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GRAVITY-INDUCED TORSION AND INTRAVERTEBRAL ROTATION IN IDIOPATHIC SCOLIOSIS

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Abstract: Vertebral rotation is an important aspect of spinal deformity in idiopathic scoliosis, associated with ribcage asymmetry. This paper investigates the hypothesis that intravertebral (within the bone) rotation in idiopathic scoliosis is caused by growth in the presence of gravity-induced torsions.

Three dimensional spinal curvature was measured for a small group of idiopathic scoliosis patients using standing radiographs, and equations of static equilibrium were used to calculate gravity-induced torsion profiles along the length of each spine. Intravertebral rotations were then measured for the same patients using Aaro & Dahlborn's technique with reformatted computed tomography images. Torsion curves were compared with rotation measurements to see whether gravity-induced torsion is a likely contributor to intravertebral rotation in scoliosis.

Results showed gravity-induced torques as high as 7.5Nm acting on the spines of idiopathic scoliosis patients due to static body weight in the standing position, and maximum intravertebral rotations (for a single vertebra) of approximately 7°. General agreement exists between measured intravertebral rotations and profiles of gravity-induced torsion along the length of the spine. Gravity-induced torsion is therefore a potential cause of vertebral rotation in idiopathic scoliosis.

Introduction

Vertebral rotation is an important aspect of the deformity in idiopathic scoliosis, associated with ribcage asymmetry which can lead to reduced respiratory capacity and the presence of a cosmetically disfiguring 'rib hump'. For these reasons, correction of vertebral rotation is a goal of idiopathic scoliosis surgery [1].

Although both lateral curvature and rotation appear to increase together in progressive scoliosis, the mechanisms driving vertebral rotation are not clearly established and it is not known whether lateral curvature precedes rotation, or vice versa [2].

Recent studies using computed tomography (CT) or magnetic resonance (MR) imaging have allowed detailed measurements of vertebral rotation not possible with standard radiographs. Birchall et al [3] found that the most axially rotated vertebrae occurred at the coronal apex of the curve, and also that the largest intravertebral (within the bone) and intervertebral (within the disc) rotations occurred towards the ends of the curve, with smaller relative rotations at the apex. Acaroglu et al [4] found that the coronal apex and the transverse apex (most rotated vertebra) coincided for only 10 out of 33 structural curves however, with the most rotated vertebra occurring as far as two levels from the coronal apex in some cases.

To the best of our knowledge, previous studies have not explicitly identified the concept of gravity-induced torsion or attempted to quantify the role which it may play in producing vertebral rotation. This study investigates the hypothesis that vertebral rotation in idiopathic scoliosis is caused by growth in the presence of gravity-induced torsions, the twisting moments generated by body weight forces acting on the scoliotic spine.

Materials and Methods

Consider a column-like structure subjected to a compressive force. If the structure is of very simple geometry (e.g. a cylinder or prismatic bar) then the stress in the structure will be simple and uniform throughout. If the column-like structure is curved in one plane only, the compressive load will induce bending moments in the plane of the curvature. Note that this case is analogous to the geometry of the healthy spine with its thoracic kyphosis and lumbar lordosis in the sagittal plane. In the most general case however, the column may be curved in three dimensions, such that its curvature does not lie in any one plane. We refer to this case as out-of-plane curvature (Figure 1).

For out-of-plane curvature, the compressive load will induce bending components in orthogonal reference planes, but a torsional moment is also induced which tends to twist the column about its own axis. The action of the torsional moment may be thought of as the same effect which occurs in a coil spring, whereby compression of the coil causes twisting of its cross-section.

In some cases, a column may appear to be curved out-of-plane since its projections in each of two orthogonal observation planes are both curved, whereas in fact its curvature is completely contained within a third plane which lies at an angle to the two observation planes. Compression of such a column would not generate torsional moments, only in-plane bending moments. Perdriolle et al [5] suggest that the scoliotic spine is a true out-of-plane curve however, since although local curves (thoracic or lumbar) may be approximately planar there is no single plane which can contain the entire thoracolumbar spinal curve.

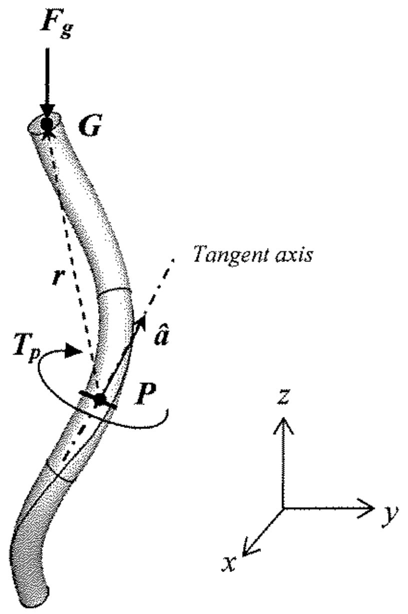


Figure 1: Torsional moment applied to a curved column by an applied compressive force

Calculating torsion for a curved column

The magnitude of the induced torsion at a particular cross-section is dependent on both the applied compressive force and the relative orientation of the column's axis at the location of interest. In Figure 1, we define the *xy* plane as the transverse plane, the *yz* plane as the coronal plane, and the *xz* plane as the sagittal plane. Point $\boldsymbol{P}$ is the location on the spinal column axis at which the torsion is to be determined, $\hat{\boldsymbol{a}}$ is a unit vector tangential to the spinal column axis at $\boldsymbol{P}$, $\boldsymbol{F}_g$ is a gravity force vector $(0,0,-F_g)$ applied at point $\boldsymbol{G}$. Note that for this example point $\boldsymbol{G}$ has been located at the top of the column (representing the weight of the head and neck), but in general point $\boldsymbol{G}$ will not lie on the column axis. The displacement vector $\boldsymbol{r}$ is given by $\boldsymbol{r} = \boldsymbol{G} - \boldsymbol{P}$, and the *total* moment $\boldsymbol{M}_p$ induced by force $\boldsymbol{F}_g$ about point $\boldsymbol{P}$ is given by the vector cross product

$$\boldsymbol{M}_p = \boldsymbol{r} \times \boldsymbol{F}_g \qquad (1)$$

The three components of the total moment vector represent bending moments in the coronal, sagittal and transverse planes respectively, denoted by $\boldsymbol{M}_{cor}$, $\boldsymbol{M}_{sag}$ and $\boldsymbol{M}_{trans}$. Note that $\boldsymbol{M}_{trans}=0$ since a vertical (gravitational) force induces no moment in the transverse plane. Once the total moment $\boldsymbol{M}_p$ about point $\boldsymbol{P}$ has been determined, the induced torsional moment T_p is given by the projection of the total moment vector onto the tangent axis at point $\boldsymbol{P}$

$$T_p = \boldsymbol{M}_p \cdot \hat{\boldsymbol{a}} \qquad (2)$$

The preceding discussion applies to a single vector $\boldsymbol{F}_g$ acting at point $\boldsymbol{G}$. In reality however, the gravitational forces acting on a spinal column are better expressed as the sum of a number of gravity force vectors $\boldsymbol{f}_g$ acting at the centre of gravity of various body segments in the thorax and head/neck. For an arbitrary number of gravitational force vectors, the overall torsional moment T_p about point $\boldsymbol{P}$ is simply given by summation of the individual torsional moments t_p induced by each body segment gravity vector

$$T_P = \sum t_P \qquad (3)$$

Relationship between torsion and rotation

The static equilibrium approach just described allows determination of the torsional moments induced by gravitational forces for any given column geometry and weight distribution. Predicting the *response* of the spinal column to these torsional moments is much more complex however. The torsion is resisted by both passive (bone, discs, facets, ligaments) and active (muscle) spinal structures, and the load-bearing contributions of each of these structures is difficult to determine due to the complex geometry and material properties. Despite these uncertainties, it is reasonable to assume that some proportional relationship exists between torque and rotation, ie the higher the applied torque, the greater the vertebral rotation (so that the shape of the torsion and rotation profiles should be similar).

To assess this hypothesis, spinal curve geometry and intravertebral rotations were measured for a small group of four idiopathic scoliosis patients. Spinal curvature was measured using pre-operative coronal and sagittal standing radiographs. The three-dimensional profile of the standing spine was approximated by defining a curve located along the anterior edge of the vertebral canal. This approach is based on a recent study by Petit et al [6] who located instantaneous centres of rotation (ICRs) of the scoliotic spine in the neural canal. On coronal radiographs, landmark points at the anterior edge of the canal were defined as those points bisecting the line between the innermost edges of the pedicles for each vertebra. On sagittal radiographs, landmark points were defined as those points at the junction between the pedicle and the vertebral body, midway between the superior and inferior edges of the pedicle. High order polynomial functions were used to fit equations to the spinal canal centroid points in the sagittal (*xz*) and coronal (*yz*) planes respectively, providing a continuous description of the spinal curvature in three dimensions.

Gravitational body forces in the standing posture were estimated from anthropometric data on body segment masses and centres of gravity [7]. Gravitational forces on the standing spine were approximated using two vectors; $\boldsymbol{F}_{g1}$ representing the weight of the head and neck, and $\boldsymbol{F}_{g2}$ representing the weight of the arms and torso (Table 1).

The spinal curve geometry and gravity forces $\boldsymbol{F}_{g1}$ and $\boldsymbol{F}_{g2}$ were then used to determine the torsional moment distributions along the thoracolumbar spine using equations (1) to (3).

Table 1: Gravity vector magnitudes and locations

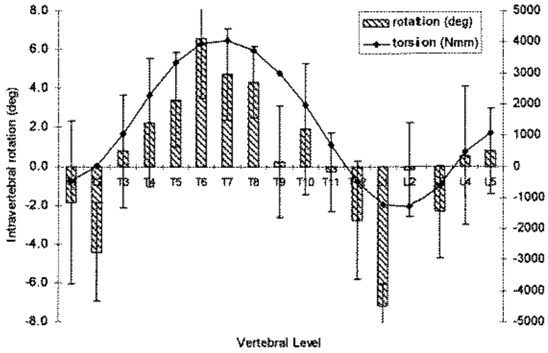
Vector	Body segments	Location	% body weight
F_{g1}	Head & neck	Centroid of T1 sup. endplate	8.1
F_{g2}	Torso & arms (excl. pelvis)	Vertically above sacral promontory	45.5 (scaled T1 to S1)

Low dose pre-operative thoracolumbar CT scans of the same patients (previously performed for endoscopic surgery planning) were then used to measure vertebral rotation using Aaro's technique [8] from levels T1 to S1. Rotation was measured using reformatted CT slices through the plane of each vertebral endplate, thus avoiding angulation errors associated with the use of transverse CT slices [3,9]. Each rotation measurement was repeated by three observers on three separate occasions for a total of nine manual measurements per endplate. The relative rotation between superior and inferior endplates of each vertebra is a measure of the torsional deformation in the bone, and is referred to as intravertebral rotation. Measured intravertebral rotations were compared with gravity-induced torsion profiles.

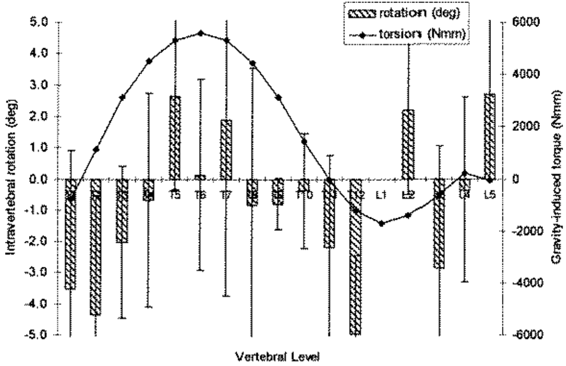
Results and Discussion

Figure 2 shows a comparison of intravertebral rotation and gravity-induced torsion profiles for the entire thoracolumbar spine for each patient in the group. The error bars in Figure 2 correspond to ±1 standard deviation of the intravertebral rotation measurements (n=9). For all of the patients shown, general agreement is apparent between the shape of the intravertebral rotation profile and the shape of the gravity-induced torsion profile along the length of the spine, supporting the hypothesis that gravity-induced torsions are a driving force for vertebral rotation during skeletal growth in idiopathic scoliosis.

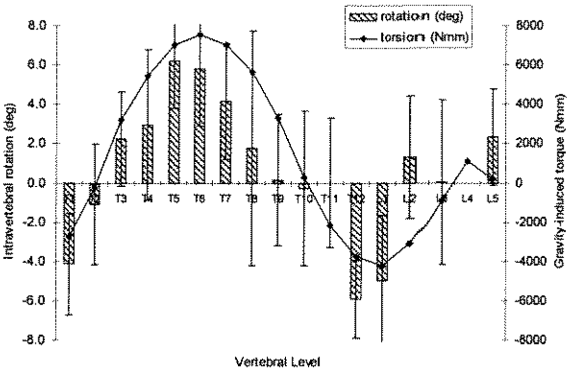
Table 2 gives details for each patient including maximum intravertebral rotation and maximum gravity-induced torsion. Table 2 shows that gravity-induced torques as high as 7.5Nm can act on the spines of idiopathic patients due to static body weight in the standing position (although the typical maximum seems closer to 4-5Nm based on this small patient group). Maximum intravertebral rotations (for a single vertebra) are in the 5-7° range, and these mainly occurred at the lower end of the major curve. The rotation measurements confirm the finding of previous authors that maximum intravertebral rotations occur at the ends of a scoliotic curve (with little relative rotation at the apex), and this finding would be expected based on the shape of the calculated gravity-induced torsion profiles. The rotation measurements also confirm the observation of Birchall et al [3] that a significant proportion of total vertebral rotation in idiopathic scoliosis can occur in the bone. This finding is clinically significant, since intravertebral rotation is 'built into' the vertebra and cannot be corrected by surgery.



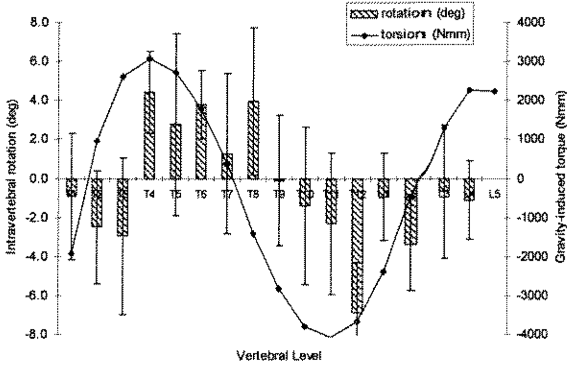
Patient A



Patient B



Patient C



Patient D

Figure 2: Comparison of gravity-induced torsion and intravertebral rotations for thoracolumbar spine

Table 2: Gravity-induced torsion and intravertebral rotation summary for each patient

Patient	Max intra. rotation	Max gravity-induced torque	Coronal Apex
A	6.9° at T12	4.1Nm at T11	T7/T8
B	7.2° at L1	4.0Nm at T7	T9
C	5.0° at T12	5.6Nm at T6	T9
D	6.2° at T5	7.5Nm at T6	T9

In all four patients, the head/neck weight made a much smaller contribution than torso weight to total gravity-induced torsion.

In the lumbar region, muscle forces acting to keep the spine in an upright posture apply additional (internal) compressive loads to the spine. These internal loads may generate additional torques, although the torsion would be a consequence of compression on a three-dimensionally curved column rather than direct muscle action [10]. The effects of these internal muscle forces are not included in this analysis, and are a possible reason for the discontinuities in measured intravertebral rotation between adjacent vertebral levels in the lumbar region (for example between L1 and L2 for Patient B in Figure 2).

The results are also subject to a degree of uncertainty in the intravertebral rotation and spinal curve measurements. The quality of standing radiographs (especially lateral) is an issue for defining spinal curve geometry in three dimensions, and future studies will incorporate biplanar radiography to ensure more accurate measurement of standing spinal geometry. The error bars for intravertebral rotation in the graphs (±1 standard deviation, n=9 manual measurements per endplate) also show that observer variability can be significant for these measurements. Our research team has recently developed a computer algorithm for automatic measurement of vertebral rotation, thus avoiding inter and intra-observer measurement variability [11], and this algorithm will allow improved precision in future rotation measurements.

Gravitational body weight forces in the upright posture are the primary sustained loads experienced by the spine. As already mentioned, predicting the response of spinal tissues to gravity-induced torsional loads is difficult, however we suggest that in the same manner as the Heuter-Volkmann principle describes modulation of epiphyseal growth by compressive loads, gravity-induced torques may modulate intravertebral rotation. Little is known about the effect of shear stresses on vertebral growth, and further exploration of this area is required.

Conclusions

The analysis in this study indicates that gravity-induced torsion will produce vertebral rotation in idiopathic scoliosis. Profiles of gravity-induced torsion and intravertebral rotation showed general agreement in a small group of idiopathic scoliosis patients.

From a pathomechanics perspective, the spine must be curved in three dimensions to produce gravity-induced torsion, therefore coronal curvature would be expected to precede vertebral rotation in idiopathic scoliosis. Studies postulating transverse plane perturbation as a mechanism for initiating scoliosis cannot be discounted on the basis of this analysis, but our results suggest that initial lateral deviation induces gravity-induced torsion which in turn causes rotational bone growth (in an analogous manner to the Heuter-Volkmann principle for longitudinal growth).

Future work will apply this methodology to a wider group of idiopathic scoliosis patients using an automatic rotation measurement computer algorithm to remove observer error from the intravertebral rotation measurements. Investigation of the effect of (torsional) shear stresses on vertebral growth is also required to better understand the pathomechanics of vertebral rotation in scoliosis.

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