SPONDYLOLYTIC FRACTURES

B. M. CYRON, W. C. HUTTON and J. D. G. TROUP, LONDON, ENGLAND

A method is described whereby fractures of the neural arch similar to those in spondylolysis are produced experimentally. The forces, bending moments and displacements required to initiate the fractures are given. The mechanical aspects in the aetiology of spondylolysis are explained by a simplified two-dimensional force analysis.

The strength of the lumbar neural arch is of clinical interest because of the occurrence of spondylolysis. This is due to a defect, generally bilateral, which arises between the superior and inferior articular processes in the narrowed region of the neural arch, the pars interarticularis (Fig. 1). There is then a tendency for the body of the vertebra involved to slip forward in relation to the subjacent vertebra, becoming separated from the spinous and inferior articular processes. The defect is not congenital, though genetic factors may predispose the individual to develop it. Spondylolysis is present in about 5 per cent of adult males, most commonly at the fifth lumbar level, the incidence being greater among some athletes (Hector 1972; Kotani, Ichikawa, Wakabayashi, Yoshii and Koshimune 1971; Chapman, Hodgson and Troup 1974).

The precipitating factor in spondylolysis is considered to be mechanical, arising from impact or fatigue failure (Newman 1959, 1963; Murray and Colwill 1968). Pfeil (1971) believed the defect to be due to fatigue failure. He subjected specimens of the lumbar spine in children to cyclic impact loading. As a result, he reported typical spondylolytic defects at the fifth lumbar level, but he did not attempt to analyse the forces applied or to relate his results to an equivalent body posture. Thus, little is known of the forces which lead to occurrence of the defect. Stewart (1953) suggested that stooping with the trunk at or below horizontal was a significant factor in producing the defect, whereas Roberts (1947), Newman (1959) and Kotani and colleagues (1971) pointed to the stress in the lumbo-sacral region in erect load-bearing postures with the spine extended.

In a typical spondylolysis the defect appears across the pars in the plane of its narrowest cross-section. The defect thus crosses both the dense layers of cortical bone in the pars, the antero-lateral zone of cortical bone extending from the inferior articular process into the inferior margin of the pedicle, and the postero-medial layer spreading from the superior articular process into the lamina (Krenz and Troup 1973).

A simplified two-dimensional analysis of the forces acting at the level of a plane midway through the lumbo-sacral disc is shown in Figure 2. Angle $\alpha$ is the angle between the plane and the horizontal; $O$ is the instantaneous centre of rotation; $S$ is the cumulative effect of all the extensor muscle activity (mainly sacrospinalis and multifidus), acting at a right angle to the plane; $W$ is the weight of the upper part of the body plus any load being carried and acts through its centre of gravity. The component effects of $W$ and of $S$ are resisted by two forces, $f_p$ and $f_p$.

Dr J. D. G. Troup, Dawn Trust Unit for Spinal Research, Institute of Orthopaedics, Royal National Orthopaedic Hospital, Brockley Hill, Stanmore, Middlesex HA7 4LP, England.

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N and P. N acts perpendicular to the plane at O and represents the resistance to compression of the intervertebral disc. P acts parallel within the plane and represents the resistance to shear of the intervertebral disc and to backward bending of the neural arch through the action of a force applied to the inferior facets. By observation of the lumbar spine it can be seen that the angle between the plane and the surface of the inferior facets is approximately a right angle. This allows us to resolve the forces in these two mutually perpendicular directions so that the inferior facets do not take any component of the force N.

For static equilibrium the following equations apply: forces acting perpendicular to the plane, \( N = S + W \cos \alpha \); forces acting parallel within the plane, \( P = W \sin \alpha \); taking moments about O, \( SI = LW \).

The forces acting on the neural arch posterior to the pars interarticularis are shown in Figure 1. Fp, the force on the inferior facets, is the portion of P not taken up by the shearing resistance of the intervertebral disc (Fig. 2). Fp is large when the disc is not able to take its full share of the shearing force P, and when P is large— that is, when the angle \( \alpha \) is increased, as when the trunk is bent forward or when erect and the lumbar region is markedly lordotic. Sp is some portion of the total extensor force S. Sp would be produced mainly by the net action of those parts of the sacrospinalis muscle and the multifidus muscle which are attached to the spinous process of the vertebra. S and so Sp are large in flexion when L is large (Fig. 2), although intra-abdominal pressure is available to offer some relief to the spine in this posture (Bartelink 1957; Morris, Lucas and Bresler 1961; Davis and Troup 1964; Eie 1966, 1973). These two forces (Fp and Sp) represent the mechanical factor which may lead to the occurrence of spondylosis. Because of the incremental effects of gravity, W is greater at L.5 compared with elsewhere in the lumbar region.

### TABLE 1

**Details of the Specimens Tested**

<table>
<thead>
<tr>
<th>Specimen</th>
<th>L.1</th>
<th>L.2</th>
<th>L.3</th>
<th>L.4</th>
<th>L.5</th>
</tr>
</thead>
<tbody>
<tr>
<td>Number</td>
<td>Age (Years)</td>
<td>Sex</td>
<td>Force F (kN)</td>
<td>B. Moment (Nm)</td>
<td>Displacement d (cm)</td>
</tr>
<tr>
<td>1</td>
<td>26</td>
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<td>283</td>
<td>26.8</td>
<td>-48</td>
</tr>
<tr>
<td>2</td>
<td>35</td>
<td>Male</td>
<td>283</td>
<td>26.8</td>
<td>-48</td>
</tr>
<tr>
<td>3</td>
<td>18</td>
<td>Male</td>
<td>283</td>
<td>26.8</td>
<td>-48</td>
</tr>
<tr>
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<td>Male</td>
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<td>33.2</td>
<td>-49</td>
</tr>
<tr>
<td>30</td>
<td>69</td>
<td>Male</td>
<td>1.384</td>
<td>26.3</td>
<td>-30</td>
</tr>
</tbody>
</table>

* Fracture across the pedicles.

Specimens 1, 2, 3 were fresh, the rest were preserved.

**FIG. 2**

Free body diagram showing the forces acting across and along a plane midway through the lumbo-sacral disc.

**Rate of change of displacement: 0.5 centimetre/second**

<table>
<thead>
<tr>
<th>Specimen</th>
<th>L.1</th>
<th>L.2</th>
<th>L.3</th>
<th>L.4</th>
<th>L.5</th>
</tr>
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<tbody>
<tr>
<td>Number</td>
<td>Age (Years)</td>
<td>Sex</td>
<td>Force F (kN)</td>
<td>B. Moment (Nm)</td>
<td>Displacement d (cm)</td>
</tr>
<tr>
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<td>72</td>
<td>Male</td>
<td>0.990</td>
<td>20.6</td>
<td>-325</td>
</tr>
<tr>
<td>6</td>
<td>68</td>
<td>Male</td>
<td>0.990</td>
<td>20.6</td>
<td>-325</td>
</tr>
<tr>
<td>7</td>
<td>73</td>
<td>Male</td>
<td>0.990</td>
<td>20.6</td>
<td>-325</td>
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<tr>
<td>8</td>
<td>49</td>
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<td>0.990</td>
<td>20.6</td>
<td>-325</td>
</tr>
<tr>
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<tr>
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<td>Male</td>
<td>1.780</td>
<td>37.3</td>
<td>-79</td>
</tr>
</tbody>
</table>

**Rate of change of displacement: 5 centimetres/second**
In addition, angle $\alpha$ (and so $\sin \alpha$) is also greater at the lumbo-sacral level than elsewhere in the lumbar region. These two facts are consistent with the greater frequency of spondylolysis of the fifth lumbar vertebra.

In addition to the muscle activity considered in the above analysis, there is a force exerted on the lumbar spine resulting from activity in the psoas muscle. Nachemson (1966), from an electromyographic study of the vertebral portion of the psoas muscle, suggested that the muscle might aid in stabilising the lumbar part of the spine, especially in unsupported sitting and standing. The line of action is such that the main component of force will compress the intervertebral disc. A small component of force will add to the shearing component P.

Mechanical tests on the neural arch were carried out on cadaveric specimens of lower lumbar vertebrae. The aim of the tests was to produce a bending moment across the pars interarticularis by means of a force applied to the inferior articular facets. Although it is unlikely that spondylolysis in vivo is produced solely by loads to the inferior articular facets, it was thought that these preliminary tests would help in understanding the nature of the bony resistance to spondylolysis.

**MATERIALS AND METHODS**

**Preparation of the cadaveric specimens**—Specimens consisting of lumbar vertebrae and sacrum were removed during routine necropsies. The first three specimens (Table I) were stored at -20 degrees Celsius, but because of a change in the regulations for handling cadaveric material the others were stored in a solution of 10 per cent formaldehyde in normal saline. It is recognised that this variation in treatment of the cadaveric material could produce differences in the mechanical properties of bone; so no comparison across specimens was made.

The specimens were from subjects aged from twenty-six to seventy-five years. All specimens were free of bone disease. Twelve specimens, consisting of a total of forty-four lumbar vertebrae, were prepared and tested (Table I). The frozen specimens were placed in a refrigerator for twenty-four hours before dissection to allow for slow defreezing.

Each vertebra was carefully separated from the column by cutting the ligaments and halving the discs. The half discs were subsequently removed to facilitate clamping without slipping. The specimens were kept moist with normal saline at all times during preparation and testing. Just before the test the soft tissue around the pars interarticularis was thoroughly cleaned off so that the propagation of any fracture could be observed during the loading process.

**Mechanical tests**—The apparatus used for loading the inferior processes of a vertebra is shown in Figure 3. The vertebra was clamped to the inclined platform with its superior surface downwards, with the rig clamped to the ram of a Mayes hydraulic servo-controlled testing machine.

The upper crosshead of the machine incorporated a load cell and the base unit held the hydraulic actuator and displacement transducer. The outputs from the displacement transducer and the load cell were fed on to an "X—Y" plotter, an oscilloscope and a U.V. recorder.

As the ram of the testing machine moved upwards a force was applied to the inferior articular processes by means of a plate fixed to the crosshead of the machine. Surgical Simplex cement was moulded to the inferior facets to ensure the application of an even distribution of force, and to the superior facets to prevent any rotation or slipping of the vertebral body during the tests. Simplex cement was chosen because before hardening it can be shaped and after hardening it is a very stiff material in comparison with bone.

The angle of inclination of the platform was set for each vertebra, so that the force applied to the facets in the mechanical tests was not applied perpendicular to the plane of the facets but in the plane of the cross-section of the narrowest region in the pars interarticularis. This method of loading allowed a pure bending moment to be applied across the pars. The distance from the site at which failure was propagated to the line of application of the force allowed the bending moment applied to be readily calculated.

![Figure 3](image-url) The arrangement of the apparatus for loading the inferior processes of a lumbar vertebra.

Twenty-one vertebrae were tested at a slow displacement rate of 0.05 centimetre per second, so that the propagation of the fracture could be observed. The remainder were tested at a faster rate of 5.00 centimetres per second in an attempt to stimulate a more realistic in vivo fracture rate. Graphs of load versus displacement (from the "X—Y" plotter) were obtained for the slow rate and graphs of load against time (from the U.V. recorder) and load against displacement (from the oscilloscope) were obtained for the faster rate.

**RESULTS**

The results of the mechanical tests are summarised in Table I. Forty-four vertebrae were mechanically tested and fractured as follows. Thirty-two fractured across the pars interarticularis; ten fractured across the pedicles. Attempts to fracture the fourth and fifth lumbar vertebrae...
failed in specimen 10. The maximum force applied in each case was 2,800 N, when the vertebral bodies and the superior processes began to collapse.

Figure 4 shows a typical fracture of the pars interarticularis. It is similar to that present in spondylosis. With the exception of vertebrae from specimen 10, the fractures tended to be symmetrical, minor differences being due to the asymmetrical nature of the neural arch. In each case, the broken surfaces were irregular and sometimes showed bone spicules.

Two typical force/displacement results are shown in Figure 5, one for the fast rate and the other for the slow rate. For the fast rate, the time to fracture was 100 milliseconds, whereas that for the slow rate was 11·5 seconds. In both cases the fracture was initiated in the antero-lateral layer of the pars interarticularis and propagated obliquely through it after a load of about 2,000 N had been applied. It is interesting that the displacement (d) to initiate the fracture in each case was over 0·4 centimetre. The displacement for each specimen is also tabulated in Table I. The values of d range from 0·3 centimetre to 1·21 centimetres. This means that the neural arch is well able to bend under the action of a force applied to the inferior facets. This may allow the disc, in vivo, to take a considerable share of the shearing load P (Fig. 2).

DISCUSSION

The fracture produced in the mechanical tests tended to propagate obliquely across the pars interarticularis rather than in the plane of its narrowest cross-section. This was probably a reflection of the technique of application of the force. Fractures did, however, begin in the zone typical of spondylosis, and the forces recorded are therefore relevant. In some cases the vertebrae fractured at the pedicles; this type of fracture is seldom seen in clinical practice, though one healing fracture extending vertically from the antero-lateral cortical zone into the pedicle has been reported at necropsy (Krenz and Troup 1973). For the vertebrae from specimen 10 in which damage was done primarily to the vertebral bodies, it may be assumed that an in vivo spondylytic fracture would never have developed.

The fact that the force required to produce a fracture increases from the first to the fifth lumbar vertebra is consistent with the fact that the pars interarticularis becomes progressively thicker and more sturdy lower down the lumbar region. The bending moment at failure also increased lower down the lumbar spine, but at a lower rate than the force because the inferior processes become shorter at the fourth and fifth level so that the distance between the fracture line and the plane of the applied force decreased.

The strength of femoral cortical bone decreases after the fourth decade of life (Wall 1974). It is difficult to draw the same conclusion for the spine from the results shown in Table I although for the fifth lumbar vertebrae lower fracture forces were recorded for the specimens from older subjects (numbers 5 and 26).

The neural arch is not a stiff structure and is able to bend. The force Sp would produce a forward bending moment on the neural arch, but the superior facets of the subjacent vertebra are able to brace the arch when subjected to a bending moment in this direction. The force Fp would produce a backward bending moment on the neural arch, and it is this direction of bending moment which is potentially the more damaging.

In flexion, especially while the subject is lifting a weight, the forces acting on the neural arch (Sp and Fp) are much higher than those when the subject is in the
erect posture, but the resultant mechanical stress generated would be different. The resultant of these two forces would produce a tensile force rather than a bending moment on the neural arch because the bending moments generated by Fp and Sp would tend to cancel each other out.

In the erect posture Sp would be less than Fp and the resultant force could generate backward bending, although the magnitude of the resultant in this posture would be small. The neural arch seems well protected when the subject is lifting or holding heavy loads in the flexed or in the erect posture.

It now seems likely that the mechanical factor in the aetiology of spondyloysis is fatigue failure. Walking with a heavy pack could produce an alternating loading situation with $P$ large. The disc is visco-elastic and may creep under the action of continuous shear. This would result in each inferior facet being subjected to an increasing and alternating load until the force on the inferior facets Fp is equal to $P$. There is no brace for the neural arch when subjected to a backward bending moment through the action of Fp, and a critical fatigue stress may produce a fracture in the antero-lateral region of the pars interarticularis.

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