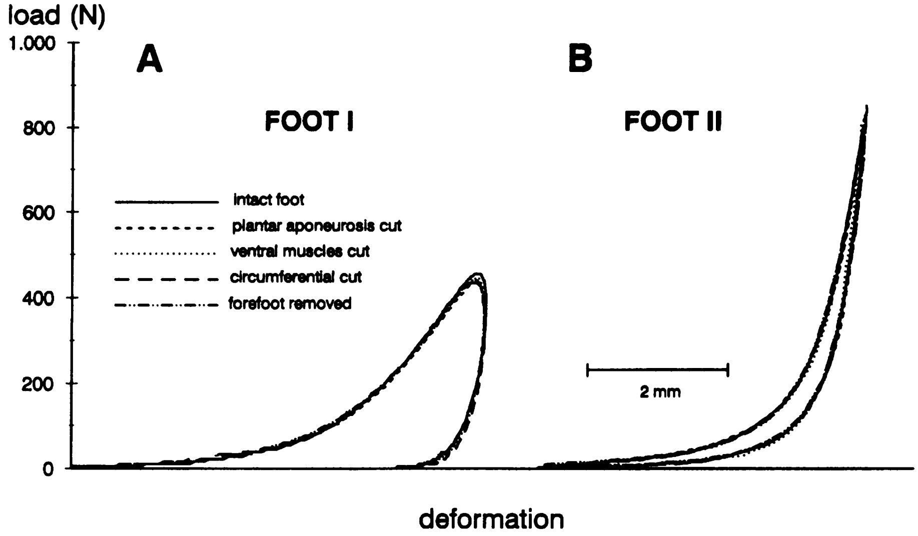

Fig. 2. Superposition of load-deformation loops obtained from tests at different stages of heel pad isolation (stages 1–5; see text) for FOOT I (*A*) and FOOT II (*B*).

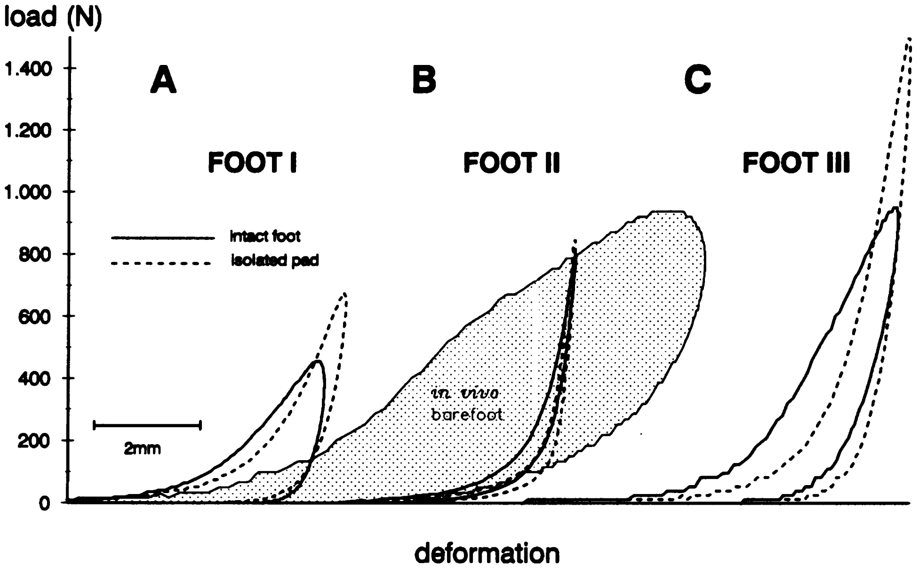

Fig. 3. Superposition of load-deformation loops from tests on the intact foot, mounted on steel rods, and on the completely isolated pad on a flat steel plate (stages 1 and 6; see text) for FOOT I (*A*), FOOT II (*B*) and FOOT III (*C*). A typical in vivo barefoot loop is added for comparison (from Aerts & De Clercq, 1993).

video image, movements of the calcaneus could not be detected.

Figure 3 shows the effect of the stage 6 operation (i.e. isolation of the pad by sawing the calcaneus) for the 3 feet. The load-deformation loops for stage 1 (intact feet) and stage 6 (isolated heels) are superimposed. (For comparison, an in vivo barefoot loop from the experiments described by Aerts & De Clercq (1993) is added). The loops of these stages no longer coincide. For all 3 feet, the stiffness over the 200–400 N loading range is considerably larger when the calcaneus is sawn (FOOT I: 303 kN m^{-1}; FOOT II: 876 kN m^{-1}; FOOT III: 380 kN m^{-1} vs 296 kN m^{-1} for the intact foot). For FOOT I only, the percentage of energy dissipation also changed considerably (FOOT I: 69% vs 89%; FOOT II: 38% vs 35%; FOOT III: 60% vs 67% for the intact foot).

Panels *A* and *B* of Figure 4 present the results of the compliance tests of the frame for the pendulum and the INSTRON setups, respectively. For the pendulum, a 147 kN m^{-1} linear steel spring was impacted on the frame (impact velocity = 0.40 m s^{-1}). The loading range obtained in this way is comparable to the foot tests. The stiffness (slope of the line on Fig. 4*A*) equals 144 kN m^{-1}, and the energy loss in the linear part (< 0.01 J) is much smaller than the total amount of work spent in deforming FOOT I (see

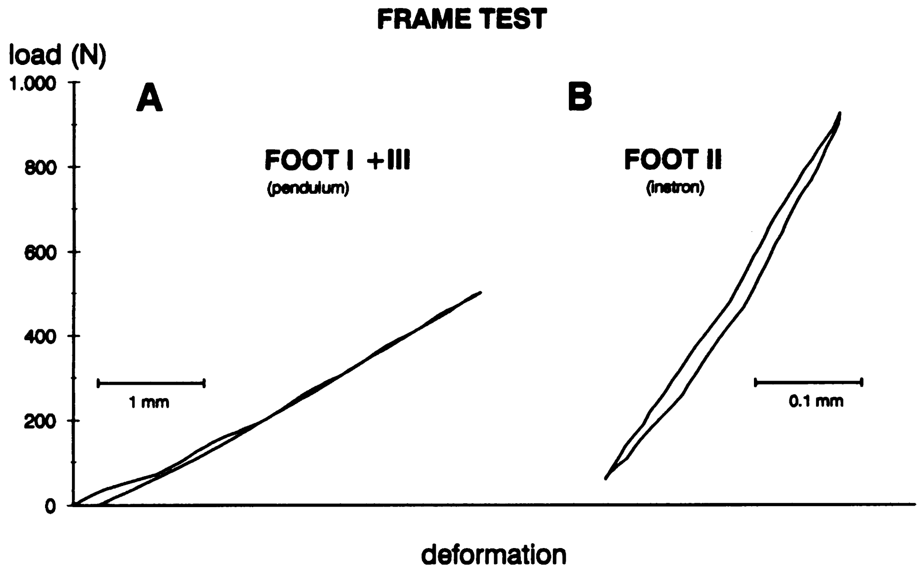

Fig. 4. Load-deformation loops of the mechanical tests on the supporting frames used in the pendulum (*A*) and INSTRON (*B*) tests (see text).

above). Note that the initial deviation from linearity is inherent to the construction of steel springs, because of the flattened outer windings. As the measured stiffness in fact represents that of the serially arranged construction of the spring, the frame and the wall, the 'frame + wall' stiffness can be estimated and equals about 7100 kN m^{-1}. For the INSTRON, the frame was loaded directly (2.2 Hz; loading range comparable to the actual foot tests). The stiffness of the construction (measured over the total loading range) equals 3900 kN m^{-1}, and again only about 0.01 J becomes dissipated (see Fig. 4*B*; compare with 0.58 J spent in deforming FOOT II).

DISCUSSION

Judging from Figure 2 it is obvious that removal of plantar forces (i.e. cutting the plantar aponeurosis and cutting the deep muscles), elimination of skin tension (circumferential cutting of the skin) and detaching the entire forefoot do not influence the mechanical behaviour of the heel pads. This is true for the first strain cycle (pendulum tests on FOOT I), as well as for a pad under repetitive loading (INSTRON tests on FOOT II). The suggestion that the mechanical behaviour of the heel pad might be codetermined by stresses arising from surrounding structures (see Introduction) is thus disproved. At stage 5 of the isolating procedure, the fat pad is completely free of the rest of the foot and is only kept in place by its firm attachment to the calcaneus. This means that the assembly of fat-filled, collagen reinforced chambers can be considered as an independent hydrostatic structure. The collagenous framework prevents bulk movements of the semifluid fat, even after the cuts have been made. This suggestion fits in with the observation by Bennett & Ker (1990) that even cutting the pad right away from the calcaneal bone does not alter the percentage of energy dissipation. Therefore, at this stage of isolation, sawing the calcaneus seems most unlikely to impose any effect on the pad configuration, and consequently on its mechanical properties.

Yet Figure 3 shows a marked effect on removing the steel rods from the foot and using instead a flat metal plate applied to the sawn surface of the calcaneal bone. What was happening became apparent when the pad of FOOT I, by then isolated from the rest of FOOT I, was retested on steel rods using the INSTRON. It was held, in its original position on the rods, by glueing the calcaneus back together again. Loads greater than 1 kN could not be applied. At this level the bone beneath the forward rod was crushed, elongating the hole in which the rod fitted. Distortion (compression) is inevitable at all loads and seems likely to have been significant. Clearly, this should be allowed for in asssessing the 'pad component' of the results shown in Figure 2. However, since this allowance is the same for each of the successive tests, the conclusion remains valid: cutting the soft tissues does not make a significant contribution to the difference between in vivo and in vitro results.

The trabeculae of the calcaneus are presumably arranged so as to effectively transmit the stresses arising from loads applied, in life, to the cortical shell (see, for example, Currey (1984*a*, *b*) for a discussion on the arrangement of trabeculae). This loading pattern will be better simulated by the tests with a plane cut surface against a flat steel plate, than by those with rods. In the rod tests, not only is the load concentrated on a small proportion of the bone, but also this bone is likely to be inappropriately arranged. It is therefore not surprising that the tests should lead to significant distortion within the bone. Starting from the stiffness values for the feet and the frames presented in Results, and assuming zero compliance for the calcaneus when sawn and glued to the steel plate (argued above), the extent of bone deformation can be very roughly estimated for the experiments with the feet mounted on the steel rods. Over the 200–400 N loading range, 32% (FOOT I), 30% (FOOT II) and 18% (FOOT III) of the total compliance can be assumed to be due to distortion of the bone under the rods.

Mounting the calcaneus on the steel bars should leave the general hysteresis relatively unaffected, as long as the strain imposed on the bony material allows a pure elastic response. This appears to be true for FOOT II and FOOT III. Sawing the heel bone in FOOT I, however, also reduces the percentage of energy loss very markedly (about 20%). This suggests that the stress-concentration is too high for the cancellous bone of this specific foot when it is only supported by the 2 transverse steel bars, and that energy is most likely lost in the formation of small cracks when impacted with the pendulum mass. Some arguments make this assumption plausible: FOOT I is small and slender compared with the 2 other feet, and the bony material might have been in an infirm condition (an elderly woman with vascular disease and possibly with osteoporosis). Both other test specimens belonged to younger men and were amputated for other reasons (accident and muscle tumour). It is assumed that the condition of these calcaneal bones was healthy.

Figure 3 also shows a noticeable difference between the loop shape of FOOT I and III on the one hand, and FOOT II on the other. It has to be stressed that this is not related to the distinct test procedures (pendulum versus INSTRON). Indeed, both experimental approaches on the isolated pads of FOOT I and FOOT III resulted in identical load-deformation loops (see Aerts et al. 1995). The divergence between the feet illustrated in Figure 3 (besides an expected biological variability) is largely due to mechanical settling of the heel pad, which readily occurs when it is loaded repetitively (see Aerts et al. 1995; the consequences of this phenomenon for human locomotion will be discussed elsewhere).

In conclusion, it can be stated that the elimination of interactions with adjoining structures by isolation of the heel pad does not alter its mechanical behaviour. These findings, together with the results presented in Aerts et al. (1995) establish that the output of dynamic in vivo tests of the human heel pad (e.g. Fig. 3) is largely influenced by the inherent incorporation of the entire lower leg in the test setup. Using information from such tests in an effort to describe or understand the in vivo function of the heel pad sensu stricto inevitably leads to misconceptions. Generally, stiffnesses as deduced from in vivo tests (typically 150 kN m^{-1} at body weight; cf. Aerts et al. 1995) can be estimated to be about one order of magnitude too low, whereas percentages of energy dissipation (75%–95% for in vivo tests) are about double those lost through the fat pad (see Bennett & Ker, 1990; Aerts et al. 1995). With respect to human locomotion, the load-deformation relation of the heel pads as described by Aerts et al. (1995) is the most appropriate to date.

ACKNOWLEDGEMENTS

We are grateful to Professor R. McN. Alexander for advice and encouragement throughout this work. We wish to thank Dr S. Crerand of the Royal Liverpool Hospital for his assistance in providing specimens. Dr J. Van Damme of the Biology Department of the University of Antwerp is thanked for his assistance in completing the illustrations.

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