THE FATIGUE STRENGTH OF THE LUMBAR NEURAL ARCH IN SPONDYLOLYSIS

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The inferior articular facets of lumbar vertebrae were subjected to a loading pattern calculated to simulate walking with a heavy pack on the back. The results indicate that the lumbar neural arch, at the partes interarticulares, is vulnerable to mechanical fatigue.

Spondylolysis is a fracture of the bone in one or both sides of the narrow regions of the neural arch, the partes interarticulares. The fifth lumbar vertebra is the most commonly affected.

Although spondylolysis is not considered to be of congenital origin (Rowe and Roche 1953; Newman and Stone 1963), genetic factors may predispose the individual to it (Baker and McHollick 1956; Saha *et al.* 1970; Wiltse, Widell and Jackson 1975). There are also racial differences, the Eskimos having an unusually high incidence of the defect (Stewart 1953; Lester and Shapiro 1968; Kettelkamp and Wright 1971). The most generally favoured theory, however, is that spondylolysis is a fracture caused by mechanical stress and that the mode of failure is fatigue (Pfeil 1971; Wiltse *et al.* 1975). This theory was enhanced by experiments to determine the bending strength of the lumbar neural arch (Cyron, Hutton and Troup 1976). In order to achieve a fracture, an increasing force was applied to the inferior articular facets of a lumbar vertebra and the neural arch was bent away from the vertebral body by about 0.5 centimetre. This relative movement would be difficult to accomplish *in vivo,* except possibly in hyperextension.

When a static force acts on a material, stress is generated within the material. As the applied force increases the material will eventually fail when the stress reaches a certain value, the "ultimate stress". However, the material will also fail when it is subjected to cyclic repetitive stresses which never reach the ultimate stress. This mode of failure is known as fatigue failure. The fatigue life, defined as the number of cycles to failure, is dependent on the amplitude of the cyclic stresses and the method by which they are imposed.

It is relatively easy to determine the fatigue life of inert materials such as metal. In bone, however, a fatigue fracture will only develop *in vivo* when the cellular mechanism of repair fails to keep pace with the microscopic damage caused by the repetitive force. It has been suggested that this occurs in "shin soreness" (Devas 1958). It is thought to be caused by prolonged periods of unaccustomed or strenuous activities such as running.

Walking with a heavy pack on the back and working in the fully flexed posture are activities that produce cyclic stresses within the partes articulares of lumbar vertebrae. If the stress generated during these activities reaches a critical value and a sufficient number of cycles is accumulated, the neural arch may fracture. This has already been considered as a likely explanation of the occurrence of spondylolysis (Stewart 1953; Newman and Stone 1963).

There is little published information on the fatigue properties of the lumbar neural arch. Pfeil (1971) reported on fractures resembling spondylolysis. He subjected lumbar spines from children to repetitive impact loads, but he did not measure the applied force or the number of cycles to failure.

This paper describes experimental work carried out on cadaveric lumbar vertebrae to determine the fatigue life of the lumbar neural arch when subjected to forces comparable with those encountered *in vivo*.

MATERIALS AND METHODS

Cadaveric material. Twenty-eight lumbar spines consisting of the lowermost three lumbar vertebrae and the sacrum were removed during routine necropsies. The specimens were taken from subjects aged between fourteen and eighty years who had no known history of bone disease and had not been immobilised for long periods of time. Of the seventy-four vertebrae tested, fourteen had been preserved in a solution of 10 per cent formaldehyde in physiological saline (Table I), and the rest were fresh (Tables II and III).

The vertebrae were separated by cutting the muscles and ligaments and halving the discs. Care was taken not to prestress the neural arch, which could have resulted in microfractures. The discs were subsequently removed to facilitate clamping without slipping. The soft tissue surrounding the vertebrae was left to prevent dehydration of the specimen. The fresh vertebrae were then stored in an ordinary refrigerator, in a sealed polythene bag, until required for testing.

Mechanical tests. The rig was designed for loading the inferior articular processes of a lumbar vertebra and consisted of a variable angle plate

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Table I. Results of the fatigue test on the lumbar neural arch in the group aged 14 to 30 years (all specimens were preserved)

Specimen			L3			L4			L5		
Number	Age *(years)*	Sex	Displacement *(millimetres)*	Number of cycles applied	The site of failure	Displacement *(millimetres)*	Number of cycles applied	The site of failure	Displacement *(millimetres)*	Number of cycles applied	The site of failure
15	18	M	±0.25	43 614	pars	±0.17	37 820	pars pedicle	±0.25	3 527	*pars
16	14	M	—	—	—	±0.23	1 536	pars	—	—	—
17	20	M	±0.20	39 546	*pars	±0.22	36 425	pars	±0.17	41 825	*pars
18	17	M	±0.30	54 543	pars	±0.27	14 335	pars	±0.18	29 263	pars
23	19	M	±0.23	44 669	pars	±0.17	26 865	*pars	±0.20	38 425	pars
27	26	M	—	—	—	±0.30	32 582	pars	—	—	—

* Fracture across the narrowest region of the partes interarticulares

which was similar to that used by Cyron and colleagues (1976) during bending tests on the lumbar neural arch. The vertebra was rigidly clamped to an inclined platform with its superior surface facing downwards. The rig was then clamped to the ram of a hydraulic servo-controlled testing machine which had an upper crosshead incorporating a load cell and a base unit holding a hydraulic actuator and a displacement transducer. As the ram of the machine moved upwards a force was applied to the inferior articular processes by means of a plate fixed to the crosshead of the machine. The force was shared by the inferior articular processes and evenly distributed over their facet areas by moulding surgical Simplex cement to the facets. Simplex was chosen because before hardening it can be shaped and after hardening it is very stiff material in comparison with bone.

The angle of inclination of the platform was so adjusted for each vertebra that the force applied to the facets during the test was not applied perpendicular to the plane of the facets but in the plane of the cross-section of the narrowest regions of the partes interarticulares.

The loading pattern. What force do we apply to the inferior articular facets in order to determine the fatigue life of the neural arch?

There are two forces that act on the neural arch and produce stress across the partes interarticulares (Cyron *et al.* 1976; Hutton, Stott and Cyron 1977). First, there is a force on the inferior articular facets which is some portion of the total intervertebral shear force. This shear force F_s is given by $(W_t + W_l) \sin \alpha$, where W_t is the weight of the arms, head and trunk above the level considered (the lumbosacral level in the case of L5). This is calculated to have an average value of 388

Table II. Results of the fatigue test on the neural arch in the group aged 40 to 60 years (all specimens were fresh)

Specimen			L3			L4			L5		
Number	Age *(years)*	Sex	Displacement *(millimetres)*	Number of cycles applied	The site of failure	Displacement *(millimetres)*	Number of cycles applied	The site of failure	Displacement *(millimetres)*	Number of cycles applied	The site of failure
47	40	M	±0.22	436 619	pars	±0.18	587 560	N/F	±0.19	455 609	N/F
37	44	F	±0.28	2 856	pars	±0.40	139	pars	—	—	—
46	44	M	±0.35	197	pars	±0.25	24 947	pedicle	±0.20	49 535	pars
44	45	F	±0.18	5 286	pars	±0.22	318 376	pars	±0.18	24 424	*pars
54	50	M	—	—	—	±0.16	467 762	N/F	±0.16	462 528	N/F
39	51	M	±0.18	256 212	pars	±0.19	104 465	pars	±0.21	14 597	pars
40	51	F	±0.25	58 119	pars	±0.22	166 393	pars	±0.20	75 824	pars
41	51	M	±0.18	84 704	*pars	±0.20	488 853	N/F	±0.18	509 626	N/F
49	51	F	±0.25	5 763	pars	±0.18	486 329	N/F	±0.17	466 464	N/F
45	52	M	±0.21	440 838	N/F	±0.22	450 742	N/F	±0.21	544 180	N/F
52	53	M	±0.20	364 482	pars	±0.18	489 251	N/F	—	—	—
51	54	F	—	—	—	—	30	pedicle pars	±0.23	12 053	*pars
56	56	M	—	—	—	±0.16	451 628	N/F	±0.16	452 135	N/F
48	58	F	—	—	—	±0.22	154 714	pars	±0.19	3 833	pars

*Fracture across the narrowest regions of the partes interarticulares N/F = No fracture

Table III. Results of the fatigue test on the neural arch in the group aged 60 to 80 years (all specimens were fresh)

Specimen			L3			L4			L5		
Number	Age *(years)*	Sex	Displacement *(millimetres)*	Number of cycles applied	The site of failure	Displacement *(millimetres)*	Number of cycles applied	The site of failure	Displacement *(millimetres)*	Number of cycles applied	The site of failure
33	68	F	—	17	pars	—	28	pedicle	—	37	pedicle
61	73	M	±0.30	285	pars	±0.27	1185	pars	±0.21	28 753	pars
62	74	F	±0.35	160	pars	±0.27	695	pedicle	±0.24	7 854	pars
63	75	F	±0.21	3215	pars	±0.22	5316	pars	±0.20	32 531	pars
59	75	M	±0.35	198	pars	±0.21	1999	pars	±0.20	32 567	pars
60	75	M	±0.37	421	pars	±0.24	583	pars	±0.19	48 687	pars
58	76	M	±0.27	458	pars	±0.26	2844	pedicle	±0.20	43 172	pars
55	80	M	—	85	pars	±0.27	529	pars	±0.22	26 018	pars

newtons. W_t is the weight carried and α is the angle at which the midsectional plane through the lumbosacral disc is inclined to the horizontal. In the partially flexed posture when carrying a 50 kilogram pack on the back this angle is equal to about 40 degrees. Therefore, $F_s = 570$ newtons. The force F_s is opposed by the resistance to shear of the lumbosacral disc and the stiffness of the neural arch to backward bending. These two structures have been estimated to play an equal role in resisting F_s (Hutton *et al.* 1977).

Secondly, there is the muscle force of the multifidus which is attached to the tip of the spinous process and acts downwards. This force counteracts the force acting on the inferior articular facets by producing an opposite bending moment acting on the neural arch (Cyron *et al.* 1976; Hutton *et al.* 1977).

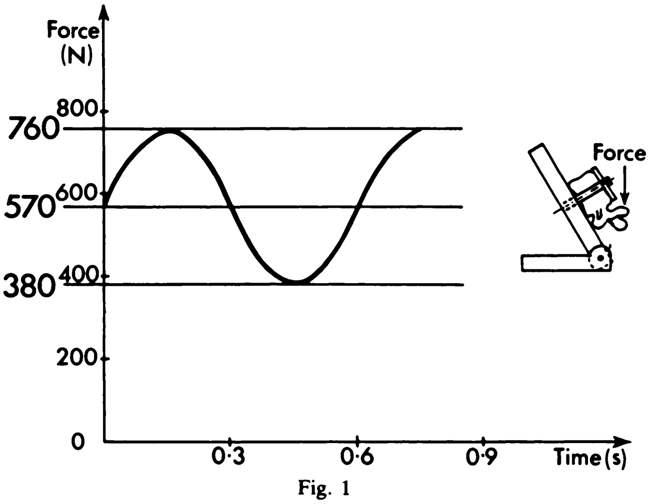

Fig. 1

The loading pattern applied to the inferior articular processes during the fatigue tests.

For these experiments we have simulated the worst situation, whereby the lumbosacral disc plays no part in resisting the intervertebral shear force and the muscle slips attached to the spinous process are inactive. This may not be altogether unphysiological since, after prolonged and repetitive stress, the disc may creep. Under these circumstances the force of 570 newtons acts on the inferior articular facets of L5 when the subject is standing with a 50 kilogram pack on the back.

During walking there is a fluctuation in the force due to gravity. This fluctuation is nearly sinusoidal and is equal to about one-third of the total force acting (Murray, Drought and Kory 1964; Lamoreux 1971). Consequently, we have assumed that during walking with a 50 kilogram pack on the back there is a cyclic repetitive force equal to 570 ± 190 newtons acting on the inferior articular facets of L5. The testing machine was therefore programmed to apply a sinusoidal repetitive force of 570 ± 190 newtons at 100 cycles per minute (Fig. 1), the rate being chosen to simulate walking at 100 steps per minute. At the L4–5 and L3–4 intervertebral levels the intervertebral shear force will be smaller since both W_t and α are less. However, since the calculation of 570 newtons is somewhat arbitary, all the vertebrae were tested under similar conditions.

To prevent dehydration of the specimens during testing, cotton wool which had been fully saturated with physiological saline was placed around the vertebral body and the neural arch as well as within the spinal canal.

After the application of the first 100 cycles the displacement of the neural arch due to the cyclic portion of the applied force (i.e. 190 newtons) was measured using a dial gauge. This was carried out in an attempt to relate this displacement with other variables such as age, vertebral level and fatigue life. It was impracticable to monitor this displacement continually throughout the test.

RESULTS

Seventy-four vertebrae from twenty-eight lumbar spines were tested. Fifty-three fractured across the partes interarticulares, five across the pedicles and two across the pars on one side and the pedicle on the other. Fourteen specimens did not fracture after about seventy hours of testing (over 400 000 cycles) and the tests had to be abandoned due to deterioration of the specimens.

Of the vertebrae that fractured across their partes, seven fractured across the narrowest regions. The fractures were initiated in the anterolateral layers of cortical bone within the partes (Fig. 2).

The specimens tested were divided into three age groups: Group 1 (Table I), fourteen to thirty years; Group 2 (Table II), forty to sixty years; Group 3 (Table III), sixty to eighty years.

There were fourteen vertebrae from six male subjects in Group 1, and they all fractured within ten hours, across the partes. In four of the specimens (numbers 15, 17, 18 and 23) all three vertebrae were tested, and in three cases L3 had the longest fatigue life. All the specimens within this group were preserved, although embalming does not supposedly change the mechanical properties of bone (Swanson 1971).

Group 2 was the largest group and consisted of fifteen vertebrae from six female subjects and twenty-one vertebrae from eight male subjects. Of the female specimens two of the vertebrae (L4 and L5 for number 49) failed to fracture. Of the twenty-one male specimens one third lumbar, six fourth lumbar and five fifth lumbar vertebrae failed to fracture. For the vertebrae within this group the time to fracture ranged from less than two minutes (L3, number 46) to nearly 100 hours (L4, number 47) when the test was abandoned.

In Group 3 there were twenty-four vertebrae, nine from three female subjects and fifteen from five male subjects. The fatigue life for every vertebra was short and there was little difference between the female and male specimens. Eleven of the vertebrae tested fractured within ten minutes and the strongest (L5, number 60) fractured after eight hours. The fifth lumbar vertebrae had the longest fatigue life.

The displacement due to the cyclic portion of the applied force varied considerably for all groups when this was measured after 100 cycles. Generally, when the displacement was high the fatigue life was short.

DISCUSSION

On the basis of these findings the neural arch is clearly suspect, at the partes interarticulares, when repetitive stresses act upon it.

The loading regime was sufficient to demonstrate the vulnerability of the vertebrae from the subjects in the group aged fourteen to thirty years. The intervertebral disc is more elastic under the age of thirty (Cyron 1977) and thus may allow a large proportion of the intervertebral shear force to reach the inferior articular facets. If the partes interarticulares of L5 are also vulnerable under fatigue, then this may explain the higher incidence of spondylolysis in individuals under the age of about thirty. Young people also more frequently engage in strenuous activities and may thus be exposed to critical fatigue. In addition, the ossification of the neural arch may not be complete until the age of twenty to thirty years. The strength of the neural arch is dependent on the laminae and the spinous process completing a rigid bony ring. This may explain the higher incidence of defects in the pars interarticularis of L5 found among patients with spina bifida occulta at L5 and S1 levels (Roche and Rowe 1952; Jackson, Wiltse and Cirincione 1976).

Spondylolysis occurs most frequently in the fifth lumbar vertebra. This vertebra lies on the steep sacral table and this, together with the abrupt change in stiffness between the flexible spinal column and the more massive pelvis, makes the fifth lumbar vertebra the most vulnerable. The extensor muscles, principally multifidus, tend to stabilise the joint by countering any intervertebral shear force. However, in the event of a weak or absent multifidus, the neural arch of L5 will be subjected to a net backward bending moment (as in our fatigue tests) and thus liable to fatigue. The forces applied to the vertebrae were calculated on the basis of L5, and they were theoretically rather high for L4 and L3. Thus, the result in Group 1 of L3 having the longest life, in three out of four specimens, is interesting. The neural arch of L5 looks the most sturdy, but this may not reflect the amount and distribution of cortical bone within the partes interarticulares.

Fig. 2

A typical fracture produced during the fatigue tests. The specimen is shown after maceration (L5, specimen 44). The photograph shows the inferior aspect of the vertebral body and the superior aspect of the detached neural arch.

For Group 2 the number of vertebrae remaining unfractured, after over seventy hours of fatigue testing, indicates that the neural arch increases in strength up to the fourth or fifth decade of life. Although the fifth lumbar vertebrae appear to be stronger than the third, there is little to choose between the fifth and fourth. The fact that the female specimens fractured more frequently than the male specimens is not unexpected. The loading pattern of 570 ± 190 newtons may be considered too high for most women.

With increasing age the disc becomes more fibrous and narrower, and osteophytes appear around the peripheries of the vertebral bodies. This, together with any increase in strength of the neural arch, suggests that the possibility of developing a spondylolytic fracture is less in middle age. By the age of sixty to eighty the disc will become even more stiff and fibrous and the chance of a critical force reaching the inferior facets must be rather low. Thus the marked reduction in the fatigue life shown by vertebrae in Group 3 is not an indication of increased vulnerability to develop the defect. In addition, there is less chance of a critical stress situation being set up by strenuous activity.

In vivo, while walking with a pack, the upper part of the body rotates thus loading each inferior facet alternately. This may result in fatigue stresses higher than in our example which may reach the neural arch and reduce the fatigue life still further.

CONCLUSION

Mechanical fatigue can cause the neural arch to fracture. This can occur during any strenuous activity, such as walking with a heavy pack or working for long periods in the flexed position, provided a high enough stress reaches the neural arch and persists for a long enough time. Young people are more likely to develop spondylolysis since they frequently engage in strenuous activities at a time when their intervertebral discs are more elastic and their neural arch may not be completely ossified.

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