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BONE DEFORMATION RECORDED IN VIVO FROM STRAIN GAUGES ATTACHED TO THE HUMAN TIBIAL SHAFT

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It is generally accepted that mechanical circumstances can profoundly influence the course of growth, remodelling and repair in bone. How this influence exerts itself is obscure and is unlikely to be clarified until more is known of the mechanical circumstances involved. A knowledge of these circumstances also becomes increasingly important as greater emphasis is placed on the internal fixation and prosthetic replacement of skeletal components.

Instrumentation of a bone's surface with strain gauges has made it possible to record bone deformation during various activities in animals (Lanyon & Smith 1970, Lanyon 1973, 1974). Such data are of limited significance being relevant only to a small area of the bone surface. However this method is the only one at present available which has produced direct information on how a bone responds to normal loading. The value of such information is to some extent determined by whether generalisations concerning this skeletal response in one species are applicable to others, in particular to man. In an attempt to determine the relevance of animal data to man it was decided to instrument part of the human skeleton using the techniques previously employed on experimental animals. The antero-medial aspect of the tibial midshaft was chosen for its surgical accessibility.

MATERIALS AND METHODS

A foil 45° rosette strain gauge was attached to the anteromedial aspect of the tibial midshaft of a 35-year-old, normal, active man 1.7 m in height, weighing 68 kg (W.G.J.H.). The gauge was prepared in a similar way to those used in the animal experiments previously mentioned.

The tissues overlying the proposed gauge site were infiltrated with local anaesthetic solution and an incision 10 cm long made down to the periosteum. A 15 mm square was removed from the periosteum, haemostasis was obtained, and the back of the gauge flooded with adhesive (isobutyl 2-cyanoacrylate monomer) before being pressed into position on the bone surface. The wires leading from the gauge were sutured to the periosteum and the wound closed leaving them to emerge from the proximal end of the incision. Within an hour of the operation the subject was walking and running on a moving belt machine. Recordings were then taken at this time and on the two subsequent days. On the third day the wound was reopened and the gauge removed.

The gauge recordings were actually a display of the change in resistance of the three separate elements of the rosette. These were interpreted in terms of strain by using the known relationship between change in the length of the gauge and change in its resistance (Gauge Factor). An indication of zero strain was obtained by recording the strain level when the limb was bearing no weight. This approximated to the level indicated during the period of slow strain change when the limb was in mid-swing (Figure 1). However, as the final positioning of the

Fig.1

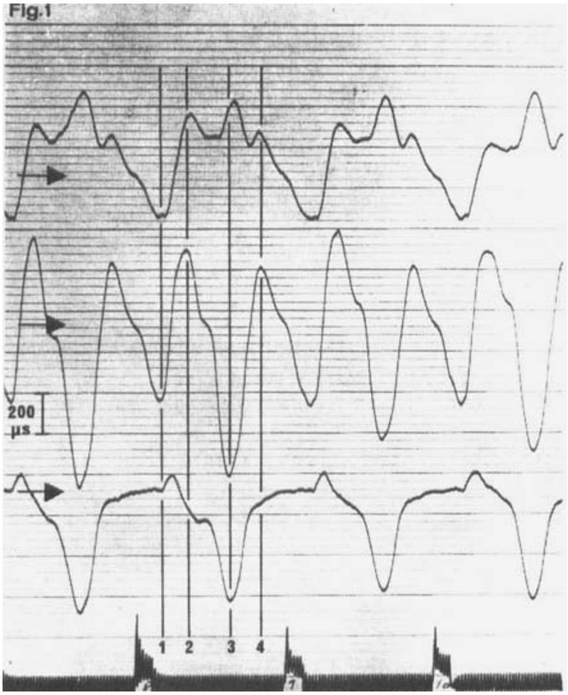

Figure 1. Part of the recording taken soon after the operation during walking at 1.5 m/s on the belt wearing shoes. The traces from the three gauges are shown, the zeros are arrowed. Points 1–4 correspond to those in Table 1 and in the analysis Figure 2.

Table 1. The mean and standard deviations of the principal compression (E_2) and tension to the tibia's long axis (θ_1) in degrees, calculated for a number of 1, 1 and 2, Figure 4). The maximum strain rate encountered during this typical value it refers. Tension is expressed positive, compression negative, the angle to the long

	Max. strain rate	1. Heel strike E_1	E_2	θ_1
Day 1. Belt walk, no shoes at 1.4 m/s	$-4 \times 10^{3*}$	73	—154	—85.5
Stride duration 0.97 ± .01 s		± 5	± 7	± 1
Day 1. Belt walk, with shoes at 1.5 m/s	$-3.37 \times 10^{3*}$	98	—178	—87.5
Stride duration 0.99 ± .01 s		± 5	± 6	± 1
Day 2. Floor walk, with shoes, no load	$-2.3 \times 10^{3*}$	64	—113	—83
Stride duration 1.08 ± .02 s		± 7	± 6	± 0.5
Day 2. Floor walk, with shoes and 27 kg	$-2.15 \times 10^{3*}$	58	—113	—84
Stride duration 1.03 ± .01 s		± 11	± 6	± 2
Day 2. Floor walk, with shoes and 45 kg	$-2.7 \times 10^{3*}$	43	—109	—82
Stride duration 1.10 ± .01 s		± 4	± 7	± 1
Day 2. Floor walk, with shoes and 71 kg	$+4.2 \times 10^{3*}$	41	— 89	—82
Stride duration 1.10 ± .01 s		± 10	± 6	± 1
			1. Toe strike	
Day 1. Belt run, no shoes at 2.2 m/s	$+11.75 \times 10^{3*}$	124	—220	—83
Stride duration 0.73 ± .02 s		± 12	± 18	± 1
Day 2. Belt run, with shoes at 2.2 m/s	$+13 \times 10^{3*}$	177	—300	—84
Stride duration 0.69 ± .01 s		± 11	± 13	± 1

zero line was subject to some error, indications of strain and strain angle at, or near, zero should be treated with suspicion.

The traces recorded during repetitive activities such as walking were treated as follows: using the estimated zero strain the strain level on all three gauges was measured at the four distinct inflections (1–4, Figure 1) for 10 consecutive cycles while walking on the belt, or for five consecutive cycles walking on the floor. By using standard formulae (Dally & Reilly 1965) the principal strains and principal angles were calculated for these positions (Table 1). A typical cycle was then chosen whose parameters fell as near as possible within one standard deviation of the mean for that recording. The strain levels during this cycle were measured and calculated for every 0.02 second interval (Figures 2–7).

Correlation of the subject's position and the gauge recordings was made possible by filming at 64 frames per second (Figure 5 ii).

the principal tension (E_1) expressed in microstrain, and the angle of the principal consecutive strides for the activities described at the points illustrated (1–4, Figure stride is given in microstrain per second; the asterisk indicates to which peak strain axis is given proximal to the gauge, postero-medial positive, antero-lateral negative.

2. Full foot-heel off			3. Heel off-toe off			4. Forward swing		
E_1	E_2	θ_1	E_1	E_2	θ_1	E_1	E_2	θ_1
254	—140	— 3	395	—434*	—53	35	— 34	+ 4
± 40	± 18	± 3	± 76	± 28	± 1	± 7	± 5	± 3
210	—104	+11	311	—368*	—54	171	— 98	+ 6
± 54	± 20	± 3	± 40	± 44	± 1	± 7	± 6	± 1
128	— 82	+20	237	—308*	—52	92	— 67	+ 9
± 12	± 14	± 1.5	± 18	± 21	± 1	± 7	± 11	± 0.5
185	—106	+16.5	328	—393*	—51	137	—104	+15
± 42	± 21	± 2.5	± 22	± 26	± 1	± 23	± 29	± 1
241	—131	+13	366	—412*	—50	162	— 96	+11
± 27	± 21	± 2	± 81	± 98	± 1.5	± 21	± 13	± 1
387*	—224	+12	341	—425	—49	196	—113	+13.5
± 49	± 36	± 1.5	± 51	± 57	± 1.5	± 18	± 14	± 1
2. Toe strike-toe off								
847*	—578	— 4						
± 59	± 31	± 3						
746*	—450	— 5						
± 64	± 37	± 3						

RESULTS

The results presented concern the strain gauge recordings taken during the subject's locomotion both on the moving belt and on the floor. The traces illustrated in Figure 1 were obtained while he was walking on the belt within an hour of the operation. The analysis of such traces (Figures 2 and 3) shows the changing principal strains and strain angle during typical strides walking on the belt with and without shoes. The strain angle illustrated is that of the principal tension relative to the tibia's long axis proximal to the gauge. The postero-medial direction is expressed as positive and the antero-lateral direction as negative. By definition the principal compression acts at 90° to the principal tension at all times.

The overall pattern of deformation change during a walking stride appeared to occur in four definite phases. Two of these were during the

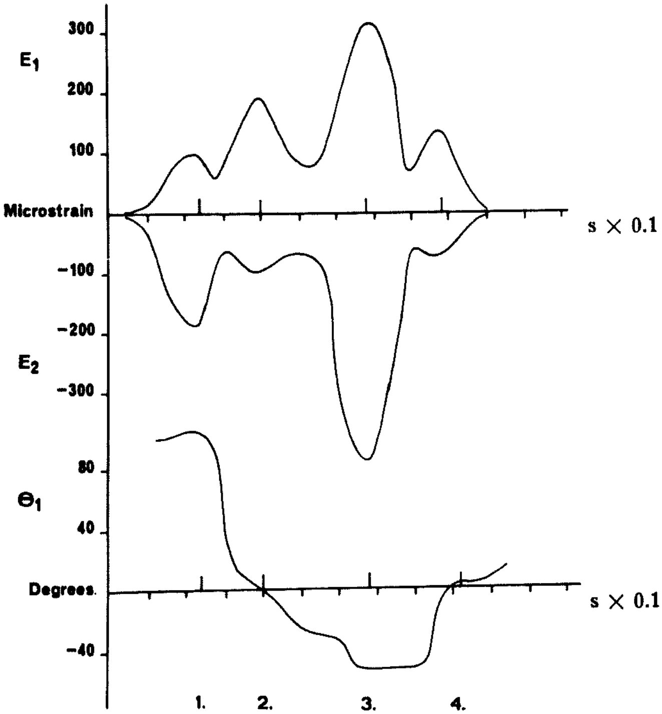

Figure 2. Analysis of the recordings in Figure 1 to show the changing principal strains E_1, and E_2, and the angle of the principal tension to the bone's long axis (strain angle, θ_1) during one stride. The points 1–4 correspond to those in Figure 1.

limb's swing period, one at the end, prior to 'heel strike', and one at the beginning as the limb was swung forward. During the one prior to 'heel strike' the principal compression was larger than the principal tension and practically in line with the long axis (Table 1). During the swing forward this was reversed. The remaining two deformation phases occurred during the stance period of the limb. The first was between 'full foot' and 'heel off', during which time when walking on the belt the direction of the principal tension crossed that of the bone's long axis. The second was between 'heel off' and 'toe off' when the angle of the principal tension to the long axis remained a constant – 53 to – 54 degrees.

The wearing of shoes made the deformation cycles more definite and discrete. The amount of deformation was increased during the swing period phases and decreased during those when the foot was on the ground.

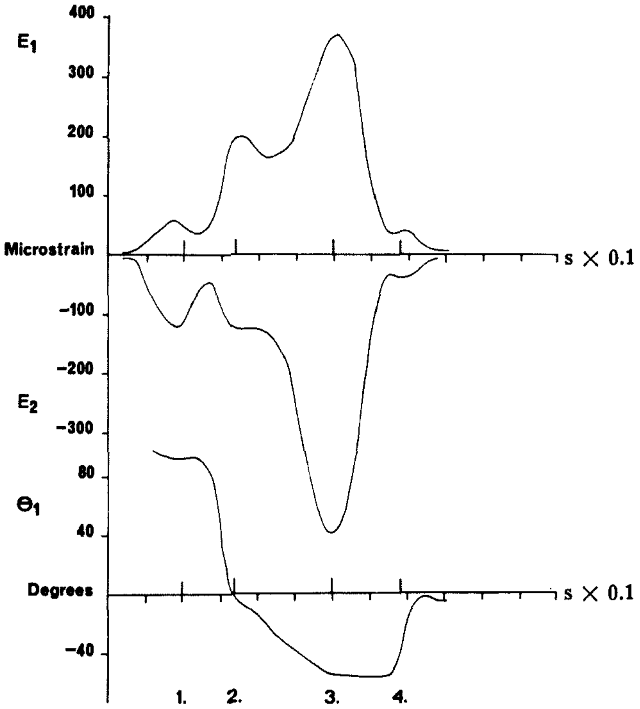

Figure 3. Analysis to show the changing principal strains and strain angle during one stride walking on the belt without shoes at 1.4 m/s soon after the operation. The points 1–4 correspond to those in Table 1 and Figures 1 and 2.

Table 1 shows the principal strains and the strain angle calculated for the four distinct inflexions illustrated on the original gauge traces (Figure 1, 1–4). These coincided approximately with the principal strain peaks. The maximum strain rate given was the maximum increase per second which occurred in either principal strain at a constant angle during the typical stride of that particular recording.

In addition to walking on the moving belt the subject walked on the concrete floor with and without a rucksack containing various loads. Figure 5 i shows the analysis of a stride taken on the floor, wearing shoes but carrying no load. The strain change pattern differed from those obtained on the belt in that the strain angle between 'full foot' and 'heel off' remained more constant. This seemed to be a real difference between walking on the floor and on the belt; it was not related to the speed of walking, nor in subsequent cine film analysis

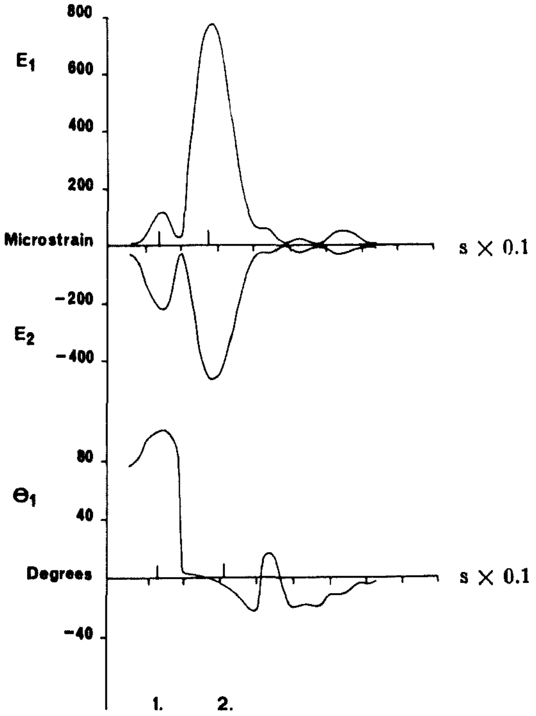

Figure 4. Analysis to show the changing principal strains and strain angle during one stride running on the belt without shoes at 2.2 m/s soon after the operation. The points 1 and 2 correspond to those in Table 1.

have we been able to observe any gross difference in the positioning of the leg during a stride on a moving and non-moving surface.

Figures 6 and 7 show the analyses of strides taken while walking on the floor under increasing loads. The angle change pattern remained practically the same, the amount of deformation increased especially during the stance periods. The greater increase occurred during the mid-stance phase between 'full foot' and 'heel off'. Under a load of 70 kg, this became larger than the 'toe push' phase.

It was not possible to run on the floor with trailing wires so this was done only on the moving belt. Figure 4 shows the analysis of a stride taken during such a run without shoes. Only two deformation cycles of any size occurred. One of these was at the end of the swing phase prior to 'toe strike' and differed little from that which in the walks occurred prior to 'heel strike'. The other, during the stance phase was much larger, the deformation reached a maximum mid-way between

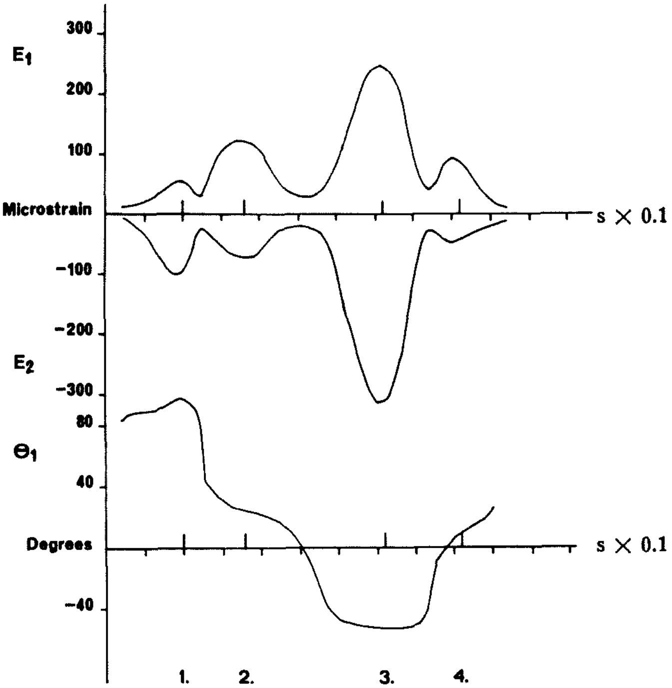

Figure 5 i. Analysis to show the changing principal strains and strain angle during a single stride while walking on the floor the day after the operation wearing shoes but carrying no load.

‘toe strike’ and ‘toe off’. At this time the principal tension, which was the larger principal strain, was aligned along the bone’s long axis.

Recordings were taken during these and other activities over a period of three days. Qualitatively there was no change in deformation pattern over this time. The amount of deformation however was less by about 25 per cent on the second and third days than on the first.

DISCUSSION

At best the results presented relate solely to the strain at the surface of a small area of the tibia in one individual. In addition although the directional and comparative data should be valid the quantitative data have not been substantiated in absolute terms. We have assumed that the changes in dimensions of the gauge reflected those which occurred in the bone beneath it. Although this is standard engineering procedure the bonding of strain gauges is usually done under more favourable

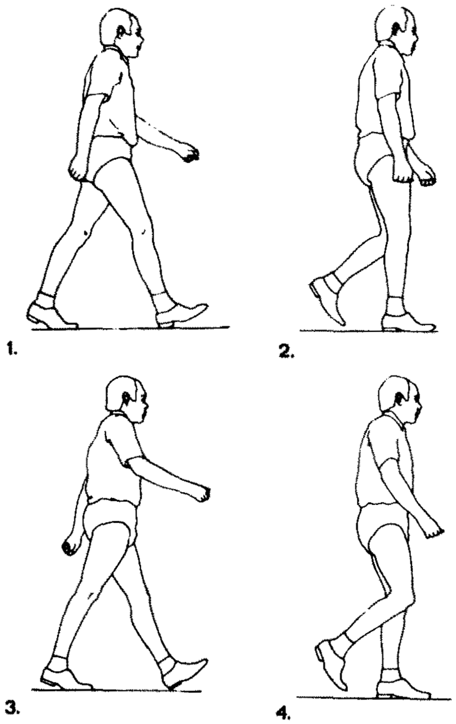

Figure 5 ii. The man's position as taken from cine film at the points 1–4 in Figure 5 i. These correspond to those in Table 1 and Figures 1–3.

conditions than those existing *in vivo*. In our previous experiments the most common results of faulty technique have been defective bonds between gauge and bone and/or pulling on the lead wires. Both of these give misleading recordings but it has usually proved possible to detect the difference between the aberrant results produced under these conditions and those obtained from a gauge which is satisfactorily attached. In this experiment there were no grounds for suspecting any such unreliability in the recordings. Working on the assumption that they were reliable and considering the extent of the surgical interference necessary for the experiment it was not considered justifiable to repeat it for the sake of duplicate results. Our intention was not to investigate the human tibia *per se* but only to establish whether generalisations concerning the loading conditions of bone in other species were at variance with those in man.

Moving belt walking has the great experimental advantage of

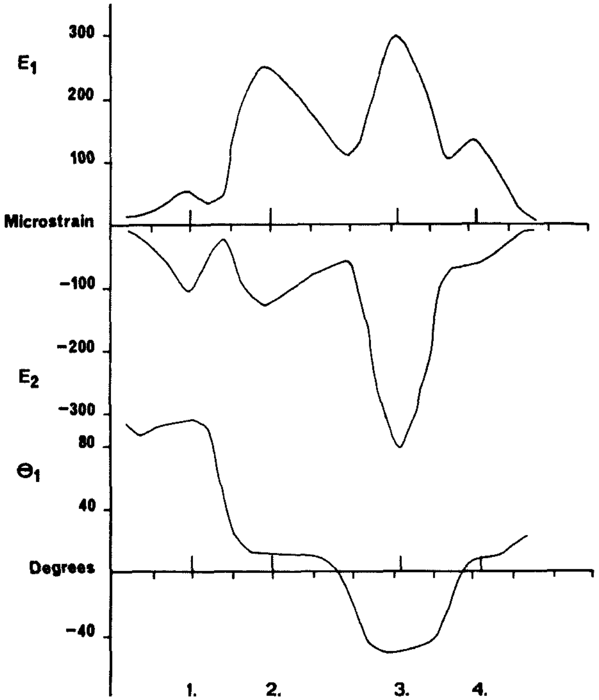

Figure 6. The analysis of a single stride while walking on the floor, wearing shoes, and carrying 27 kg. Points 1–4 correspond to those in Table 1 and Figures 1–5.

allowing the subject a lengthy period of locomotion at a variety of speeds while still connected by wires to the recording apparatus. However, although no obvious difference in gait was detectable from the films of the subject walking on a moving or a non-moving surface, there was a consistent difference between the two in the strain angle change during the mid-stance period. No comparison was possible between running on the belt and the floor; however, alterations in the movement of the centre of gravity such as those reported by Nelson et al. (1972) would probably be reflected in differences in the mechanical circumstances of the limbs. In these respects at least, conveyor belt walking must be considered abnormal.

The reduction in amount of deformation over the three days of the experimental period is unexplained. Possibly the bone-gauge bond was weakening, although there were no obvious signs that it had done so when the gauge was removed. Possibly also on the first day, with the operation site still partially anaesthetised, the subject's walking was

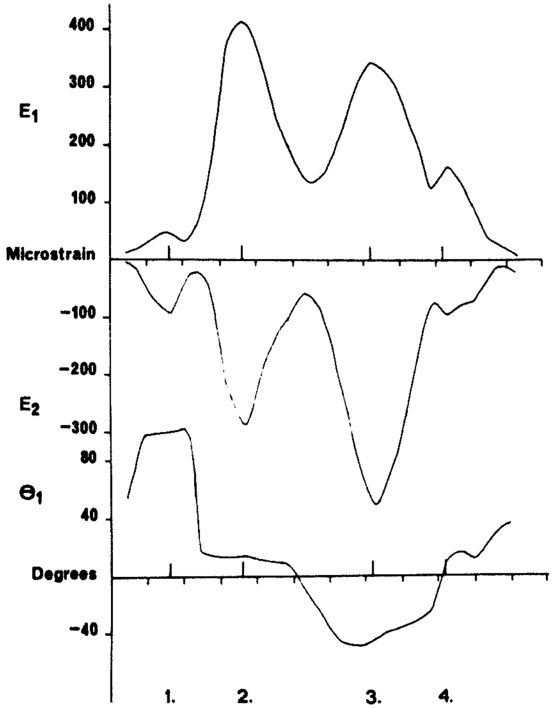

Figure 7. The analysis of a single stride while walking on the floor, wearing shoes, and carrying 71 kg. Points 1–4 correspond to those in Table 1 and Figures 1–6.

more definite than on the subsequent days when more reaction was present.

The differences between wearing and not wearing shoes were distinct and constant. Presumably their extra weight on the end of the limb could contribute to the increased deformation recorded during the swing period, and their cushioning effect to the decrease during the stance period.

Of greater significance than these variations is the fact that each stride was not characterised by a gradual progression or continuum of loading conditions but rather it consisted of a series of discrete events during each of which the bone was deformed from a particular direction, released at least partially, and then loaded from another direction.

The deformation was presumably the result of the combined effects of muscle pull and body weight. However the tibia's orientation with respect to gravity was under continual change throughout the stride while the strain direction was not. This implies that during each deformation phase there was an alteration in the strength and direction of muscle pull at least as fast as that in tibial alignment. Between phases this alteration was much faster.

The existence of a series of definite angles at which any particular piece of bone is customarily deformed has some experimental implications. If in the laboratory it is required to reproduce physiological loading of skeletal fragments there are certain directions in which this should be done which do not necessarily coincide with the bone's overall axis or that of its tissue. However if the customary strain direction in cortical bone does have some orienting effect on bone architecture the tissue direction should bear some consistent relationship to it. Unfortunately little is known at present of the mechanisms by which continued intermittent deformation influences bone structure and so the relative importance of large or small deformation cycles and the significance of their alignment is at present speculative. Except for knowing that mechanical conditions are 'important' we know nothing of which aspect of them is relevant and how it acts.

The amounts of deformation and the strain rates encountered in this experiment are directly comparable to those in similar experiments on animals. The deformation phases with constant loading directions are another feature common to both. It is probable that any information obtained in such experiments on animals will have a common significance to man.

SUMMARY

A strain gauge rosette was attached to the midshaft of a man's tibia. This demonstrated that during every stride the bone surface was subjected to a number of discrete deformation cycles. During each cycle the bone was deformed from a particular direction, released at least partially and then deformed from another direction.

This feature has been observed from a number of sites in experimental animals.

The largest deformation occurred while the subject was running; the principal tension then reached 850 microstrain applied in line with the bone's long axis at 13×10^3 microstrain per second. When walking the largest deformation occurred prior to 'toe off'; compression was then the larger principal strain about -400 microstrain applied at 37° to the bone's long axis at -4×10^3 microstrain per second. These strain values are the same order of size as those recorded from the long bones of sheep and pigs during their locomotion.

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