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BONE STRAIN IN THE TIBIA DURING NORMAL QUADRUPEDAL LOCOMOTION

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Many studies have been made on the mechanical response of bone and bones to forces applied to them. These have frequently involved the removal of a small sample from the body, its reduction to a convenient shape both for mathematical analysis and for handling in a test machine, and its subjection to various loads (Ascenzi, Bonucci & Checcucci 1966, Cooke 1955, Coolbaugh 1952, Currey 1959, Dempster & Coleman 1961, Evans & Lebow 1952, Evans & Bang 1966, Forssblad 1959, Sedlin & Hirsch 1966, Semb 1966, Smith & Walmsley 1959, Weaver & Chalmers 1966).

Other investigations have been carried out using whole bones either *in situ* or removed from the cadaver and denuded of their surrounding tissues (Evans 1953, 1957, Evans & Lissner 1948, Evans, Lissner & Patrick 1962, Evans, Lissner & Pedersen 1948, Gurdjian & Lissner 1944, 1945, Hirsch & Brodetti 1956, Hirsch & Evans 1965, Kalen 1961, Lissner 1964, Lissner & Roberts 1966, Martz 1956, Stevens & Ray 1962).

These investigations involved stressing the bone artificially and studying its response in various ways. Many of these workers used strain gauges either bonded to a test piece (Forssblad 1959, Frankel & Burstein 1964), to the isolated bone, (Gurdjian & Lissner 1944, Hirsch & Brodetti 1956, Hirsch & Evans 1965) or to the bone *in situ* (Evans et al. 1962, Lissner 1964, Lissner & Roberts 1966). Evans (1953) mentions the use of strain gauges as a possible method of measuring strain *in vivo* and cites an experiment, the results of which seem to be unpublished, in which he, Coolbaugh, and Lebow bonded a gauge to the tibia of a dog. Lissner bonded gauges to the vertebral bodies of dogs and human cadavers during ejection seat trials. Kilpatrick (1967) mentions some unpublished experiments where gauges were bonded to living bone. But apart from a short preliminary report (Lanyon & Smith 1969) no results appear in the literature from gauges implanted into a living animal which would record the bone's behaviour in its normal biological and mechanical environment.

To gain any relevant understanding of the behaviour of bone as a skeletal unit, it is essential that it be studied under these conditions. The scrutiny of fracture types or their experimental production (Evans 1957, Hirsch 1954) yields information concerning the forces within the living system at the instant of failure, but these circumstances are patently not normal. To obtain information regarding the response of various parts of the skeleton to the forces they normally encounter, it was decided to implant gauges into the living animal and subsequently study their behaviour during normal locomotion.

The medial aspect of the tibial shaft was a suitable gauge site for preliminary work since it is readily accessible and has no muscles attaching to it. It could also be expected to have a characteristic strain pattern during locomotion closely related to the movements of the hind limb.

Sheep were used as experimental animals, as they are a convenient size for handling, anaesthesia presents no special problems, and they do not require any complicated husbandry. Once trained they will readily walk on a moving platform; long trailing wires and a large work space are thus not necessary and filming is made much easier.

METHOD

In the initial experiments polyester-backed wire strain gauges with a gauge factor of 1.9 were used in a D.C. bridge circuit. (In tension or compression, strain is the change of length per unit length, $\delta L/L$. The gauge factor is the ratio between change in electrical resistance and change in length, gauge factor $= \delta R/R \,/\, \delta L/L$.) Although results were obtained with this apparatus, it was plagued with many problems which were eliminated by transferring to an A.C. system and semiconductor strain gauges whose gauge factor was fifty times as great (100). These consisted of a U-shaped semiconductor strain-sensitive element encapsulated in an epoxy-bonded glass fibre carrier.

The gauge wires from each arm of the U were soldered to PTFE (poly-tetra-fluorethylene) covered leads of silver-plated copper wire. The soldered joint was protected by a slightly flexible epoxy resin coating (Prepot No. 1, Fleming Services, Cambridge) expanded laterally to form two flanges just proximal to the gauge. Another flange was moulded round the leads 1 cm proximal to the first. At their other ends the leads were connected to a multipin socket embedded in an epoxy resin casting. In this way all connections were protected from their environment.

Several gauges were implanted at a time. One of these instead of being fixed to the tibia was bonded to a piece of stainless steel and placed near the others. Although under similar conditions, it would not be attached to any stress-bearing structure. From the behaviour of this "dummy" we hoped to be aware of any conditions, other than strain, which cause an alteration in gauge resistance.

Each unit consisting of "active" and "dummy" gauges, leads, and multipin socket was disinfected by a low temperature steam and formaldehyde process (Alder et al. 1966).

The sheep were operated on under general (Halothane) anaesthesia. A small incision was made in the flank to receive the epoxy-embedded multipin socket and another longer one to expose the medial surface of the tibial shaft. The gauges were fed along a polythene tube connecting the two incisions which, when removed, left the leads in place.

The tibial periosteum was reflected and the gauge site, after being carefully wiped, was treated with surface activator (X83/272 Ciba (A.R.L.) Ltd.,Cambridge). Once this had evaporated, the adhesive (Isobutyl, 2-cyanoacrylate monomer, Ethicon Ltd.) was applied to the undersurface of both gauge and flanges and these were speedily pressed in position. The monomer rapidly polymerized if the gauge site had been properly prepared. Each "active" gauge was treated in the same manner. The periosteum was sutured and the "dummy" gauge positioned nearby. The wound was then closed.

Healing was good; the animals, although lame for twenty-four hours and favouring that limb for a few days, walked perfectly soundly within a week.

A bony outgrowth and dense fibrous tissue reaction developed where the periosteum had been reflected. However this did not seem painful and served to hold the leads firmly in place.

Once walking soundly, the sheep, which had been previously trained, was put on the moving platform. A multipin plug was attached to the socket in the animal's flank so connecting the implanted gauges to transducer meters (C.52. Boulton Paul Aircraft Ltd., Wolverhampton). Each gauge formed one arm of a bridge circuit; any change in its resistance produced an out-of-balance signal across the bridge. The output from the transducer meters resulting from this signal was fed via suitable filters to the galvanometers of an ultra-violet recorder. Thus the strain pattern from each gauge was instantly recorded as the animal walked.

In addition to the gauge trace, signals were recorded from a small variable inductance accelerometer strapped to the dorsal aspect of the middle phalanges. From the shape of the trace that this instrument produced we could determine the phase of the stride. To ensure that the accelerometer was providing a reliable indication of limb movement and to allow for more detailed analysis a slow motion film (64 frames per second) was also taken.

Paper trace and film were synchronized with the aid of a large clock face which was included in the photographic field. An eccentric cam on the hand-shaft triggered a micro-switch once every revolution, causing a bulb on the clock face to flash and a spike to appear on one of the recorder channels. By this means any incident on the film could be accurately timed on the traces and vice versa.

RESULTS

Varying numbers of semiconductor and wire resistance strain gauges were implanted during ten operations.

Figure 1. The trace of an "active" gauge bonded to the medial aspect of the right tibia of a walking animal and a "dummy" bonded to a piece of stainless steel and positioned nearby. Below these is the trace from the accelerometer strapped to the right hind limb.

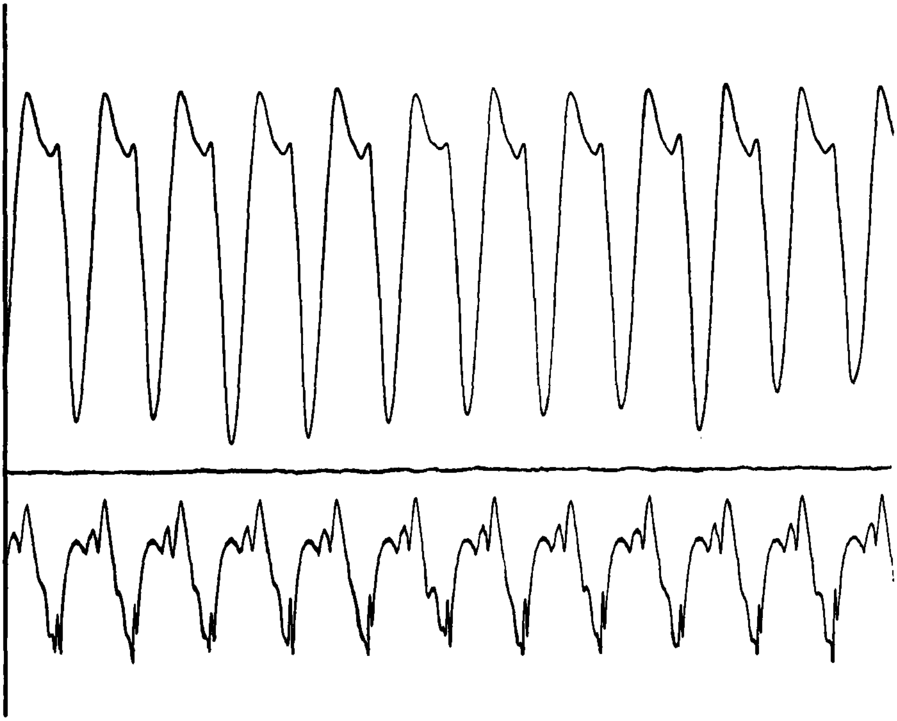

Figure 2. The trace from the same gauges taken during trotting. The accelerometer trace is also shown.

The traces shown (Figures 1 and 2) are typical and were obtained from one animal during walking and trotting on the moving platform. Traces from both "active" and "dummy" gauges are shown; the "active" gauge was bonded to the cranio-medial aspect of the midshaft of the right tibia. The "dummy" gauge was positioned nearby. Whilst the "dummy" trace shows no response to the animal's movement, the "active" trace conforms to a regular pattern related to the movement of the limb as indicated by the trace from the accelerometer strapped to it.

This was a constant and expected finding during these experiments; any pattern present in the "dummy" trace produced by a gauge supposedly not subjected to any change in strain would have been an artefact and would have undermined confidence in the reliability of the "active" traces.

Traces were reproducible daily over a period of two or three weeks after which the animals were killed. Many similarities existed between strain patterns from different sheep; naturally differences existed also. Although all gauges were orientated along the long axis of the bone, no effort was made to use exactly the same gauge site. In any case there was considerable individual variation in the style of gait shown by each animal.

In some cases results became erratic and were no longer considered reliable. If this occured the experiment was terminated. The commonest cause of failure was fatigue fracture of the leads usually near the femoro-tibial joint where they were subjected to continual bending. Damage to the insulation, failure of soldered joints, and deterioration of the bond caused failure in some cases.

Once removed from the cadaver all tibiae were placed in a test apparatus where a rhythmical bending force could be applied to the midshaft, both ends of the bone being supported. Results obtained *in vivo* were only considered reliable if the gauge traces so obtained conformed to the expected sine curve pattern thus producing qualitative evidence that the gauges were still accurately responding to bone strain.

From a frame-by-frame analysis of the slow motion film it was shown that the trace conformation was related not only to movements of the test limb but also to those of the other limbs as weight was distributed amongst them. This is shown in Figures 3 and 4. During walking when the right hind foot (test limb) was seen to contact the ground (Figure 3, point 1) there was an immediate tensional rise on the trace which reached its peak just before the sole of the left hind foot was seen to lift (Figure 3, point 2). The compression imposed

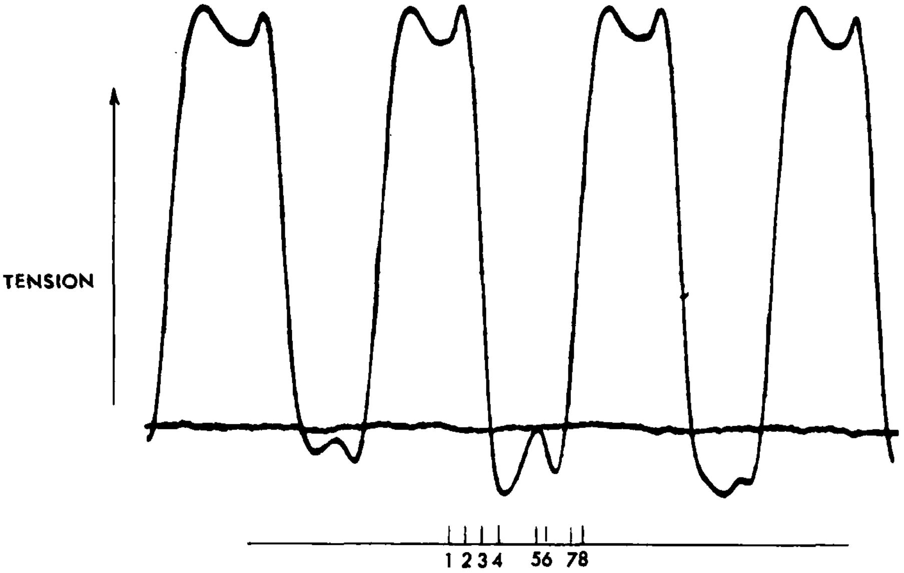

Figure 3. Analysis of a trace obtained during walking. The numbered instants correspond to those in the text and to the numbered illustrations in Figure 4.

upon the tibia during the consequent diagonal support phase was only halted when the right fore foot was placed to the ground (Figure 3, point 4).

This transitory triangular support phase was terminated when the left foot was lifted (Figure 3, point 5) leaving a right unilateral support. The resulting transfer of weight to the test limb coincided with a reimposition of compression. By now this limb was nearing the end of its stride. The contralateral hind limb was placed on the ground (Figure 3 point 6), allowing a compressional release which continued during the initial part of the swing phase (Figure 3, point 8) and appeared to overshoot before returning to the level immediately preceding the foot being replaced on the ground.

A trot consists of alternate diagonal support phases. With the absence of any complicated transference of weight during triangular and unilateral support phases, there is no inflexion at the base of the compressional period which occurs on the walking traces. The overshoot following the release of compression during the swing phase is similar to, but more exaggerated than, that which occurs during walking.

The total change in strain (trace height) occurring during at least 10 consecutive strides was measured on the daily recordings. The overall

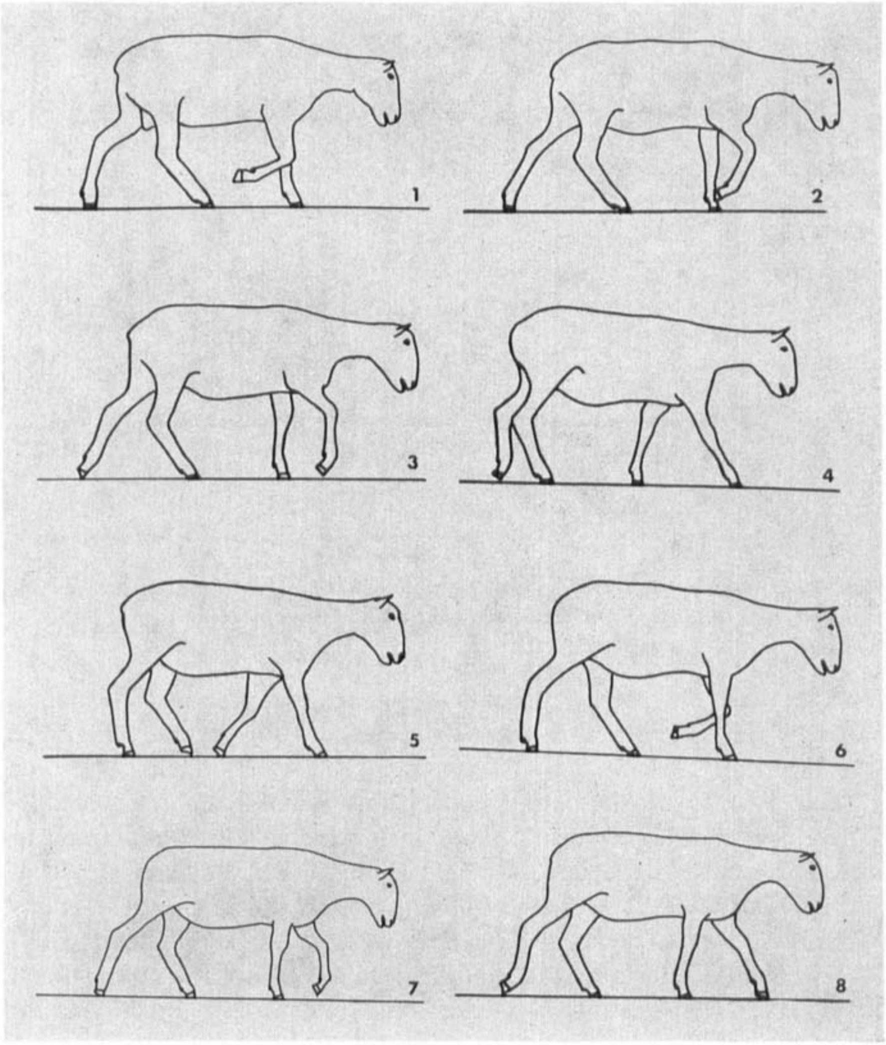

Figure 4. (1) Right hind foot (test limb) contacts the ground, triangular support phase. Small initial tensional phase on the trace. (2) Sole of left hind foot lifts. Period of sustained compression begins. (3) Left hind limb enters its swing phase. Compression continued. (4) Right fore foot placed on the ground, triangular support phase. Some release in the compression. (5) Left fore foot leaves the ground, right unilateral support phase. Compression reimposed. (6) Left hind foot placed on the ground, triangular support phase. Period of sustained compressional release begins. (7) Sole of right hind foot lifts. Compressional release continues. (8) Right hind limb enters its swing phase. Compressional release continues and overshoots before the foot again contacts the ground.

average from the 4th–28th day postoperatively is shown in Table 1. The reasonably large standard deviation for this figure is related to the changing conditions over the experimental period. Although appearing to walk soundly by the 4th day, it is unlikely that full weight was placed on the limb so soon. Inevitably the animal gained confidence and walked more easily as the experiment progressed. The daily trace height increased until the 14th day and then gradually diminished. The average figure for five-day periods at the beginning, in the middle, and at the end of the experiment are shown. The decrease in value from 14th–28th day is probably associated with deterioration in the bone-gauge bond.

Table 1. Sheep S. 11

		Mean trace height microstrain	Standard deviation
Walking			
Per day overall	4th–28th day inclusive	262	40.3
Per 5-day period;	4th– 8th day	238	12.3
	14th–18th day	317	13.9
	24th–28th day	221	23.3
Trotting			
Per day overall	12th–28th day	305	51.3
Per 5-day period;	14th–18th day	353	17.9
	24th–28th day	255	28.6

1 microstrain is 1 × 10^{-6} cm/cm.

DISCUSSION

The significance of findings from one gauge in one position can only be of limited value in determining the stress patterns existing in the bone. The strain-sensitive elements were only 2 mm by 0.5 mm and could only respond to the strain in the small area of bone to which they were bonded. For a complete analysis, theoretical predictions of the strain pattern that would be expected should be made and these verified by experimental means. This would entail many gauges being bonded to selected sites on any one bone.

Until some knowledge is available concerning the working loads of various skeletal components and their response to them, design for their artificial replacements can only be based on surmise assisted by theoretical computations of forces due to body weight, muscle pull, etc. which of necessity so simplify the picture as to be of doubtful value unless supported experimentally. The large and variable forces exerted by muscles on small areas of bone must produce an extremely complicated stress pattern.

Although in this report bone strain has been related to weight-bearing alone, the greatest potential source is muscular. The massive local deformation that culminates in fracture is in many cases the result of uncoordinated muscular action.

Confidence in the experimental method and realization of its limitations are essential. The existence in these experiments of constant strain patterns from day to day with similarities between animals is encouraging. From the qualitative experiment described on the isolated tibia, we know that the gauges do respond to bone strain. However, not yet having any quantitative means of verification, we were greatly concerned that changes in bone strain might not be the only stimulus. Great care was taken in the use of two flanges, each bonded firmly to the bone, to eliminate any effect of the leads pulling on the gauge and producing false indications of strain. If this lead pull occurred one would expect large signals during the time that the leg is undergoing its most violent movement, i.e. the swing phase. In our experiments no great change of strain was indicated during this phase.

If it is assumed that the only variable producing a signal is strain in the bone, there is still the possibility that the magnitude of strain indicated is far less than actually occurs. If the bond is not transmitting 100 per cent of the strain, then the gauge cannot respond to it. Even if the strain values in different experiments seem to agree, this may only indicate the maximum efficiency of bonding possible and not actual bone strain. To test the efficiency of the bond in this respect, it is necessary to develop a quantitative method of calibration, the gauge must be removed with the piece of bone to which it is bonded and strained to a known extent. Difficulties arise in machining the piece of bone and not disturbing the attached gauge; calibration and test would not be under identical conditions, one *in vivo* and one *in vitro,* and even with a machined test piece computation of the actual strain in the gauge area may be inaccurate.

Although much confirmatory work has yet to be done, we believe that this approach will yield valuable basic information concerning the response of the skeleton to its mechanical environment which has not been available using less direct techniques.

SUMMARY

A method has been reported which enables *in vivo* recordings of bone strain to be made in the walking animal.

Semiconductor strain gauges have been used on the tibia of sheep to develop this technique and the incidental results showing the strain pattern from one gauge on the medial surface of the midshaft are illustrated.

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