MECHANICS OF THE HUMAN SPINE

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①This talk on some aspects of the mechanics of the human spine will contain six sections:

Section I - Evolutionary Considerations

Section II - A list of the components of the spinal support system

Section III - Kinematics or motion without regard for forces

Section IV - Will deal with statics or force interactions under conditions of static equilibrium

Section V - Mechanics of the deformed spine

and Section VI - Will be a few comments on analogs of the spinal support system, and if time permits, I will demonstrate a few examples of buckling.

I. EVOLUTIONARY CONSIDERATIONS

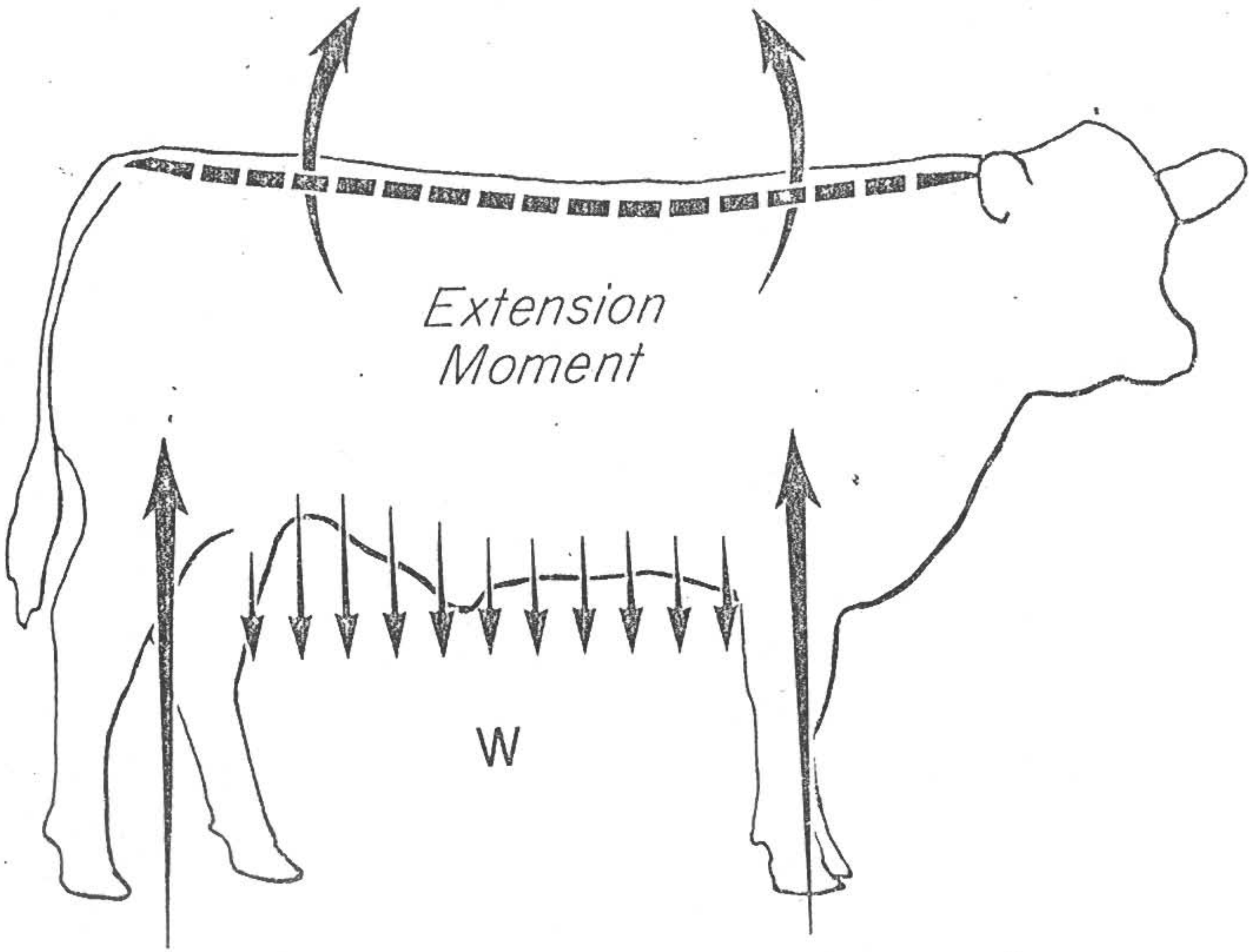
②

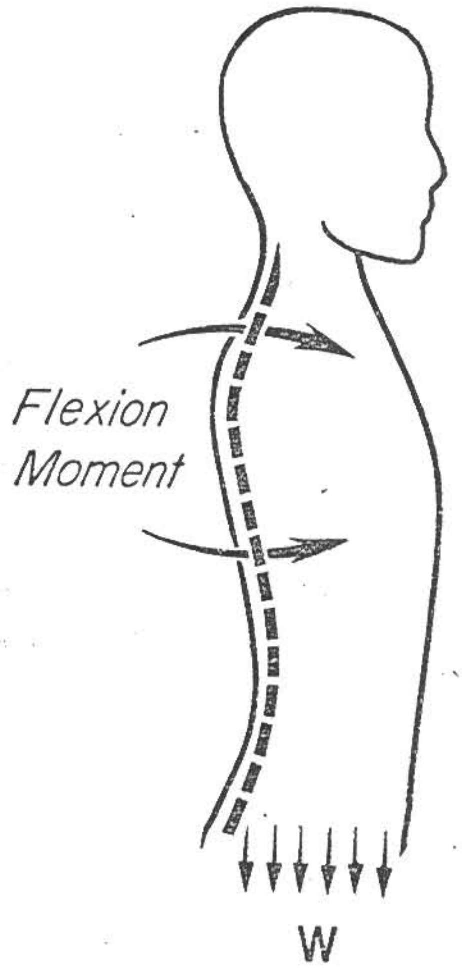
Despite similarities of form, articulations, connections to the thorax and position in the trunk between the vertebrae of the cow and the vertebrae of the human, it is most commonly loaded in a very different, almost opposite manner. We all realize that the upright stance creates an axial load on the vertebral column. However, the differences are even more appreciable when we consider the nature of the task the muscles must perform and the size of the axial loading.

/*The normal standing posture of the quadriped produces a gravitational and ground reaction loading configuration which subjects the spine to an extension moment. Actively generated forces must counteract by exerting a flexion moment on the spine. Neither of these loading systems is likely to generate very large axial loading on the spine.

3 ⊛The normal standing and sitting posture of the biped produces a gravitational loading configuration which subjects the bipedal spine to ^not only an axial load, but to a a flexion moment. The actively generated forces must counteract by exerting an extension moment. Both the gravitational loading and counteracting muscle forces (especially the latter) exert large axial compressive loads on the bipedal spine.

The similarity of design but large differences in loading seem paradoxical within the scheme of nature. Evidently, skeletal evolution has not yet fully responded to the advent of bipedal stance. Some musculo-skeletal instability problems, particularly of the spine and hip might be better understood if we look closely at them as somewhat atavistic and not yet redesigned by evolution to best suit our upright stance.


Extension
Moment
W


Flexion
Moment
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III. PRIMARY COMPONENTS OF THE SPINAL SUPPORT SYSTEM

The primary components of the spinal support system are the:

1. Vertebrae
2. Intervertebral Discs and Facet Joints
3. Ligaments
4. Muscles (including abdominals and costals)
5. Costal Elements

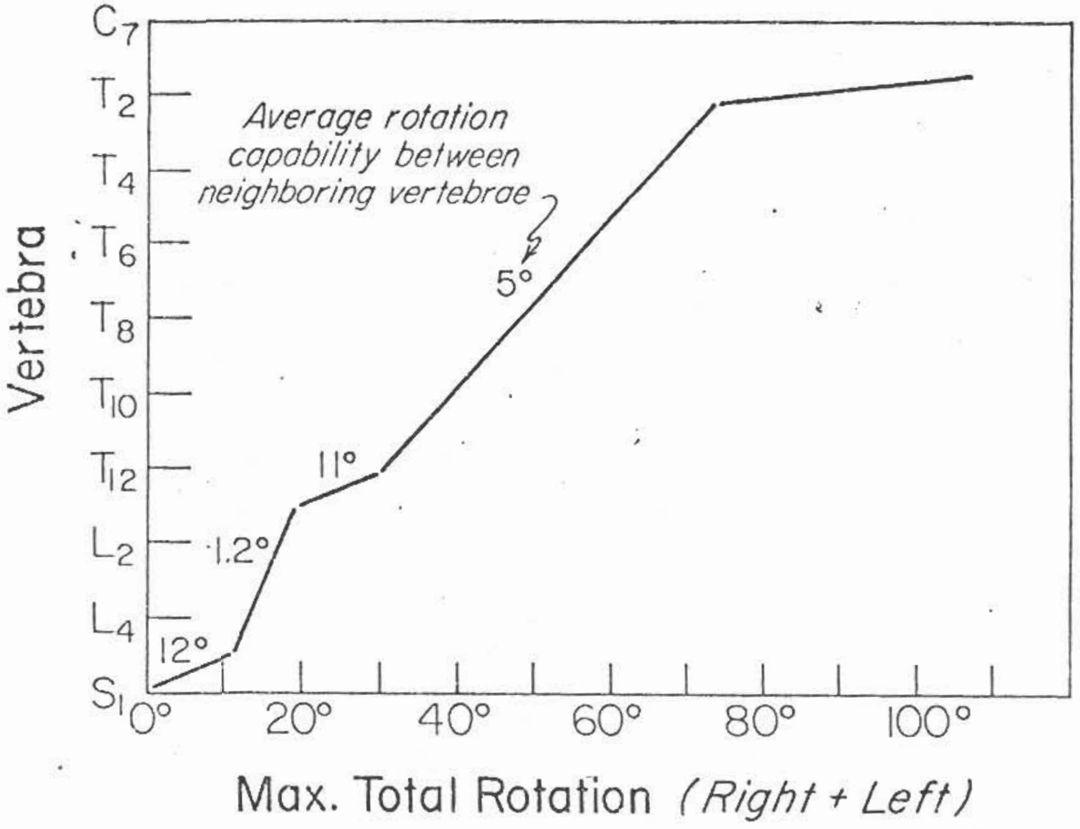
III. KINEMATICS OF THE SPINAL COLUMN

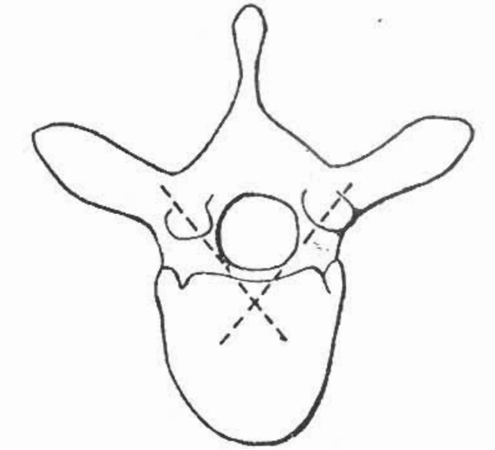
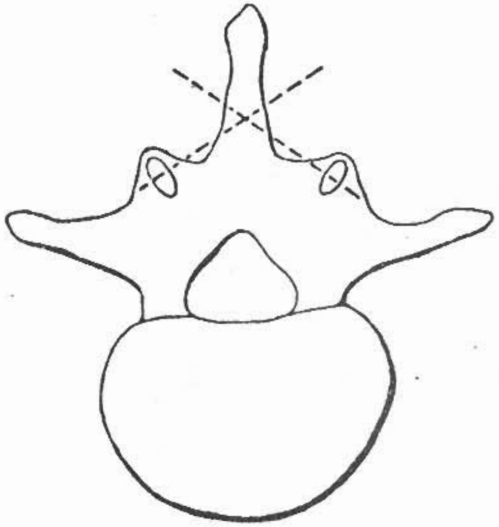
The vertebral elements are solid bodies separated from each other by the discs. The discs act like resilient, limited motion, spherical bearings. Posterior facet joints also play an important role in dictating the nature and extent of intervertebral motion as do the ligaments.

5 The intervertebral rotational range of motion is well illustrated in a graph of experimental data collected by Gregerson and Lucas. The graph shows the accumulated sum of both left and right rotation at each vertebral level relative to the sacrum. Average rotational capability between lumbar elements is less than 1° each way. Average rotational capability between thoracic elements is about 2.5°. Considerably greater rotational movement is possible at the lumbo-sacral junction and at the thoraco-lumbar junction. Gregerson and Lucas's data in the high thoracic region looks too questionable to draw conclusions from.

6 The primary reason for the lack of rotational mobility of the lumbar spine is the orientation of the posterior facet joints. The facets dictate an axial rotation motion center posterior to the disc. The facets of the thoracic spine are oriented to allow a motion center within the disc, and this, of course, is conducive to greater rotational mobility between vertebrae.

The relative capabilities for spine forward flexion, lateral flexion, and extension are also summarized on this slide. The rib cage is probably the limiting factor in thoracic spine extension and lateral flexion. When reviewing side bending films to judge the relative flexibility of scoliotic curves, remember the normal difference in lateral flexibility between the lumbar and thoracic spine.


Vertebra
C7
T2
T4
T6
T8
T10
T12
L2
L4
S1
Average rotation capability between neighboring vertebrae
5°
11°
1.2°
12°
0°
20°
40°
60°
80°
100°
Max. Total Rotation (Right + Left)

	FORWARD FLEXION	LATERAL FLEXION	EXTENSION	AXIAL ROTATION
 THORACIC	Good	Fair	Poor	Greater
 LUMBAR	Good	Good	Good	Lesser

IV. STATICS OF THE SPINAL COLUMN

The vertebrae and discs are the compressive elements of the spinal system. The discs are extraordinary in their ability to resiliently dissipate energy while serving as compression members. This is accomplished by containing a liquid (nucleus pulposus) within an extremely strong but flexible annulus (annulus fibrosus). The annulus is so strong that extreme axial loading will usually cause herniation of the nucleus into the vertebral body before failure of a healthy annulus (James Morris).

The ligaments and muscles are the tension elements of the spinal system. Compared to gross physiological movements, ligaments are relatively inelastic (in the short range of time scale). As such, they contribute little to the stability of the spinal column until the limits of its range-of-motion are approached (Lucas and Bresler have shown that the ligamentous spine buckles under an axial load of only two kilograms). However, as these range-of-motion limits are approached, the ligaments become taunt and contribute greatly to spine stability. A combination of movements (e.g., rotation plus flexion) will make some ligaments tight before the limits of either pure rotation or pure flexion are approached.

As mentioned above, ligaments are inelastic in the short range. However, they are plastic in the longer range by virtue of their growth response to their ongoing state of tension (e.g., persistent tension will result in lengthening, and persistent lack of tension will result in the ligaments becoming shorter over a period of time).

It is important that we make this distinction between immediate and long range material characteristics. Later, as we discuss spine deformities, we will be dealing with the long term plasticity of ligament and bone.

7 ⊛To better illustrate their respective roles, the primary muscles affecting spine stability can be fit into four broad categories:

1. The shorter, deeper muscles
2. The longer, superficial muscles
3. The abdominal muscles
4. The intercostal muscles

8 ⊛The short, deep muscles (interspinales, intertransversarii rotatores, multifidus, semispinales), being the closest to the centers of vertebral flexion-extension motion are capable of exerting only relatively small extension and lateral bending moments. (Their effective moment arm being quite small.) Their origins and insertions are either on *neighboring* vertebra or span only a *few* vertebrae. Because of this, these muscles give the spinal column tremendous stability of the type that can resist buckling. That is their primary function.

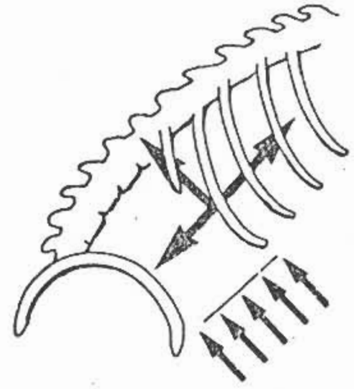
9 ⊛The longer, more superficial muscles being more posterior are capable of exerting large extension moments on the spine, giving it excellent gross stability against the large flexion moments imposed by physiology, exercise and labor. *They are the gross and powerful motors of the spine*. These muscles span many vertebra. In some cases, the origins and/or insertions are not even on the vertebrae. The longer span of the pull without *direct*, *positive*

attachments to the individual vertebrae along the span means that they contribute little to the spine's ability to resist buckling. In fact, the tremendous axial loading which they exert on the spinal column pushes the system closer to the buckling point.

10 ⊛The abdominal muscles are also extremely important to the stability and motion of the spine. The transversus abdominus and the abdominal obliques have a strong effect on the spine through their effect on intra-abdomino-thoracic pressure. As the abdominals contract to compress the intra-cavity contents, the contents behave like a hydraulic fluid. 11 ⊛The fluid pushes posteriorly on the anterior aspect of the spine and connecting fascia. More importantly, it presses down against the pelvic floor and upward against the thorax like two opposing pistons in a cylinder. The net effect of this fluid pressure is to distract the lumbar and much of the thoracic spine. There is also a net extension moment resulting because both "pistons" are anterior to the spine. The extension moment exerted by the opposing pistons is greatest when we are in a bent over or flexed lumbar posture.

This is very useful as we straighten from a forward flexed position (especially if we are lifting something). The effectiveness of the abdominals in producing their stabilizing extension moment on the torso depends on the volume of the abdomino-thoracic cavity relative to the resting length of these muscles. Portly weight lifters tend to do well. All weight lifters take a deep breath and "seal it" just before the lift (in fact, we all do it to some extent without thinking about it).

Extension Effect of Abdominal Compression in the Flexed Position



after Morris

The rectus abdominus seems clearly to be a spine flexor in the flat-belly physique. However, in the solid but portly physique where it partially encircles a large abdominal volume, it too may act to increase intra-abdominal pressure.

The role of the quadratus lumborum muscles seems to be quite straight forward. They laterally flex and extend the lumbar spine.

The intercostal muscles give active stability to the thorax over the full range of expansion or depression. They act in concert with the abdominals to compress the intra-abdominal fluid.

V. STABILITY AND BUCKLING IN THE DEFORMED SPINE

Because of balance needs and alignment reflexes, a deviation from normal spine alignment tends to induce a compensation somewhere else in the body. This is true for abnormal spine curvature in both the sagittal and coronal plane.

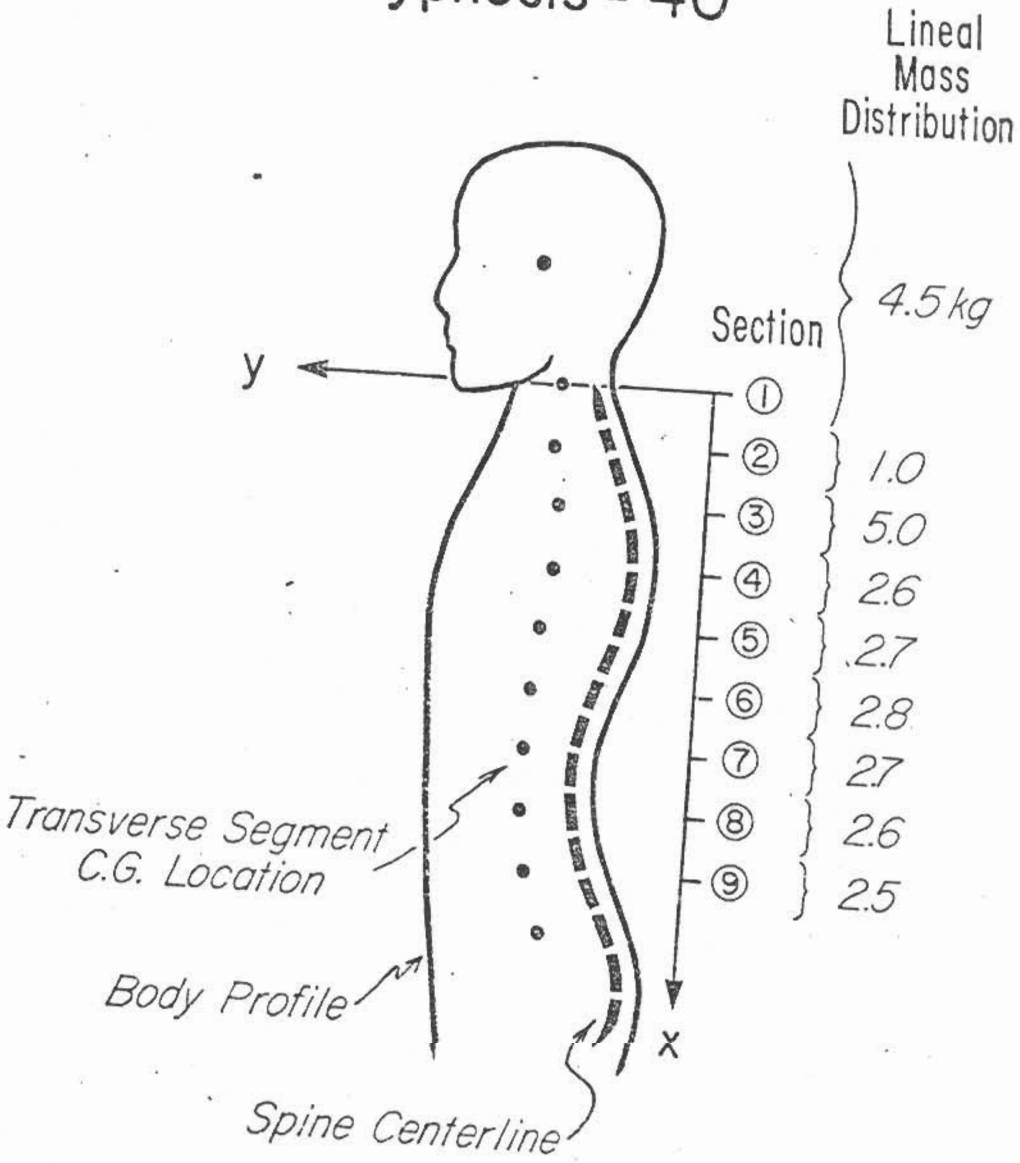
KYPHOSIS

Excessive thoracic kyphosis is usually balanced by an excessive lumbar lordosis. Occasionally, it occurs without lordosis in which case the person must stand with hips in greater extension to keep his gait and balance within comfortable limits. The classical kyphosis-lordosis probably starts in the thoracic spine. However, once established, attention *must* be given to reducing the lordosis in order to regain a normal spine.

Excessive thoracic kyphosis represents a failure of the thoracic spine complex to respond effectively to the flexion moments imposed. Failure may be in the *anterior compression* elements (anterior vertebral bodies and/or discs) or in the posterior tension elements (muscles, ligaments). We should be aware that failure in either case will bring added stress and possible harm to both anterior and posterior elements. Observing pathological changes in the anterior bodies (i.e., wedging) does not prove them to be the source of the problem. Following are some calculations which will give some idea of how much such a kyphotic deformity adds to the burden of the structure.

12

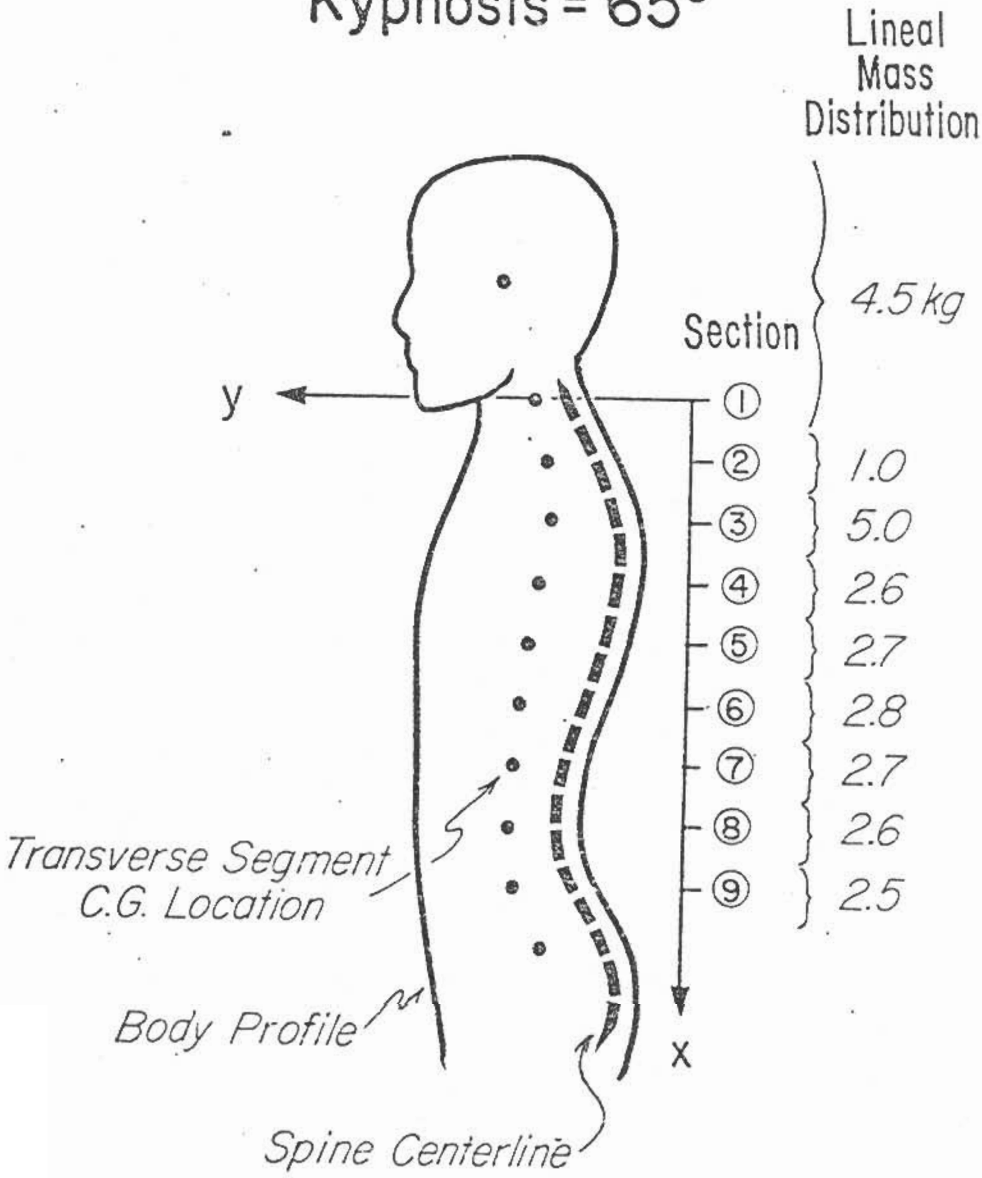
⊛I have constructed on paper two hypothetical patients. Both weigh 45 kilograms. /*One has a thoracic kyphosis of 40°, and



Kyphosis = 40°

Lineal Mass Distribution
4.5 kg
Section
y
①
②
1.0
③
5.0
④
2.6
⑤
2.7
⑥
2.8
⑦
2.7
⑧
2.6
⑨
2.5
Transverse Segment C.G. Location
Body Profile
x
Spine Centerline

Kyphosis = 65°


Lineal Mass Distribution
4.5 kg
Section
y
①
② 1.0
③ 5.0
④ 2.6
⑤ 2.7
⑥ 2.8
⑦ 2.7
⑧ 2.6
⑨ 2.5
x
Transverse Segment C.G. Location
Body Profile
Spine Centerline

Calculation of Kyphotic Bending Moment for Two Idealized Torso Configurations

$$M_b \Big|_{x_o} = g \int_0^{x_o} M(x) \left\{ L(x) - S(x_o) \right\} dx$$

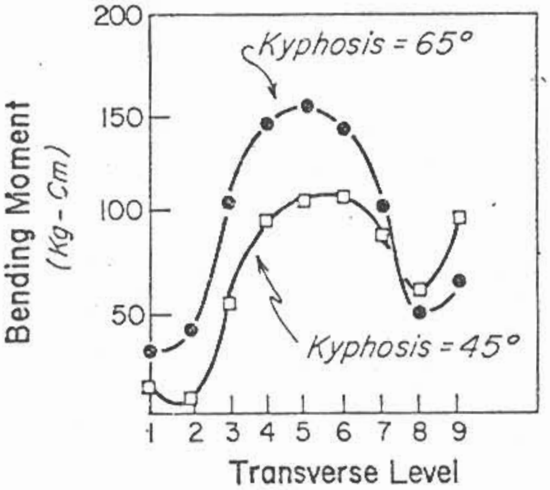
WHERE

M_b = *Gross bending moment exerted on the spine by gravity*

x_o = *Any specific choice of level*

g = *Acceleration of gravity*

$M(x)$	*Describes mass distribution as a function of level*
$y = S(x)$	*Describes position of spine in the sagittal plane*
$y = L(x)$	*Describes position of C.G. of each section level*


Kyphosis = 65°
Kyphosis = 45°
Bending Moment
(Kg - Cm)
200
150
100
50
1
2
3
4
5
6
7
8
9
Transverse Level

⊛13 the other has a thoracic kyphosis of 65°. /⊛I have made reasonable estimates of the corresponding spine morphology, mass and center of gravity location for a number of arbitrary transverse body sections, and calculated the gross gravitational bending moments for each of the two body configurations. ⊛14 These three slides give the equation which was developed and notation used. 15 16 ⊛⊛// They aren't of interest to most of you. ⊛17 However, this graph of the calculated results may be. You will notice that as we start at the top of the spine and move downward the gravitational bending moment increases and reaches a maximum at the transverse level, corresponding to about T9, and then drops off and hits a minimum at a level, corresponding to about L3.

For the patient with a 40° kyphosis, the maximum bending moment is about 100 Kg-Cm. For the patient with a 65° kyphosis, the maximum bending moment is about 150 Kg-Cm. That is a 50% increase in the bending moment burden on the spine due to a 25 degree increase in kyphosis. The increase in pressure on the anterior aspect of the vertebral bodies is surely greater yet.

⊛18

SCOLIOSIS

There has been some argument as to whether this deformity should be called scoliosis, rotation plus lordosis, or rotational lordosis. The word scoliosis seems appropriate. The important thing to realize is that the three-dimensional deflection and twisting we observe in the scoliotic spine is a typical beam buckling mode. There is nothing physiologically or pathologically deep and mysterious about the rotation aspect.

⊛19 If and how a beam buckles depends on several factors:

1. Cross section size and shape (degree of symmetry)
2. Length
3. End Conditions
4. Nature of Loading
   a. Compression
   b. Bending
   c. Direction of Application

$P_{crit} = C\,\frac{EI}{L^2}$, C depends on end Cond.

P_{crit} : Buckling load
E = Modulus of Elasticity
I = Cross section moment of inertia with respect to buckling plane
L = Beam Length

[illegible] Attention to the morphology of the buckled configuration can reveal some things about the structure and the loading which caused the failure. A buckled beam will be twisted in the direction of least resistance. The posterior and postero-lateral aspects of the human spine are tied together in a superior manner and will deviate least from the midline. The anterior longitudinal ligament proves with time to be more plastic, and it is twisted toward the convex aspect of the curve. Scoliotic patients with relatively very little rotation probably have abnormally strong, hypertrophied anterior ligaments. Large amounts of rotation indicate unusually plastic anterior ligaments.

⊛20 The asymmetry of the scoliotic curve suggests that right-left asymmetry of growth is the culprit. That may be a factor. However, the high incidence of relative thoracic lordosis (often conspicuously confined to the neighborhood of the apex of the curve) suggests a kind of A-P imbalance might be at work. Longitudinal overgrowth of the anterior bodies or overactive extensor muscles would decrease the normal thoracic kyphosis. ⊛21 A plausible hypothesis for the sequence of events is that the spinal column buckles as the anterior constraints, and the activity of posterior muscles lead to a ⊛22 super critical combination of axial loading and bending moment. Such a mechanism would be stimulated at times of growth spurt.

I will demonstrate this mechanism later.

Once a scoliotic deformity has been established, the following things will resist its progression:

⊛23
1. Hard tissues compressed on the concave aspect
2. Soft tissues under tension on the convex aspect
3. Tightness of anterior ligaments resisting rotation

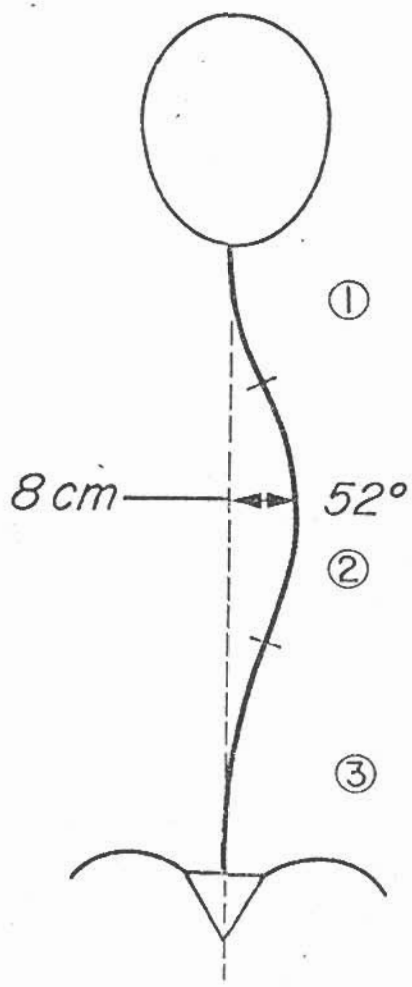
With regard to Item No. 2, the postero-convex musculature becomes, of course, progressively less effective in resisting progression, as rotation brings these muscles around toward the concave side.

⊛24 The following things will resist correction of the deformity.

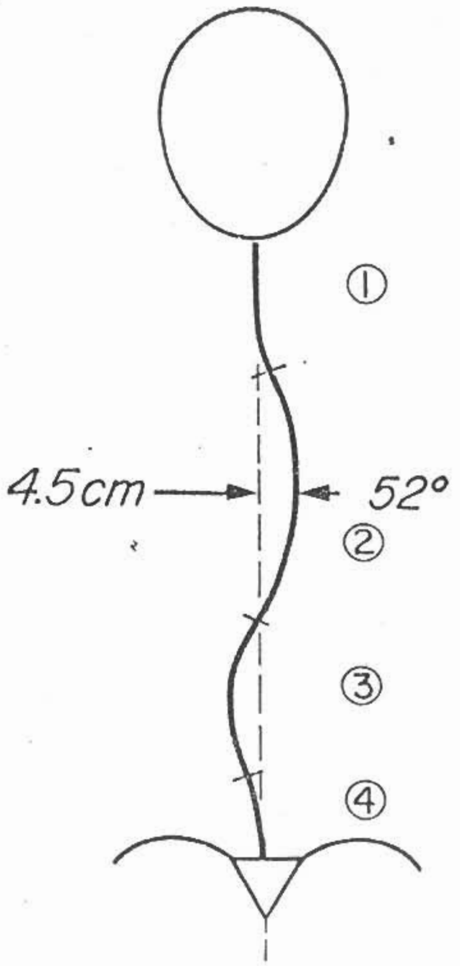
1. The initiating mechanism (unknown)
2. Gravitational force moments
3. Overgrown hard tissue on the convex aspect
4. Tight soft tissues on the concave aspect

The operation of gravity deserves some explanation to appreciate the interplay between it and the deformity.

A spine without curves in the coronal plane enjoys freedom from any significant lateral bending moment during normal relaxed sitting or standing. ⊛25 As scoliosis develops, gravitational forces acting on the superimposed body mass exert a lateral bending moment on the deformed spine. The lateral bending moment which is now a deforming moment is roughly proportional to the lateral deviation of the vertebra from the coronal mid line of the body. Using the arbitrary scale of the figures on your left, this deviation is 8 cm. for a 52° thoracic curve. I believe that a second major curve does not develop to compensate C7 over S1 alignment. This is clearly possible without developing a second full curve. It develops to minimize the size of the deforming gravitational moment. We see in the figure on your right how the moment arm of 8 cm. is reduced to 4.5 cm. by development of an opposite lumbar curve. The deforming gravitational moment acting on the apex of the curve will likewise be reduced by almost 50% through the development of this compensating curve.



"Single Curve"
plus two "fractional" curves



"Double Curve"
plus two "fractional" curves

VI. ANALOGS OF THE SPINE SUPPORT SYSTEM

Several groups have constructed idealized mathematical analogs of the spinal system. These models contain solid and elastic elements in approximation of the bones and muscles respectively. The motions are constrained mathematically to approximate the working of the ligaments and facet joints. Properties of the elements can be changed at will. A high speed computer is necessary to obtain results. In some cases, results can be presented pictorially on a Cathode ray tube.

The analogs do not possess any of the viscoelastic and anelastic features necessary to approximate what will occur over a period of months or years as a result of growth or remodeling of bones and ligaments. They contain no features which approximate the compensation mechanisms of the body.

Perhaps the greatest investments in spine modeling have been made by "Schultz, Andriacchi, DeWald, Galante, et. al." in Chicago. Their most recently reported model contains over 350 distinct elements. However, their conclusions at the end of the article stated that they could have made just as accurate and profound conclusions using a single elastic beam as the analog. Recently, I have become aware that DeWald is switching the emphasis and is relating the simple beam buckling parameters to anatomical variables. They appear to be having some success in predicting which curves will progress . With a "t" model of the spine cut from a block of polyethylene foam and fiber tape, we can demonstrate:

1. Kyphotic buckling without lateral deflection or axial rotation.

2. Three-dimensional buckling with axial rotation.
3. Buckling action of overactive spine extensors.

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