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MECHANICAL ANALYSIS OF FORCES INVOLVED IN IDIOPATHIC SCOLIOSIS

By

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As early as 1824 *Bamfield* (1) noted that there was a definite relationship between bodily growth and the progress of scoliosis, an observation that has since been confirmed by a number of workers (2,5, 8, 13, 14) and presented in orthopaedic textbooks (7, 9, 12).

It is generally agreed that in scoliosis the lateral curvature of the column is always accompanied at an early stage by a characteristic rotation of the vertebrae. Unless this rotation is extremely small there will be structural changes in, and deformation of, individual vertebrae and, especially, of ligaments and discs.

On the basis of these three phenomena—progress with growth, lateral curvature and rotation—an analysis of the mechanical forces probably involved in the development of scoliosis was performed.

The movements executed by the column can be divided into normal physiologic ones (referred to below as *acute* movements), and slow progressive ones associated with structural changes occurring in disease and deformative processes (referred to as *chronic* movements). The acute movement is characterized by the fact that it occurs suddenly and may range in extent between the limits permitted by the skeleton, articular ligaments and muscles. The chronic movement takes place over months or years, and is practically irreversible.

Both acute and chronic movements of the column can be assumed to follow mechanical laws.

The range of the acute movement of the column has been carefully analyzed. In pure flexion and extension movements there is no intervertebral rotation. In lateral bending there is, according to some workers (11), a rotation, but this, if it does in fact occur, is insigni-

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ficant compared with the rotation in scoliosis. In full turning of the trunk there is a certain rotation between adjacent vertebrae—in isolated specimens one degree for the lumbar and 3–4° for the thoracic spine. The deformation in scoliosis cannot be produced by acute movement of the spine.

The rotation in scoliosis consists of rotation of the vertebral bodies towards the convexity. The rotation of a particular vertebra can be measured with reference to, for instance, the pelvis or the subjacent vertebra, and the direction of motion will depend on which reference point is chosen. If the pelvis is taken as the reference, the rotation of every vertebral body in the primary curve will occur in the same direction—say, clockwise with the patient erect. If the vertebra subjacent to the vertebra in question is taken as the reference, the rotation will be clockwise for the upper half of the curve and anticlockwise for the lower half. This difference is not always recognized—for example, in connection with the theory that the rotation in scoliosis may be due to disturbance of the short rotators on one side (16). These muscles act

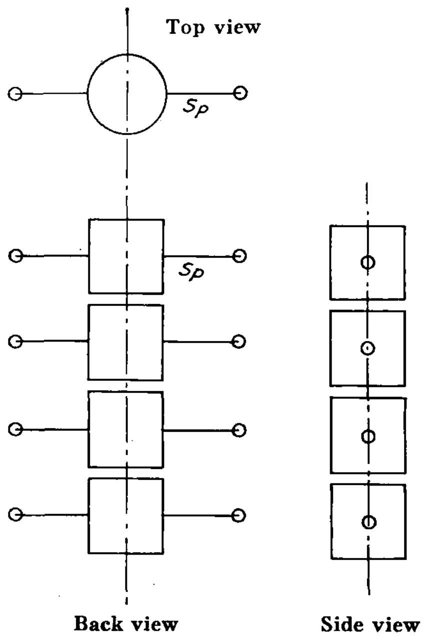

Fig. 1 A.
Model of a column consisting of four cylinders with "spacers" *sp*, and connected so as to be flexible in all directions

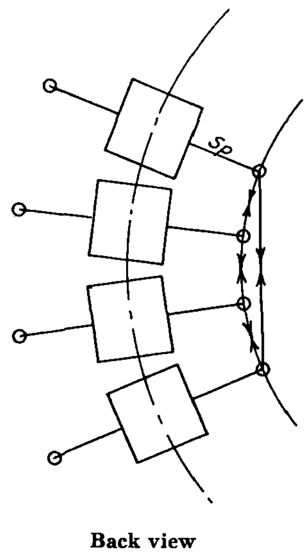

Fig. 1 B.
Lateral flexion of the column in Fig. 1 A.

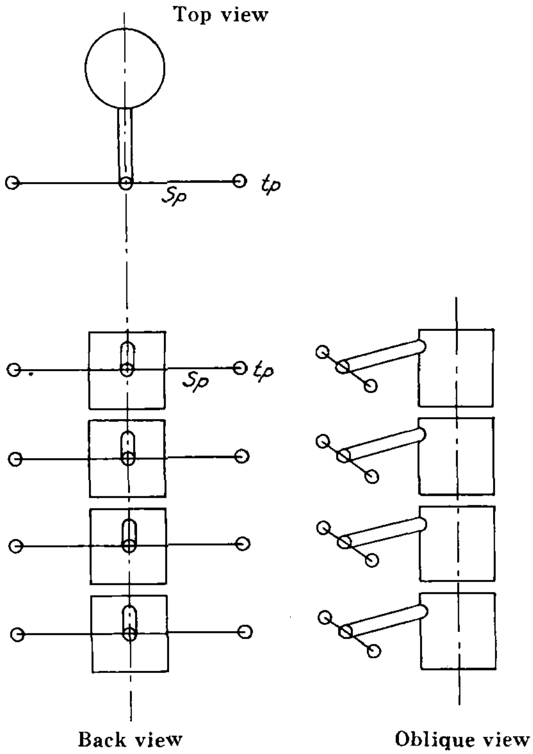

Fig. 2 A.
Model of a column similar to that in Fig. 1 except that the spacers *sp* are situated in a plane behind the column, to which they are joined by rods.

in the same direction throughout the column and therefore cannot give rise to such a scoliotic rotation.

From the mechanical standpoint, the spinal column can be regarded as consisting of two components, one column composed of the vertebral bodies and another composed of the arches and processes. This distinction between these two components is also valid on developmental grounds; for the growth of the vertebral-body column, which must be regarded as having a locomotoric function, follows the growth of the extremities, whereas the arch column, which may be considered as a protective sheath for the cord, develops in step with the cranium (10).

If these two components of the spinal column are separated by sawing them apart, it is found that the arch column can be bent to almost any extent in any direction, whereas the vertebral-body column is considerably less flexible and is therefore the one that mostly limits

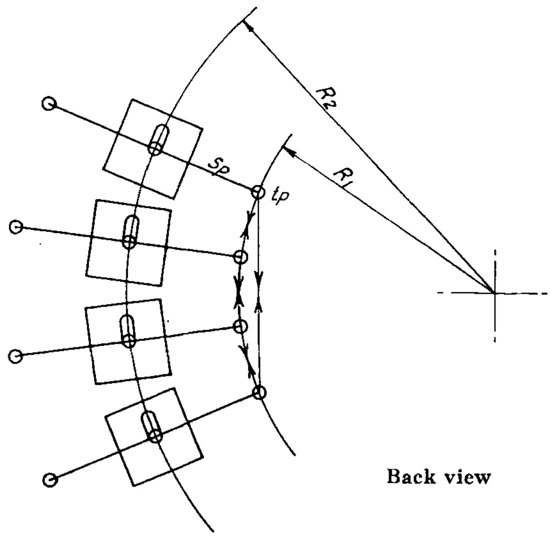

Fig. 2 B.
Lateral flexion of the column with rotation prevented. R_1, radius of curvature of line through the tie points *tp*. R_2, radius of curvature of the column axis.

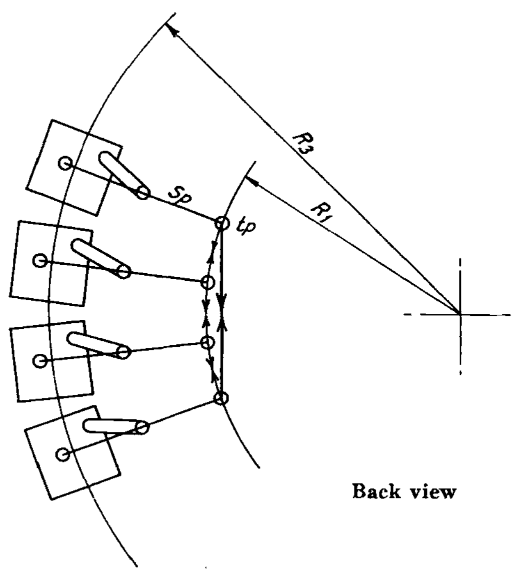

Fig. 2 C.
Lateral flexion of the column with rotation permitted. R_3, radius of curvature of the axis of the column. $R_3 > R_2$.

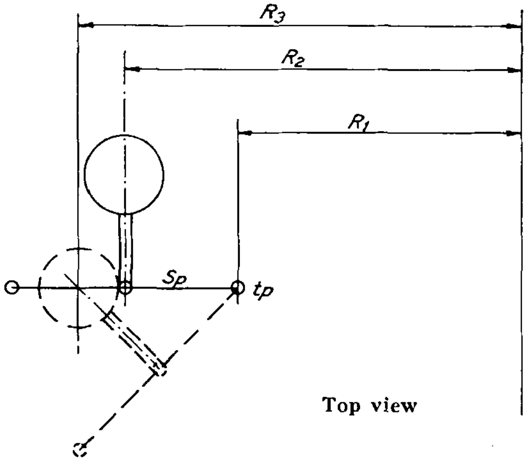

Fig. 2 D.
Top view of middle vertebra during lateral flexion without and with rotation of the column.

the flexibility of the spinal column (6). This distinction between the two components is essential to the following discussion. The vertebral-body column is the structure that offers the greater resistance to forces acting on the column and tending to deform it, and it will therefore be the less deformed, other conditions being equal.

Consider the model illustrated in Fig 1 A, which represents very approximately the spinal column. This can be bent in various directions. When the distance between the spacers (*sp*) is reduced on one side there is a lateral flexion without rotation (Fig. 1 B). The movement will be largely the same, whether the shortening occurs between adjacent pairs of spacers or only between the top and bottom ones. The same flexion is obtained if, instead of the distance between the spacers being shortened, the column is lengthened and the distance between the spacers on one side is kept constant.

The model in Fig. 2 A is a closer mechanical representation of the spinal column. Here the movements will be quite different. The tie points (*tp*) are situated in a plane on the side of, and behind, the actual vertebral-body column. If it is supposed that the column presents an elastic resistance to any change in shape, then any decrease in the distance between the tie points (*tp*) will give rise to a rotation as well as to a lateral flexion. The same movements will occur by elongating the vertebral column while keeping the distance between the tie points constant on one side. Mechanically, this rotation is due to the fact that a lateral flexion results in a more pronounced curvature of the model if there is no rotation (Figs. 2 B and D) than if there is a rotation (Figs. 2 C and D). For the radius of curvature in the former case will be smaller (R_2) than in the latter (R_3), and the model will therefore assume the position that, under the prevailing conditions, will involve the least deformation. If the uppermost and lowermost components of the model in such a bending experiment can rotate freely, all the segments (the vertebrae) will rotate by the same amount, and in the same direction in relation to a reference point outside the system. If, on the other hand, the uppermost and lowermost parts of the model can rotate only a small amount, and there is some resistance to intersegmental rotation, the maximum rotation will be a maximum at the centre of the

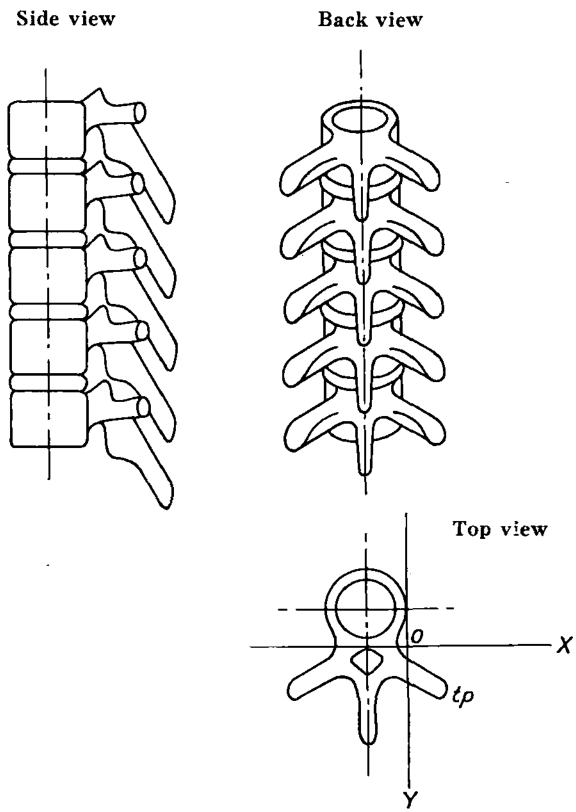

Fig. 3 A.
More representative model of the spinal column. *XOY*, quadrant where the binding forces between the transverse processes tend to produce both lateral flexion and rotation.

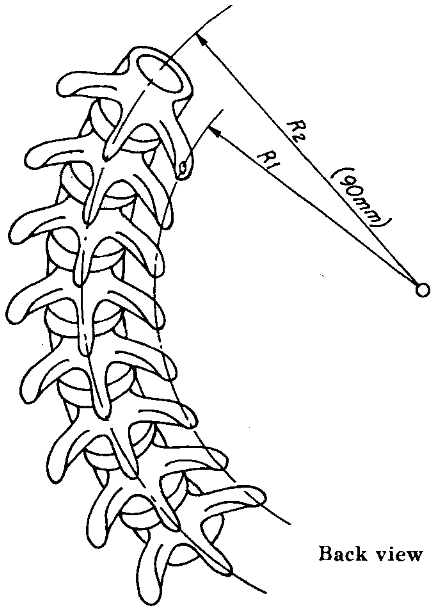

Fig. 3 B.
Lateral flexion of the column in Fig. 3 A; rotation is prevented. R_1, radius of curvature of a line through the tips of the transverse processes. R_2, radius of curvature of the axis of the vertebral column (90 mm.).

curve and will decrease with distance above and below this point. In other words, we obtain the deformation typical of scoliosis.

In the model in Fig. 3 A, which mechanically is a closer approach to the spinal column, the tie points correspond to the tips of the transverse processes. Here too, it is seen that a pure lateral flexion unaccompanied by rotation (Fig. 3 B) involves a more pronounced curvature of the vertebral-body column than if rotation is permitted (Fig. 3 C). In the model under consideration the radius in the former case will be 90 mm. and in the latter 100 mm. (Fig. 3 D). If it is supposed that the column presents an elastic resistance to bending, a decrease in the distance between the transverse processes will give rise to forces such that the spinal column will tend to be deformed in a manner typical of scoliosis. From the mechanical aspect it is immaterial whether there is an absolute reduction in the distance between the transverse processes (as, for instance, in pathologic shrinkage) or whether the reduction is relative (growth of the vertebral-body column, with a constant distance between the transverse processes).

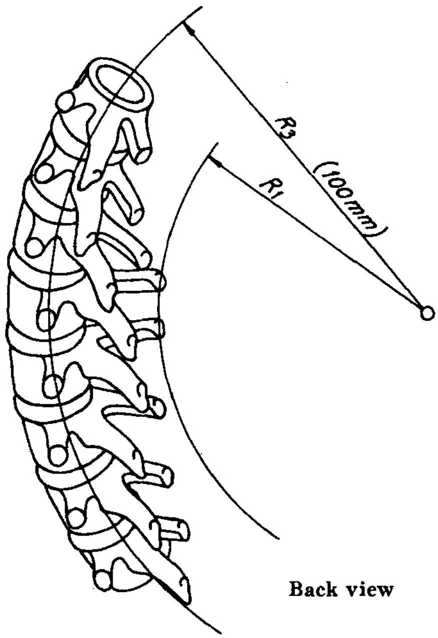

Fig. 3 C.
Lateral flexion of the column in Fig. 3 A; rotation of the vertebral bodies is permitted. R_1, radius of curvature of the line through the tips of the transverse processes (same as in Fig. 3 B). R_3, radius of curvature of the axis of the vertebral column (100 mm. and greater than in Fig. 3 B, where rotation was prevented).

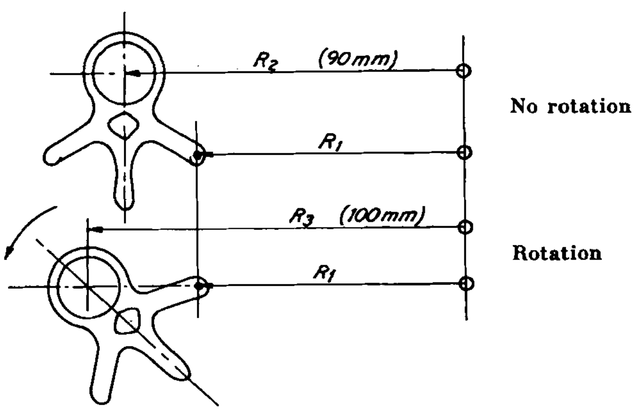

Fig. 3 D.
Top view of the middle vertebra of the model in Fig. 3 A during lateral flexion without and with rotation.

Acute movements of the human column do not permit such a deformation, but it may be supposed that under the influence of the forces discussed above, the shape of the structural parts of the spinal column gradually change in shape so that they assume the form and position that involve the minimum deformation of the vertebral-body column.

Under what conditions can such forces act in the spinal column? It has already been noted that the scoliotic rotation occurs during growth of the vertebral column. There need then be no absolute reduction in the distance between the points (*tp*) or the tips of the transverse processes. If there were forces acting unilaterally between these processes that prevented them from separating with the growth of the vertebral-body column, the same situation would arise as that discussed above. Between the transverse processes there are fairly strong intertransverse ligaments, and short and rather weak intertransverse muscles. If on one side these structures did not grow at the same rate as the rest of the spinal column, a typical scoliosis with rotation would result.

Though various models can be designed where the application of appropriate forces at the appropriate points will produce a similar deformation, such models do not provide a convincing solution of the problem consistent with the anatomy of the spinal column. A mechanical analysis, however, suggests that the deformity in idiopathic scoliosis is caused by restraining forces acting between the tips of the transverse processes on one side; such forces are exerted by the intertransverse ligaments or muscles.

The connection between the progress of scoliosis and growth has given rise to the theory that the deformity in scoliosis is due to a difference in vertical growth of each side of the vertebrae, but this is not a convincing explanation, for though such a discrepancy could account for a lateral flexion in one plane, it could not cause a rotation; this would require tensile or binding forces behind and on one side of the vertebral column.

The only anatomic structures in the spinal column that are situated in this quadrant (*XOY*) are the transverse processes (Fig. 3 A). Outside the spinal column this quadrant contains the posterior extent of the ribs and certain long dorsal muscles. Restriction of the vertical growth of these structures on one side also offers a possible mechanical explanation of the deformity in scoliosis.

If, supporting the primary cause of the scoliosis to lie in unilateral disturbance of vertebral growth or in disturbance in the disc, account is taken also of the forces acting on the intratransverse ligaments, these forces would give rise to a rotation of the vertebral bodies towards the side opposite to that on which it actually occurs.

No satisfactory explanation of the rotational deformation seems to have been presented in orthopaedic literature. *Risser* (15) has compared the column to a rubber tube which, after being partially severed from the front and behind, is bent laterally. If the incisions are not equally deep there will be a rotation-like displacement between the two parts of the tube. While this is an instructive illustration of simple mechanical laws, it cannot be regarded as explaining the rotation in scoliosis. *Tideström* (17) has suggested a similar mechanical explanation of the rotation, using a model of the spinal column where the vertebrae were connected by Polhem couplings, which permit motion only in two perpendicular planes. On bending such a model laterally there will therefore be a forced rotation. This, too, provides no explanation of the rotation in scoliosis, since the vertebrae are not linked in this manner.

Has then the mechanical explanation here presented any therapeutic application? If at an early stage of the development of scoliosis the binding forces between the transverse processes are removed on the concave side of the curve, the progress of the scoliosis would be arrested. As *Cobb* (2–4) has pointed out, we do not know if a case of scoliosis will progress at a given moment. A stationary condition after an operation of the kind implied could not therefore be regarded as proof that the operation had any therapeutic effect. It would be necessary to study a large series of cases, with comparison between treated and untreated subjects, before the value of the operation could be assessed.

It is also possible that removal of the binding forces on the concave side might be of direct therapeutic value in that it would permit gradual regression of the scoliosis. Though possible, such an effect is not necessary on mechanical grounds. *Wenger*'s study of the incidence of scoliosis after thoracoplasty provides support for such a mechanism (18, 19); he showed that the factor that was most frequently responsible for postoperative scoliosis was the resection not of the ribs but of several transverse processes. Scoliosis with rotational deformation was regularly observed after resection of several processes, and the severity of the condition then depended on the number of processes resected. The convexity appeared on the side of resection. The occurrence of scoliosis was essentially independent of the age of the patient, and even elderly persons were afflicted. The mechanical explanation of this scoliosis is approximately the same as for the models discussed. The transverse processes and the connecting ligaments can be regarded as ties corresponding to the lateral stays on a mast. The processes then function as cross-trees, or spacers. If several processes are resected, the continuity of the stay is interrupted; the dynamic balance in the spinal column will then be disturbed and the column will be subjected to largely the same forces as those discussed above. This explanation applies to an initially straight column.

If the column is already scoliotic a different situation is presented, and the weight of the body then tends to retain or to increase the deformation. Removal of the restraining forces on the concave side would arrest the progress of the condition and even render possible a regression. On the other hand, it is not certain that the excess dynamic force created on the convex side would suffice to bring the column back to its normal form, and even if it did, this process would probably take at least as long as the development of scoliosis, since a normalization of the shape of the vertebral bodies, ligaments and discs would be necessary.

On the basis of these mechanical principles, between four and seven transverse processes were removed on the concave side in cases of idiopathic scoliosis in an attempt to arrest the progress and possibly to effect an improvement. The patients were from 11 to 17 years old. The scoliosis had been progressing continuously, and the angle at operation ranged from 65 to 114°. The results of these seven operations were encouraging, but no definite conclusion could be drawn after only 3–6 months. They will be published in due course.

SUMMARY

A mechanical analysis was performed of the forces involved in the development of idiopathic scoliosis. The findings suggest that scoliosis is due to restriction of the growth of the intertransverse ligaments or muscles on one side. If this is in fact the case, the progress of the deformity could probably be arrested, and even an improvement be procured, by removal of one or more transverse processes on the concave side.

RESUME

Il a été procédé à une analyse mécanique des forces impliquées dans le développement de la scoliose idiopathique. Les trouvailles font

penser que la scoliose est due à une restriction de la croissance des ligaments ou des muscles intertransversaire d'un côté. Si c'est le cas, le progrès de la déformité pourrait probablement être arrêté et on pourrait même obtenir une amélioration par la résection d'un ou plusieurs apophyses transverses du côté concave.

ZUSAMMENFASSUNG

Eine mechanische Analyse der Kräfte, die bei der Entwicklung der idiopathischen Skoliose eine Rolle spielen, wurde ausgeführt. Die Befunde legen es nahe, dass die Skoliose infolge einer Einschränkung des Wachstumes der intertransversalen Ligamente und Muskeln auf einer Seite entsteht. Wenn sich das tatsächlich so verhalten sollte, dann könnte das Fortschreiten der Deformitet wahrscheinlich aufgehalten, ja selbst eine Besserung hervorgerufen werden, wenn man einen oder mehrere processus transversi auf der konkaven Seite entfernt.

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