J. Biomechanics Vol. 18, No. 1, pp. 1–7, 1985.
Printed in Great Britain

0021–9290/85 $3.00 + .00

MEASUREMENT OF SURFACE DEFORMATION OF SOFT TISSUE

IAN STOKES and DAVID M. GREENAPPLE

Department of Orthopaedics and Rehabilitation, University of Vermont, Burlington, VT 05405, U.S.A.

Abstract—A method is described for measuring the surface shape and deformations of soft tissue in three dimensions. The method uses close range stereophotogrammetry to record the three-dimensional locations of miniature optical targets applied to the tissue surface. This has been applied to study of the human lumbar intervertebral disc. Measurements of the strain along surface annular fibers have been made under varying loads. In this case the maximum expected errors are about 0.15 mm, which corresponds to a strain of less than 1 %. Preliminary findings have differed from predictions made in published mathematical models for the disc in that they show very little strain of the annulus in compression loading, but confirm axial torsional loading as liable to produce mechanical disruption of the disc annulus.

INTRODUCTION

Soft tissues in general have mechanical properties which are anisotropic and these tissues are incorporated into structures which have complex shapes and are subjected to complex patterns of loading. Hence, in studying the mechanics of the structures, displacement measurements by means of linear displacement transducers may produce findings which are difficult to interpret. A recent report (Arms *et al.*, 1983) showed that a miniature linear displacement transducer applied to different locations on the medial collateral ligament of the knee demonstrated highly variable deformations of the tissue depending on the region being tested.

This is a report of a method for recording the surface deformation of intervertebral discs. It probably has applicability to many other soft tissue structures. The intervertebral disc has a highly organized structure in its annulus with fibers in a criss-crossed formation, arranged in lamellae. The intervertebral disc is a remarkable structure in that it provides a high degree of flexibility for angular deformation while also having the capability to carry very large compressive loads. It appears that compressive load is carried predominantly by the central part of the disc (the nucleus pulposus) and the annulus which surrounds the nucleus is responsible for containing this high pressure. *In vivo* measurements of pressure within the nucleus pulposus by Nachemson (1960) were consistent with this model since the pressure within the nucleus was found to be about 1.5 times the mean compressive stress applied to the disc. However, measurements of pressure in the region of the annulus (Horst and Brinckmann, 1981; Ranu *et al.*, 1979) have not absolutely confirmed this concept. Part of the problem is the composite nature of the soft tissues in which the stress applied to the tissue is not necessarily the same as the hydrostatic pressure generated in its fluid component. Mathematical models (Broberg and von Essen, 1980; Hickey and Hukins, 1980) have helped to define these interactions. In these models the nucleus region is considered to be subjected to hydrostatic pressure, while the fibers of the annulus elongate and thus generate a tension force whose radial component contains the nuclear pressure.

The mechanism by which tension is developed in annular fibers is dependent upon disc bulging in most cases. For pure compression of the intervertebral disc, the two ends of an annular fiber would approximate axially by the amount of the disc compression while bulging of the disc would tend to create a longer path for the fiber between its two attachment points. Tension would result if the bulging effect were greater than the effect due to the approximation of the end points. This is a report of stereophotogrammetric method for studying these effects on the surface layer of the annulus fibrosus.

Photographic and optical methods have been used previously for studying deformation of soft tissues. Woo *et al.* (1979) stained the surface of articular cartilage with bands and used an optical technique (using a TV camera) to record the distance between these bands. This is essentially a one-dimensional measurement of deformation. Butler *et al.* (1983) cinephotographed ink bands on tendons and fascia to study the deformation under changing loads. A two-dimensional method was described by Hoffman *et al.* (1981) who photographed miniature steel spheres which had been glued to the surface of a joint capsule. By photographing this array of surface markers, the two-dimensional pattern of deformation of the structure was recorded. Klein *et al.* (1983) studied intervertebral disc surface deformation by an indirect method. They recorded, simultaneously, the compression and the amount of radial bulge of rabbit intervertebral discs, by photography. Using a simple mathe-

Received July 1983; *in revised form* 17 *July* 1984.
Supported in part by NIH Grant AM R23 29678

matical model for the presumed pathway of the annular fiber, they were able to calculate that compressive loading of the disc produced minimal strain of the surface fibers. The bulging of human intervertebral discs has been studied by Shah *et al.* (1978), Reuber *et al.* (1982), and by Brown *et al.* (1957) who all used one-dimensional, contacting methods for studying deformation. They did not make deductions about the tissue strains associated with the deformations.

METHOD

The technique described here uses close range stereophotogrammetry to record, in three dimensions, the locations of selected points on the soft tissue surface. The arrangement of the apparatus is shown in Fig. 1. Two cameras (Olympus OM1, Zuiko MC 50 mm lenses) were directed towards a spine preparation mounted in endfittings and positioned in a mechanical testing machine. The imbedding material was a dimensionally stable dental plaster (Whip-Mix Corp., Louisville, KY). The spine preparation consisted of two vertebrae with the intervening intervertebral disc, after removal of the posterior elements and the longitudinal ligament of the spine. This dissection permitted a clear view of the posterolateral part of the annulus which was the region of the disc of special interest in this study (Fig. 2). The viewing angle between the cameras was about 60°. The cameras were focused on surface microtargets which had previously been glued to the disc surface by means of cyanoacrylate cement. Illumination was by a 1 kW modelling lamp. The targets were placed along the supposed line of an annular fiber. This line was quite easily visualized, especially under manual torsion of the specimen. The visualized lines ('fibers') were seen to make an angle of about 60° with the longitudinal axis of the spine, as noted previously (e.g. Hickey and Hukins, 1980). Normally, seven microtargets were used to mark the 'fiber'. The targets were standard photogrammetric checkered targets which had been photo-reduced and printed onto 'Kodak RC' photographic paper. The miniature targets were then punched out of the photographic paper by means of the sharpened tip of a no. 16 spinal needle. The microtarget image within the thin emulsion layer of the photographic paper separated from the paper backing during this process. The tip of this needle had been prepared by firstly grinding it flat and subsequently mounting in a lathe and tapering the inside and outside of the needle to produce a sharpened circular cutting edge. The resulting microtargets were about 0.8 mm in diameter.

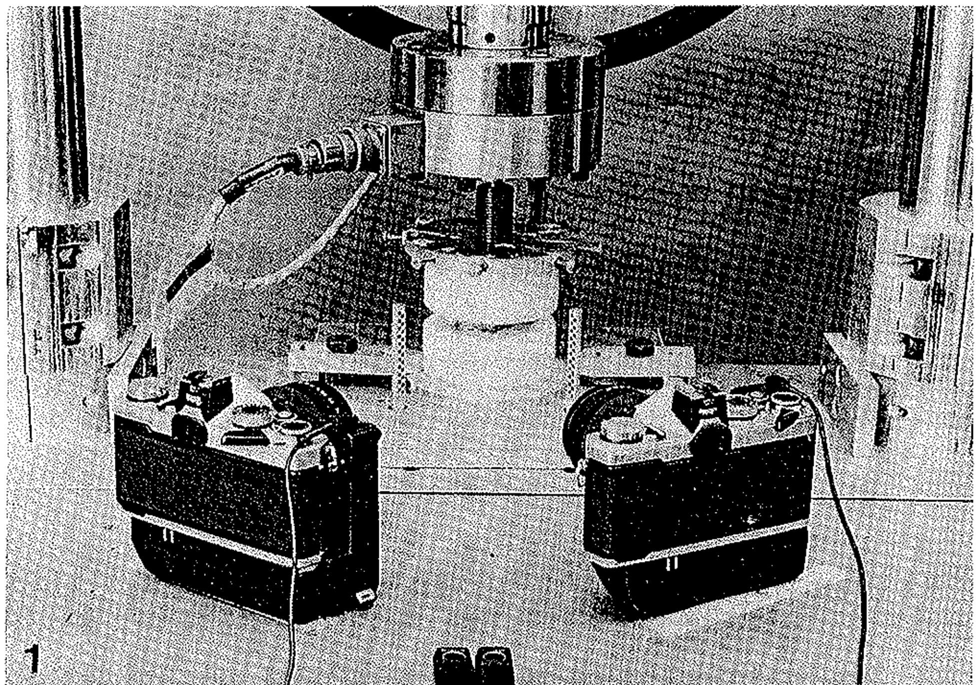
The stereophotograph pairs were analyzed using a direct linear transformation (DLT) computer program (Marzan, 1979). This computer program calculates the three-dimensional location of points which are visible in the fields of view of two or more cameras. The location of these points is calculated within a frame of reference defined by control points on a calibration object. This calibration object (Fig. 3) replaced the spine specimen for a calibration photograph at the beginning of each test. It was then removed and the spine specimen was put back in place for testing under varying loading conditions. At the completion of a test the films were removed from the cameras and developed and mounted in a film strip projector so that images could be projected onto a digitizing tablet (Summagraphics Corporation) interfaced to a Digital Equipment Corporation PDP 11 computer. The computer supervised the building of a data file consisting of X–Y coordinates of image points digitized from each of the stereo pair of photographs. Subsequently, the DLT computer program was used to generate a second file consisting of the three-dimensional coordinates of each of the microtargets, in each loading configuration of the specimen.

The three-dimensional coordinates of target points were used to calculate three characteristic dimensions of the 'fiber'. These dimensions were: the axial (vertical) distance between the endpoints of the vertebrae (H), the disc radial bulge (B) which was defined as the perpendicular distance of the most central microtarget on a 'fiber' to the line joining the endpoints of the 'fiber', and the 'fiber' length (L) which was defined as the sum of the Pythagorean distances between adjacent microtargets along the length of the 'fiber'. The method of calculating these three characteristic dimensions is illustrated in Fig. 4. Only the calculation of the first dimension, the vertical or axial height of the fiber (H) was dependent on the orientation of the specimen relative to the principal axes for measurement. To minimize variability due to this effect, both the central axis of the calibration object and the central axis of the spine were aligned as nearly as possible to the vertical.

Changes in the dimensions of the 'fiber' during a test were used to measure its deformation. The change in the height (H) measured the compression of the disc. The change in the bulge (B) gave an incremental measure of the radial dimension of the disc, and changes in the 'fiber' length (L) were used to measure average 'fiber' strain. Thus the strain was the proportional change in length of the 'fiber' as defined by the line through the seven surface markers.

ACCURACY

The accuracy of the measurement technique is limited mainly by the ability to identify target points accurately and reproducibly at the time of digitizing. This in turn depends upon a number of factors including photographic technique, lens quality, and the inherent clarity of the target point. Earlier studies which used the heads of small pins driven into the tissue as target points showed that these were considerably less easy to identify than the microtargets subsequently developed. Other sources of error include errors in the calibration jig, lens and film distortions, digitizing random errors and computer



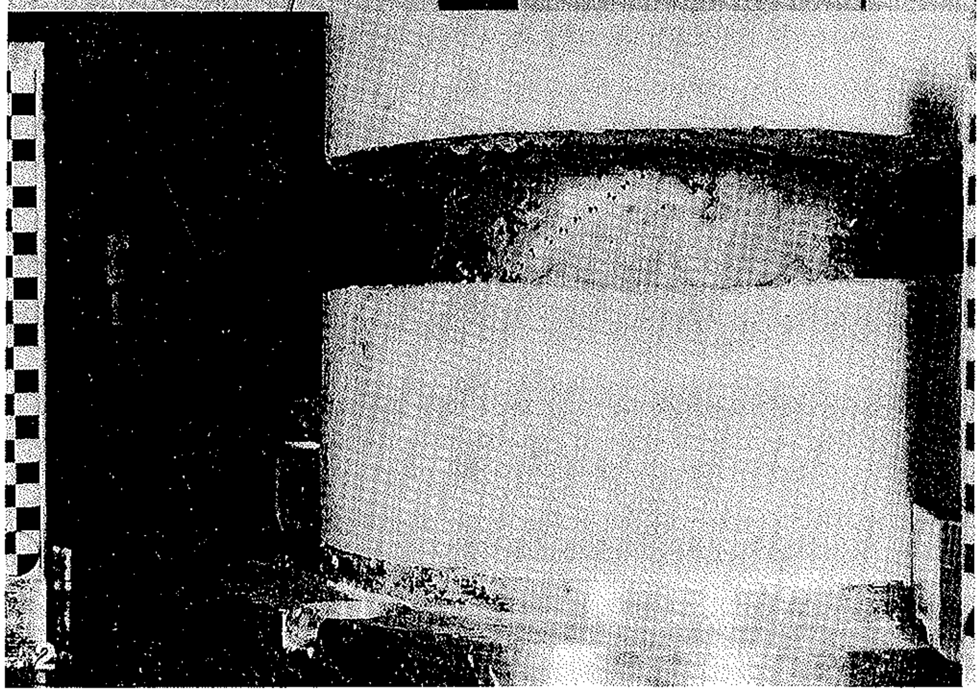


Fig. 1. Arrangement of cameras for stereophotogrammetric measurement of the surface deformation of an intervertebral disc.

Fig. 2. An example of one of a stereo pair of photographs of an intervertebral disc, ready for digitizing. Also visible on each side of the frame are fixed control points used as reference points during digitizing.

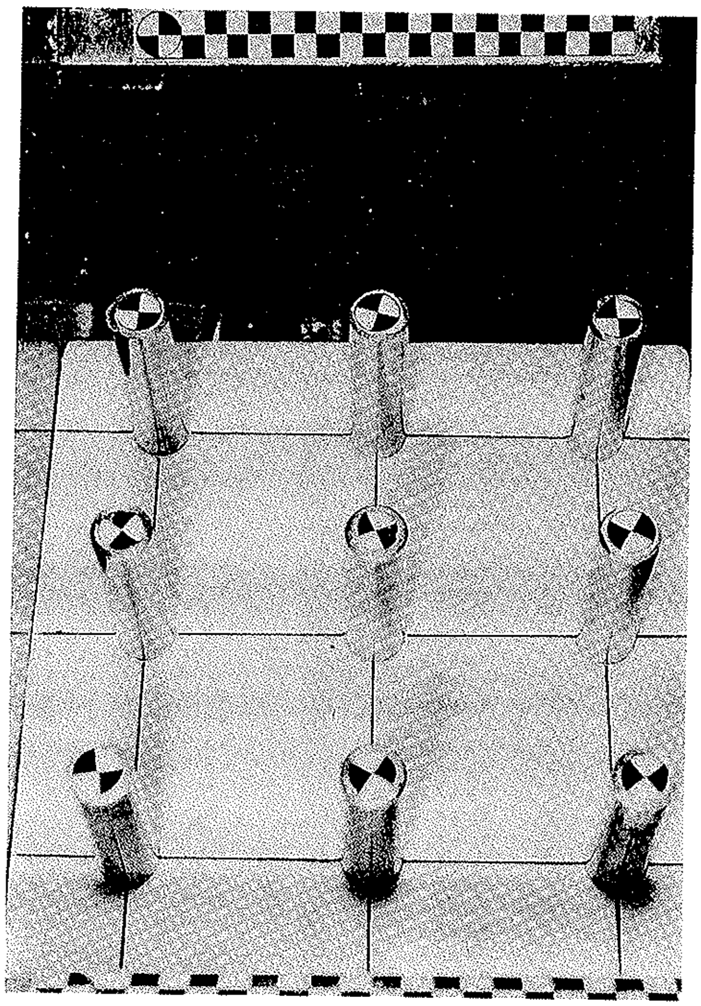


Fig. 3. Calibration object used in direct linear transformation method of close range stereophotogrammetry.

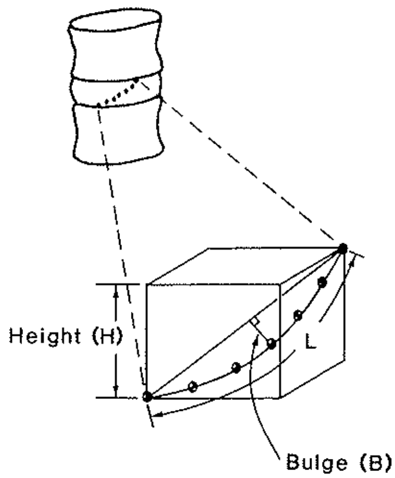


Fig. 4. Method for calculating three principal dimensions of a surface annular fiber of an intervertebral disc.

roundoff errors. Systematic errors might be due to the markers tethering the tissue and the finite thickness of the markers.

Random errors in the measurement technique were studied experimentally. Three experiments were performed. In each of these experiments, markers were attached to a human lumbar intervertebral disc which was subsequently frozen. This specimen was then set up in the test apparatus but instead of loading the disc it was tilted and rotated in each of the principal directions about 5° from a starting position in turn, and translated small distances relative to the starting position. No changes in the 'fiber' dimensions should have occurred. After developing of the films and digitizing, each of the measurements was considered as a repeated measure and the variance of the measure about the mean value gave an estimate of the measurement accuracy. In one test, the entire sequence of recordings was digitized seven times, to give an estimate of the variance due to the manual digitizing procedure.

The standard deviation of the measurements was about 0.05 mm, giving an expected error (95% confidence) of about 0.15 mm. In the case of measurement of the disc fiber elongation, this corresponds to an error equivalent to less than 1% strain. The study involving repeated digitizing indicated that about half of the variance was due to manual digitizing errors and about half arose from other sources. The ultimate strain of annulus tissue at failure was found to be about 20% by Galante (1967) and Wu and Yao (1976). The method's accuracy was therefore considered adequate for study of the disc deformation relative to the ultimate strain.

PRELIMINARY FINDINGS USING THIS TECHNIQUE

Two calf lumbar discs and three human lumbar discs have been studied. These were all fresh specimens which had been stored at −20°C prior to testing. All the discs were tested under compressive loads up to 2.5 kN. Two human discs have also been studied with axial rotation torques of up to 17 Nm. We were especially interested in the surface annular fiber average strain produced under these loading conditions. Compression load was applied by the hydraulic ram of a materials testing machine which was set to advance this ram at a rate of 2 mm min^{-1}. The cameras were fitted with motor drives which permitted photographed pairs to be made at increments of 0.2 mm of ram movement during loading and unloading of the specimen. In the case of axial torque loading, this was applied via a pair of cables attached to the endfittings of the spine and running over pulleys so that dead weights could be added in increments of 45 N. Sample graphs from these experiments are shown in Fig. 5.

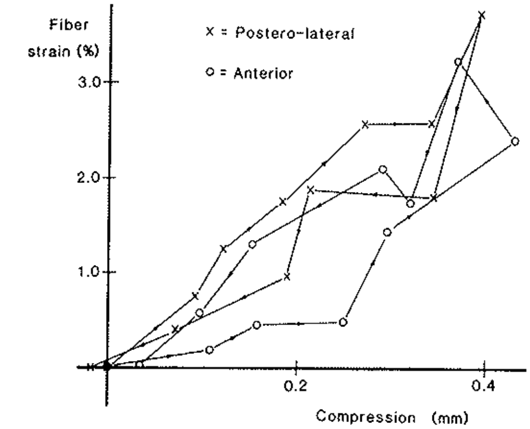
Very little elongation of the surface annular fibers was measured in seven compression tests. In one test there was an average strain of 3% at 2.5 kN axial compression (Fig. 5a). In all other tests the strain was less than 2%. This is in agreement with experimental findings of Klein *et al.* (1983), but is less than predicted by mathematical models (Broberg and von Essen, 1980). The surface annular bulge (*B*) increased by approximately 0.5 mm during these compression tests (Fig. 6). Measurements of axial compression (calculated from H) were also approximately 0.5 mm, indicating that there was compression of the vertebral bodies and embedding material as well as of the intervertebral disc, since the compression applied by the hydraulic ram was about three times the compression measured at the disc.

In tests with torsional load, a torque of 17 Nm produced elongation of the 'fiber' corresponding to positive or negative strains approaching 10%, depending on the direction of the torque relative to the line of the 'fiber' (Fig. 5b). This strain is less than half the ultimate strain of annulus material found by Galante (1967), and Wu and Yao (1976). In these tests, there was negligible change in the height of the specimen and in the radial bulge. After the test with negative torque (producing shortening of the fiber) there was a residual deformation as described by Galante (1967).

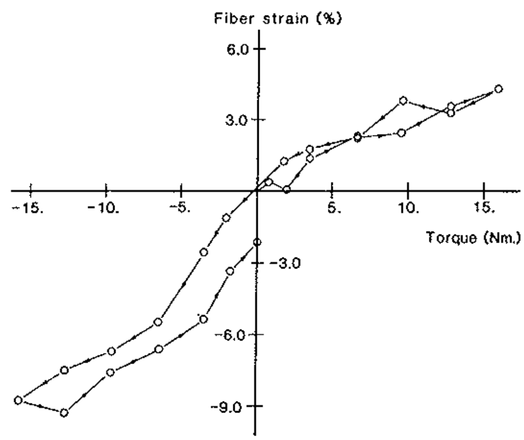
CONCLUSIONS

A technique has been developed for accurate measurement of the surface deformation of soft tissue in three dimensions. The technique is essentially non-contacting except that miniature optical targets must be applied to the tissue specimen.

The technique is inexpensive to use as described here with inexpensive 35 mm cameras and standard film materials. A digitizing tablet and on-line computer are also required. As described, the technique is 'quasi-static' and has been used to record deformations at relatively slow rates. The recording rate could be



(a)



(b)

Fig. 5. (a) Graph of annular fiber strain in a human lumbar intervertebral disc under axial compression loading up to 2.5 kN, plotted as a function of the axial compression of the disc. The open circles show results of a study of the anterior part of the disc. The crosses are for a postero-lateral part of the same disc. If fluid were lost from the disc during compression then the fiber strain during unloading would be less than that during loading, because of the volume change. In this graph the anterior 'fiber' demonstrated the opposite effect. A similar phenomenon was observed in another specimen. It may be a result of fluid displacement within the disc during loading. During the tests the specimen was not rigidly constrained to pure compression. (b) Surface annular fiber strain in an intervertebral disc under the action of axial torque, plotted as a function of this torque. Positive strain represents elongation of the fiber.

increased by use of high speed motor drives for the cameras, synchronization of shutters and electronic flash illumination.

In preliminary tests of lumbar intervertebral discs, the surface annular strain was found to be very small in

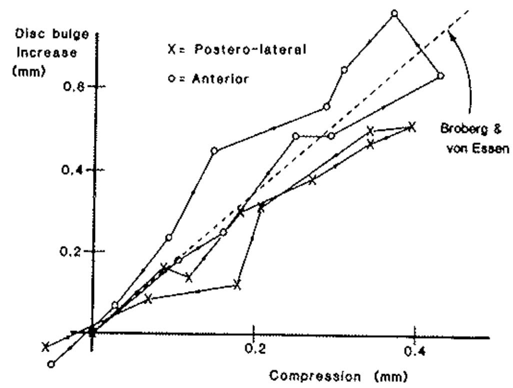


Fig. 6. Graph showing the increase in the bulge (B) of an intervertebral disc during compression loading. These measurements come from the same tests as those used in Fig. 5a. The broken line was deduced from predictions for a theoretical model in Fig. 15 of Broberg and von Essen (1980).

axial compressive loading but was much greater under the action of axial torque.

REFERENCES

Arms, S. W., Boyle, J. B., Johnson, R. J. and Pope, M. H. (1983) Strain measurement in the medial collateral ligament of the human knee: an autopsy study. *J. Biomechanics* **16**, 491–496.

Broberg, K. B. and von Essen, H. O. (1980) Modeling of intervertebral discs. *Spine* **5**, 155–167.

Brown, T., Hansen, R. J. and Yorra, A. J. (1957) Some mechanical tests on the lumbosacral spine with particular reference to the intervertebral discs. A preliminary report. *J. Bone Jt Surg.* **39A**, 1135–1164.

Butler, D. L., Grood, E. S., Zernicke, R. F., Hefzy, M. S. and Noyes, F. R. (1983) Nonuniform surface strains in young human tendons and fascia. *Transactions of the 29th Orthopaedic Research Society*, Anaheim, CA, p. 8. ORS, Chicago.

Galante, J. O. (1967) Tensile properties of the human lumbar annulus fibrosus. *Acta orthop. scand.* Suppl 100.

Hickey, D. S. and Hukins, D. W. L. (1980) Relation between the structure of the annulus fibrosus and the function and failure of the intervertebral disc. *Spine* **5**, 106–116.

Hoffman, A. H., Grigg, P., Fogarty, K. E. and Burgess, S. M. (1981) Development of a finite element based method for directly determining strains in soft tissue. Bioengineering Proceedings of 9th N.E. Conference. (Edited by Welkowitz, W.), pp. 329–332. Pergamon Press, New York.

Horst, M. and Brinckmann, P. (1981) Measurement of the distribution of axial stress on the end-plate of the vertebral body. *Spine* **6**, 217–232.

Klein, J. A., Hickey, D. S. and Hukins, D. W. L. (1983) Radial bulging of the annulus fibrosus during compression of the intervertebral disc. *J. Biomechanics* **16**, 211–217.

Marzan, G. T. (1979) Rational design for close-range photogrammetry. (Ph.D. Thesis, University of Illinois, 1976) Xerox University Microfilms, Ann Arbor, MI.

Nachemson, A. (1960) Lumbar intradiscal pressure. *Acta orthop. scand.* Suppl. 43.

Ranu, H. S., Denton, R. A. and King, A. I. (1979) Pressure distribution under an intervertebral disc—an experimental study. *J. Biomechanics* **12**, 807–812.

Reuber, M. Schultz, A., Denis, F. and Spencer, D. (1982) Bulging of lumbar intervertebral disks. *J. biomech. Engng* **104**, 187–192.

Shah, J. S., Hampson, W. G. J. and Jayson, M. I. V. (1978) The distribution of surface strain in the cadaveric lumbar spine. *J. Bone Jt Surg.* **60B**, 246–251.

Woo, S. L-Y., Lubock, P., Gomez, M. A., Jemmott, G. F., Kuei, S. C. and Akeson, W. H. (1979) Large deformation non homogeneous and directional properties of articular cartilage in uniaxial tension. *J. Biomechanics* **12**, 437–446.

Wu, H. C. and Yao, R. F. (1976) Mechanical behavior of the human annulus fibrosus. *J. Biomechanics* **9**, 1–7.