Acta orthop. Scandinav. 42, 102–112, 1971

Lecturer in Veterinary Anatomy, University of Bristol, England.

STRAIN IN SHEEP LUMBAR VERTEBRAE RECORDED DURING LIFE

L. E. Lanyon

Received 28.vi.70

It has been demonstrated that the mechanical response of skeletal structures varies drastically with the type of stress to which they are subjected. The response to a dynamically applied load is vastly different from that to a static one (Evans, Lissner & Pedersen 1948, Hirsch & Nachemson 1954), and the modulus of elasticity of bone as well as its ultimate yield strength are not constant (Sedlin 1965). The conditions encountered in the live animal are inevitably complex, and attempts to simulate their effect on test beds without any reasonable concept of their nature are bound to produce results at best speculative, at worst misleading.

A method whereby direct measurement of bone deformation could be achieved within an ambulatory animal was first suggested by Evans (1953), although it is only recently that results from such investigations have appeared (Lanyon & Smith 1969, 1970, Lanyon 1969). Strain gauges were bonded to the bare bone surface and recordings monitored from them over a period of weeks. The reliability of this approach was first verified by attaching gauges to the tibial shaft of sheep. Subsequent work involved a series of implantations using the bodies of thoracic and lumbar vertebrae as gauge sites in the same species.

Each vertebra has a complex shape, but it is the body and the arch which must be responsible for the longitudinal transmission of load. Of these the body, joined to its neighbours by intervertebral discs, is probably the more important. It was thought that a study of strain patterns in the vertebral bodies should cast some light upon the magnitude, direction, and frequency of the forces transmitted along the column.

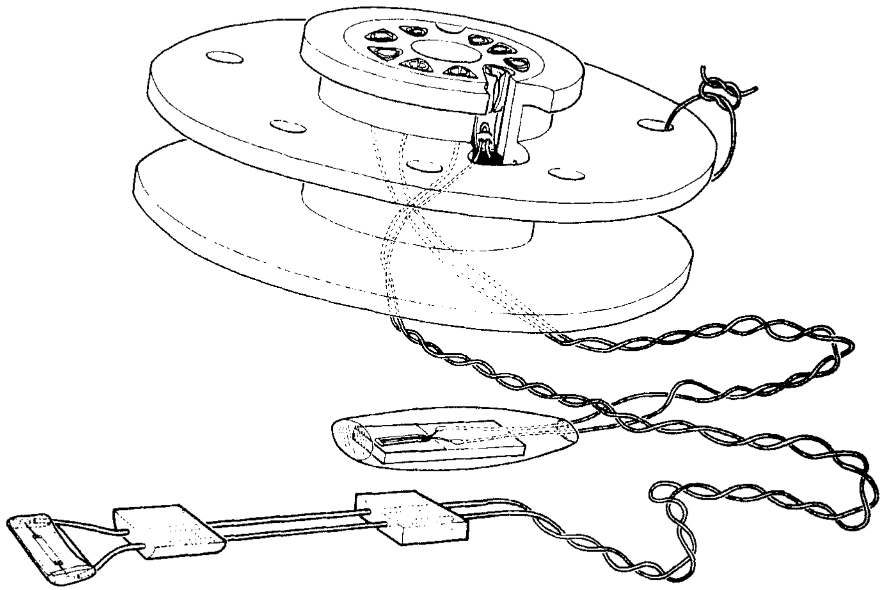


Figure 1. Schematic diagram of a gauge unit similar to those implanted during this series. The gauge to be bonded to the vertebral body is shown in the foreground, its lead wires passing through two epoxy resin flanges, one of which was attached to the vertebral body, the other to the underside of the transverse process. A 'dummy' gauge bonded to stainless steel is also shown; both these are connected by the PTFE covered wires to the epoxy resin flank plug and its inserted electrical socket.

METHOD

Each unit included a multi-pin electrical socket embedded in an epoxy resin (Araldite CT. 200, CIBA) casting so shaped as to be conveniently sutured into the skin of the animal's flank (Figure 1). This socket was connected by PTFE covered lead wires to the semi-conductor gauge element which was supported in an epoxy resin impregnated glass fibre carrier. (The principle of strain gauge function requires that the strain sensitive element, in this case a semi-conductor strip, be attached so closely to the underlying structure that it deforms as if part of its surface. This deformation causes a change in the gauge resistance which can be sensed and displayed when connected to appropriate apparatus.)

The soldered joints between the gauge wires and the lead wires were protected by slightly flexible epoxy resin cast around them. (Prepot No. 1 Fleming Services, Cambridge). Flanges were also made of this substance and moulded round the leads just proximal to the gauge. These were to be bonded to the bone to prevent any pull from the wires being transmitted to the gauge. The upper surface of the gauge was covered with a layer of silicon rubber (Silcoset 100, I.C.I.).

In addition to the bone-bonded gauges it was usual to implant a 'dummy'

Table 1. Overall daily average trace excursion in micro-

	S. 23			S. 25		
	Left side	Right side	Duration	Left side	Right side	Duration
At rest	*	15±7	2.4 ±0.4	9±3	28±10	1.2 ±0.7
After exercise	9±2	25±7	2.0 ±0.4	9±1	27±4	1.1 ±0.1
Slow walk	49±11	159±23	0.86±0.12	36±9	138±13	0.77±0.06
Medium walk	51±8	131±14	0.72±0.05	47±18	144±18	0.67±0.02
Fast walk	61±8	153±11	0.61±0.02	50±12	156±17	0.62±0.03
Slow trot	67±12	215±50	0.54±0.06			
Medium trot	74±18	196±25	0.51±0.02	49±9	189±25	0.48±0.03
Fast trot	81±20	223±34	0.49±0.09			

* Too small to measure.
1 microstrain is 1×10^{-6} mm/mm.

gauge bonded only to a piece of stainless steel. Originally these 'dummies' were used to assess whether there were any factors arising from *in vivo* implantation which could cause alteration in gauge resistance unconnected with deformation. The absence of such factors had been established many times, but the 'dummy' gauges provided a useful check on equipment under certain circumstances.

The vertebral bodies were reached by retroperitoneal dissection after making a vertical flank incision through the skin and abdominal muscles. Adhesive solution (isobutyl 2-cyanoacrylate monomer, Ethicon Ltd.) was placed on the underside of the gauge and flanges, which were then speedily pressed into position on the previously prepared site. The wound was closed and the flank plug sutured into the skin incision. The whole unit of gauge, wires, and flank plug had been sterilised prior to implantation by a low temperature steam and formaldehyde process (Alder et al. 1966).

Each animal had been trained previously on a moving platform conveyor belt machine. Although lame for one or two days postoperatively, they recovered remarkably well and seemed to walk and trot perfectly soundly by the third or fourth day.

When recording, the implanted gauges were connected via the socket in the animal's flank to transducer meters (C. 52, Boulton Paul Aircraft) with a 1 K cycle/sec carrier frequency whose D.C. output was transferred to an ultraviolet recorder (5–127, Bell & Howell). As the animals moved on the conveyor belt, recordings of the strain change patterns during their various activities were taken. This was done daily for some two weeks, after which the animals were killed, *strain and duration in seconds during various activities.*

S. 28			S. 29		
Left side	Right side	Duration	Left side	Right side	Duration
17±4	17±5	2.4 ±0.4	11±3	21±6	2.7 ±0.5
21±2	24±3	2.4 ±0.4	15±3	26±6	2.3 ±0.4
115±17	296±27	1.07±0.04	48±9	163±15	0.93±0.04
133±18	268±28	0.87±0.05	58±8	173±14	0.82±0.04
150±27	281±31	0.74±0.02	79±12	227±22	0.71±0.02
216±27	487±60	0.55±0.02	90°	216	0.52

° Satisfactory on one day only.

the vertebrae with their attached gauges dissected out, and these tested to ensure that there was good adhesion between gauge and bone and a faithful response to externally applied loading.

A purely qualitative assessment of reliability was made by imposing lateral, dorsal, ventral, and axial compression on the isolated vertebrae to establish that the strain response indicated by the gauges conformed to the expected pattern. The quantitative results quoted (Table 1) were calculated on the premise that the gauge-bone bond was perfect, and that gauge deformation accurately represented bone deformation. Thus the results are certainly comparable from animal to animal, given the same conditions of bonding, but it has not been proved that the quantitative assessments of strain values are an absolute measurement of *in vivo* bone deformation: they may only represent the maximum strain possibly transmitted by this bond.

RESULTS

Eight gauges were attached to the bodies of lumbar vertebrae in four sheep (S. 23, S. 25, S. 28, S. 29). The gauges were bonded to either side of the same or adjacent vertebrae at two operations separated by three or four days. This allowed for full recovery and enabled traces to be obtained during locomotion from the first gauge before the second was implanted.

The animals were exercised daily, recordings of strain change patterns being taken from both gauges simultaneously during the various activities. Loading of the vertebral column is likely to be affected by many factors, some unobservable and many, such as movements of the head, which although obvious are difficult either to quantify or record. However, to allow comparison between results from different animals, it was necessary to have some data on their behaviour at the time. Despite the inadequacy of recording only respirations when the animal was standing still, and limb movements during locomotion, it was obvious that there was a close correlation between these and the strain change patterns obtained. Respirations were recorded manually with an event marker, thus indicating the approximate occurrence and duration of inspiration and expiration. Slow motion cine film (64 frames per second) was taken during locomotion and later studied frame by frame.

The strain change patterns occurred in obvious cycles repeated with every respiration or stride. The quantitative results (Table 1) were obtained by measuring the total excursion of each of these. This movement, in fact an indication of the change in gauge resistance, could be expressed in microstrain using the known relationship between this and gauge deformation.

Traces obtained from all four animals during respiration showed a similar pattern which consisted of a fairly sharp compressional period at the beginning of inspiration, with a subsequent tensional recovery which merged into a period of slow strain change during observed expiration (Figure 2). Eructation, bleating, coughing, or any other movement completely obliterated this regular pattern. In general the traces from the two sides were perfectly in phase, although recordings from S. 23 at times showed some dissimilarity producing an out-of-phase response. However, some facets of the locomotory results from this animal were equally at variance with the norm of the other three, and perhaps therefore, although interesting, this idiosyncrasy should not be pursued. After exercise the cyclical pattern remained similar, and the rate and depth of respirations were naturally increased with a consequent increase in the frequency and level of bone strain recorded. The animals were not forced and they were not panting when these recordings were taken. In general the strain change recorded from the gauge on the right side indicated greater deformation than that on the left (Table 1).

The two gaits studied on the moving platform were the walk and

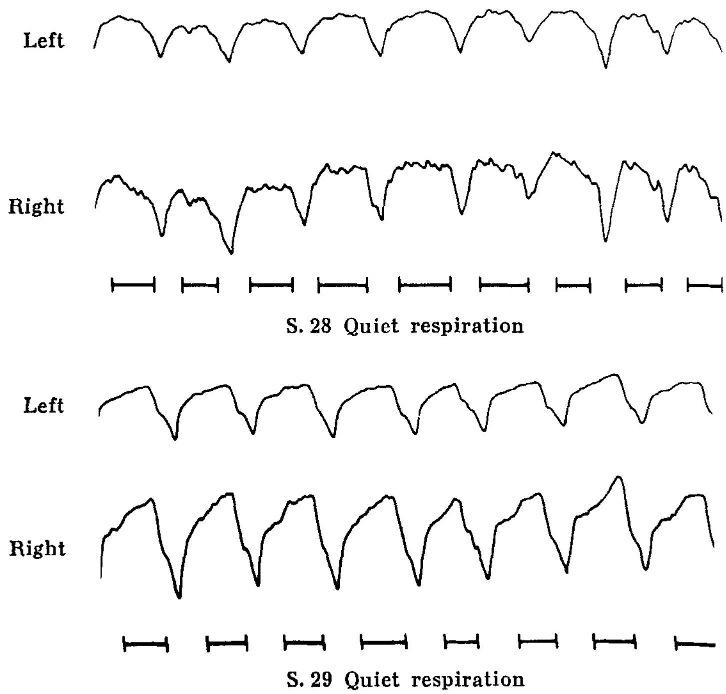
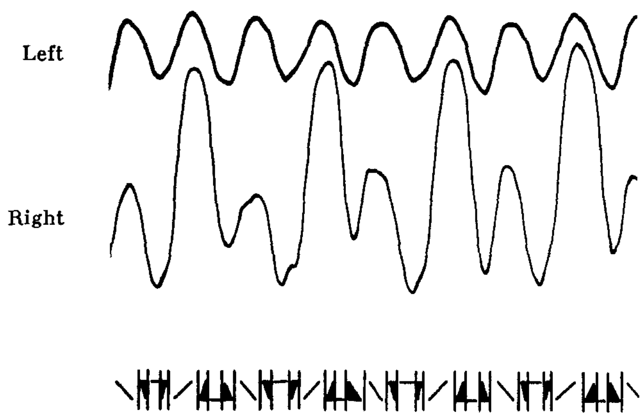
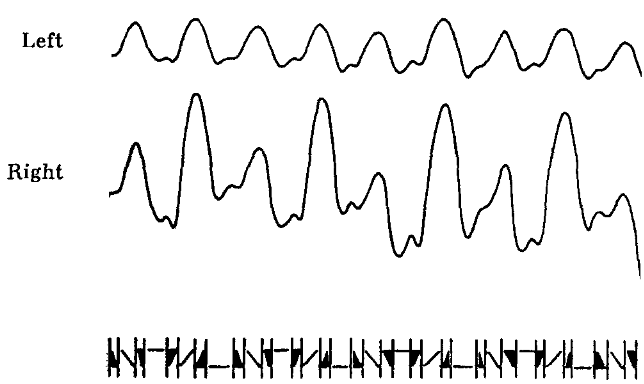


Figure 2. Part of the recordings of strain change patterns obtained from S. 28 and S. 29 when standing still. The duration of expiration, as observed from the abdominal wall and manually marked with the event marker, is indicated by the solid line beneath the various traces. In each case the trace from the left gauge is uppermost, tension is indicated in an upward position, compression downward. The period of slow strain change coincided with observed expiration, the compressional movement with inspiration, and the subsequent tensional recovery merged with the slow strain change period.

the trot. The patterns of support inferred from the slow motion films are shown beneath the relevant recordings (Figures 3 and 4) and allow comparison between animals. A normal quadrupedal walk consists of diagonal and ipsilateral support phases separated by intervening triangular ones. These become shorter as the pace increases until the animal breaks into a trot, which is a sequence of alternate diagonal supports. The inevitable irregularities of gait, even using trained animals walking in a straight line, are evident. During free natural locomotion they must be far more profound. It was assumed for convenience that a limb bore no weight once the sole of its foot could be seen lifting.



S. 28 Walking



S. 29 Walking

Figure 3. Part of the recordings of strain change patterns obtained from S. 28, S. 29 while walking on the moving platform. In each case the trace from the left is uppermost, tension is in an upward direction, and the pattern of support is shown beneath. The similarities in trace conformation and its relation to support can be seen.

The comparison of trace conformation with support pattern revealed considerable similarities between animals. In general during the walk, triangular support phases with one hind-foot off the ground led to ipsilateral support periods during which compression occurred. Triangular support periods with one fore-foot off the ground led to diagonal support periods, and during these tension occurred. Thus, for each complete stride consisting of two diagonal, two ipsilateral, and four intervening triangular support periods, there were two tension-

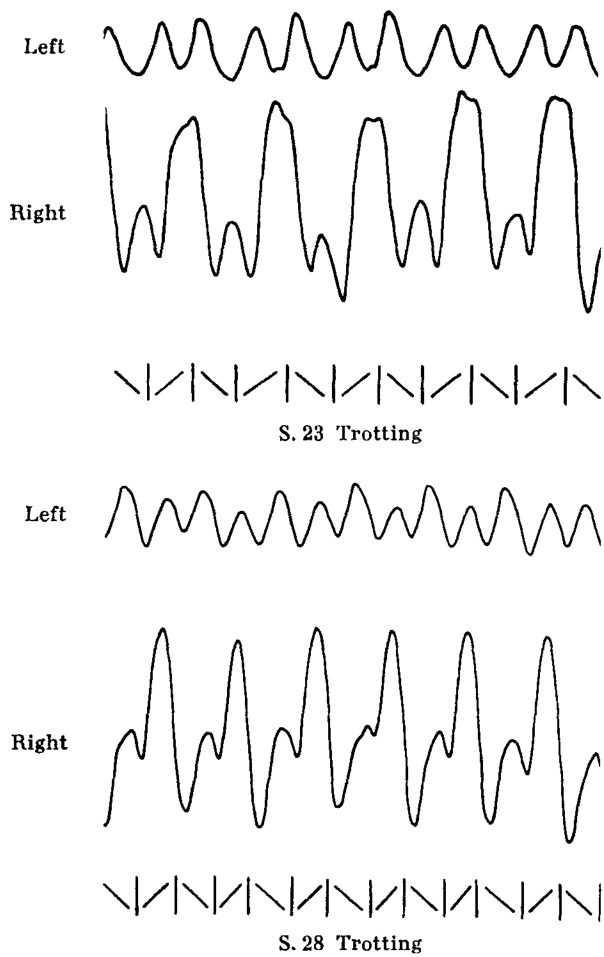


Figure 4. Part of the recordings of strain change patterns obtained from S. 23 and S. 28 during trotting. The similarity between animals was most evident at this simple gait.

compression peaks. On the left side these tended to be of equal size, whereas on the right side one was much larger than the other, the dominant tensional phase occurring during the diagonal support period involving that hind-limb. The total trace excursion, or strain change, was always larger on the right side than the left. For S. 25, although there was the same large discrepancy in size between total strain change indicated on the two sides, the trace conformation was more similar from one side to the other, there being a large period of tension during the diagonal support involving the hind-limb of the side concerned, and a small period during the opposite diagonal period.

The unexpected appearance of any discrepancy in strain change pattern and shape between two sides of the same or adjacent vertebrae caused us to suspect the validity of the experiment. It was thought that perhaps walking on the treadmill induced some asymmetrical emphasis which would be eliminated if they were allowed to walk free or loosely led on a halter. Having the animals attached by long trailing wires was not feasible, so a small radio transmitter was constructed which allowed transmission of information from one implanted gauge at a time when the animal was walking or trotting on the ground, uncluttered by any impedimenta except a small package strapped to its back (Lanyon, in preparation). This only confirmed the findings already mentioned while emphasising the difficulty of achieving regular results from an animal moving freely or loosely led.

The vertebrae concerned, with their gauges still attached and undisturbed, were tested post-mortem to establish the reliability of the bone-gauge bond.

Whereas axial compression resulted in a very small deformation for a large load, asymmetric loading, or loading the articular processes, could result in large deformations, say compression on one side, with a small tensional change on the other. By loading asymmetrically just with the hands—usually through the two adjacent bones to maintain the skeletal unit as intact as possible—it was easy to reproduce the size of signal recorded during life.

DISCUSSION

The use of strain gauges bonded to skeletal components yields information directly that would otherwise be unavailable. However, its value is limited, being only applicable to deformation in one direction in the small piece of the surface of the structure to which the strain sensitive element is adherent. The stress distribution within a vertebra is reflected by its complex shape; thus a small number of gauges cannot yield sufficient data to do more than provide a limited picture of probable loading conditions, the nature and origin of which remain speculative.

It has been confirmed that bone is a plastic structural component deforming under comparatively light loads both *in vivo* and *in vitro*. The delicacy of the skeletal response to apparently small changes in direction or magnitude of these is striking and indicates the great gulf that exists between the natural mechanical environment of skeletal components and that to which they are subjected in laboratory tests. The discrepancy found between longitudinal strain measured on the two sides of a single vertebral body was previously unsuspected, although possible sources of asymmetry in the region are easy to find.

Only a small difference in the direction of stress on the two sides would be necessary to produce a large effect in terms of the strain change patterns recorded. Post-mortem tests indicated that end to end compression of the vertebral bodies elicited a larger response from the right side than the left. If the loading of the two sides had been differently aligned during life, one would have expected some adaptation to minimise deformation in the direction in which it occurred.

Although specific findings such as those mentioned are interesting, the significance of this type of experiment lies in the verification of a technique whereby the frequency and order of strain which bone undergoes during various activities may be evaluated. Appreciation of these 'normal strain limits' is of considerable importance in any study of osteogenesis, since it seems increasingly likely that electrical activity, possibly the result of such intermittent deformation, provides one of the more important stimuli to bone growth, regeneration, and modelling.

The concept of a normal, constant, reasonable strain level and frequency, maintaining the architectural status of bone, fits well with existing knowledge of events occurring when it would be expected either to be exceeded or not attained. Once this level has been established in ambulatory animals, the way is paved for determining by relevant dead tests the possible origins and dimensions of the loads involved. Thus the service conditions of prostheses and the fundamental properties of bone may be assessed within realistic limits and not arbitrarily chosen ones.

CONCLUSIONS

A series of experiments was performed attaching strain gauges to either side of the bodies of the same or adjacent lumbar vertebrae in sheep as part of a regional mechanical survey of the vertebral column. The results showed extremely similar strain change patterns between the different animals during respiration and locomotion at various speeds. They also showed that the two sides of the vertebral column seem to be subjected to loads which differ in size or orientation. On the evidence from these animals, it was considered unwise at this stage to attempt any detailed analysis on the origin of the loads involved.

These experiments, which demonstrate the reliability of a technique allowing direct instrumentation of areas of the skeleton, are capable of threefold exploitation.

Firstly, to gain detailed information on the mechanical environment of specific areas pinpointed by clinical experience.

Secondly, to allow study of one of the fundamental stimuli for bone development and remodelling.

Thirdly, by establishing the working environment of skeletal structures to allow these, and their prosthetic replacements, to be tested under realistic conditions.

ACKNOWLEDGEMENTS

My thanks are especially due to Dr. R. N. Smith for his considerable help, co-operation, and encouragement. I am most grateful to Professor Messervy and his staff in the Department of Veterinary Surgery for their help and especially for that given by Dr. Barbara Weaver who anaesthetised the animals. I thank Miss Mary Kear for her help during the operations and afterwards, and Mr. M. A. Coombs and the technical staff of this Department for their assistance.

Ethicon Ltd. kindly provided the isobutyl 2-cyanoacrylate monomer. The project was financed by the Agricultural Research Council.

REFERENCES

Alder, V. G., Brown, Anne M. & Gillespie, W. A. (1966) Disinfection of heat sensitive material by low-temperature steam and formaldehyde. *J. clin. Path.* **19**, 83–89.

Evans, F. G. (1953) Methods of studying the biomechanical significance of bone form. *Amer. J. phys. Anthrop.* **11**, 413–435.

Evans, F. G., Lissner, H. R. & Pedersen, H. E. (1948) Deformation studies of the femur under dynamic vertical loading. *Anat. Rec.* **101**, 225–241.

Hirsch, C. & Nachemson, A. (1954) New observations on the mechanical behaviour of lumbar discs. *Acta orthop. scand.* **23**, 254–283.

Lanyon, L. E. (1969) Measurement of natural bone strain in the mammalian vertebral column. Ph. D. thesis, Bristol.

Lanyon, L. E. & Smith, R. N. (1969) Measurements of bone strain in the walking animal. *Res. Vet. Sci.* **10**, 93–94.

Lanyon, L. E. & Smith, R. N. (1970) Bone strain in the tibia during normal quadrupedal locomotion. *Acta orthop. scand.* **41**, 238–248.

Sedlin, E. D. (1965) A rheologic model for cortical bone. *Acta orthop. scand.* Suppl. 83.