Frequency response analysis of the in-vivo human spine
by Stephen Walter Radons

A thesis submitted in partial fulfillment of the requirements for the degree of MASTER OF SCIENCE in MECHANICAL ENGINEERING
Montana State University

Abstract:
In this study, a finite element model of the human spine is presented. The intent of this research is to investigate the possibility of using the frequency response analysis technique as a diagnostic tool for determining the success of spinal fusions.

Two boundary conditions are studied such that the actual boundary condition is assumed to be between those used. One boundary condition has the spine pinned at the sacrum and the other boundary condition has the spine fixed to the sacrum. An analytical solution is obtained approximating the normal spine, the fused scoliotic spine, and the fused scoliotic spine with a Harrigan rod implant.

A comparison to experimental results is made for the cases listed above as well as the different boundary conditions used.

The results indicate that the use of the natural frequencies of the spine as a diagnostic tool have major experimental and analytical problems associated with them. The possible use of mode shape changes when spinal fusions are performed may have diagnostic potential but the technique needs added experimental and analytical research before a definite decision on this method can be made. The indication of dampening calls for an extended analysis that includes the dampening effects.

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Date 10/25/78

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by

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A thesis submitted in partial fulfillment
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ABSTRACT

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CHAPTER I

INTRODUCTION

Several investigations into the response of the human spine to an externally applied harmonic excitation have been carried out. These investigations indicate that several natural frequencies, or bending modes, exist for the spine in the sagittal plane when it is excited harmonically through the frequency range of 30 to 500 hertz. The purpose of this research is to develop an analytical vibrations model of the human spine that can adequately simulate the experimental frequency response. The proposed use of the model is to determine the healing rate of the scoliotic spine by comparing frequency response of the spine after a corrective procedure with the anticipated frequency response predicted by the model.

The experimental frequency response plots in this study were obtained from Dr. John Jurist, of the Deaconess Hospital in Billings, Montana. These frequency response plots were acquired by placing a low amplitude harmonic exciter on a spinous process of one vertebra and a transducer for output on a different vertebral spinous process. The frequency response plots have peak amplitudes where the systems natural frequencies occur. The band width of these peaks indicates the damping inherent to the system. A model that accurately simulates the experimental frequency response can be used to predict the response when physical changes in the spine are encountered. This may be useful as a tool for determining rheological parameters of in-vivo human bone and tissue. Previously, in-vivo properties were obtained from, or extrapolated from, in-vitro studies resulting in somewhat inaccurate values since tissue properties change within a matter of minutes after death.

The model used in describing the spine utilizes the finite element technique. The spine is modeled as 23 rigid bodies representing the vertebrae, 23 elastic beam elements representing the intervertebral discs, and 30 curved elastic beam elements representing the ribs. Four linear springs join adjacent vertebrae representing the various ligaments and muscles associated with the spine as well as the possible fusion tissue used to stiffen the spine. The fusion material is usually calcified bone used to stiffen the scoliotic spine. The head mass is included and rests on a spring representing flesh. The ribs are likewise supported on the frontal ends by springs representing the collagenous connection to the sternum. All along the vertebral column, an elastic substrate is used to represent internal flesh. Two cases are studied; one with the spine pivoted about the sacral connection and one with the spine cantilevered to the sacrum.

Due to the large computer storage and time required in solving the resulting 270 and 269 degree of freedom systems, a reduction of coordinate scheme is used to reduce the global coordinates to 16 generalized coordinates. Validity of the model is indicated by matching natural frequencies of the model to those obtained experimentally from a 22 year old male.

CHAPTER II

LITERATURE REVIEW

Most previous work analyzing the spine as a mechanical system has been affiliated with high acceleration response. These studies were triggered by the large number of spinal injuries encountered with high acceleration ejections from aircraft.

The first models of the spine were simple lumped mass systems. Latham [2] modeled the spine as a weightless spring supporting a mass. Other similar models were developed using various means to determine the spring constant of the spine. All of these were single degree of freedom models which did not account for the change of curvature of the spine in the sagittal plane or the resulting stresses due to this change. To study sagittal plane effects, Hess and Lombard [3] modeled the spine as an elastic beam. Terry and Roberts [4] added viscoelastic effects to the Hess-Lombard model. The results of these earlier models indicated the need for a discrete model composed of mass-spring-dashpot elements representing each of the intervertebral discs and vertebrae. The necessity for a discrete model required an extensive experimental investigation of the rheological properties of the vertebrae and intervertebral discs. This investigation was first accomplished by Orne and Liu [5].

Andriacchi, et. al. [6] developed a three-dimensional mathematical model of the spine along with the interacting ribs. The model incorporated anatomical features such as sagittal plane curves, the complex geometric shape of each vertebra and rib, and level to level variations in stiffness of connective tissue. The model did not include viscoelastic effects or the upper cervical spine and head mass.

Previous vibration studies of biological systems have been limited. Jurist [7] proposed using the measurement of the resonant frequency of the ulna and other long bones as a means of disease detection or as a monitor of fracture healing. He described effects of experimental procedures, geometry, positioning, and muscle tension associated with this technique. He also discussed the reproducibility of experimental results.

Matz [8] set up an experiment similar to Jurist's and carried out a statistical analysis of a large sample of humans. He vibrated the forearm transversely at a low amplitude over a frequency range of 80 to 600 hertz. Four factors, bone size, arm length, muscle development, and fleshiness, were correlated with the first resonant frequency. Mozer [9] determined the effect of stiffness on the first natural frequency of the forearm and Harrigan [10] refined the development of equipment used in determining the dynamic response of a forearm.

Garner and Blackketter [1] extended the analysis of the forearm by developing a finite element model. A steady-state response to harmonic excitation was obtained for the three-dimensional, viscoelastic model with results in good agreement to those obtained by Matz.

Jurist and Blackketter [11] discussed possible uses of the frequency response method in the monitoring of long bone fracture healing rates, rates of osteoporosis (bone mineral content loss), and stiffening rates of the scoliotic spine.

Adelsbach [12] modeled the spine as a series of rigid bodies (vertebrae) connected by viscoelastic beam elements (intervetrabral discs) with a pinned boundary at the bottom of the lumbar spine and a rolling support at the upper cervical vertebra. The head mass and ribs were ignored in this analysis. His results show the first natural frequency of the spine to be near 40 hertz.

CHAPTER III

THE HUMAN SPINE

In order to model the human spine accurately, information on the makeup of the spine and its association with related parts of the body is necessary.

The Vertebral Column

The vertebral column (Figure 3-1) consists of 24 vertebrae held in position by strong ligaments, muscles, and by the interlocking nature of their articulations. All vertebrae have basically the same structural pattern with slight variations in size and in some of the processes. The vertebrae are classified in groups in which there are seven cervical, twelve thoracic, five lumbar, five sacral, and four coccygeal vertebrae. The sacral and coccygeal vertebrae usually fuse into one sacrum and one coccyx.

The normal vertebral column exhibits four curvatures in the lateral view; two curving frontally, known as primary curves, and two curving posteriorly, known as secondary curves. The primary curves are located in the thoracic and sacral regions.

Abnormalities in curvatures are common. An excessive thoracic curvature is acknowledged as kyphosis (known as hunchback). A pronounced lumbar curvature is recognized as lordosis and a lateral curvature is known as scoliosis.

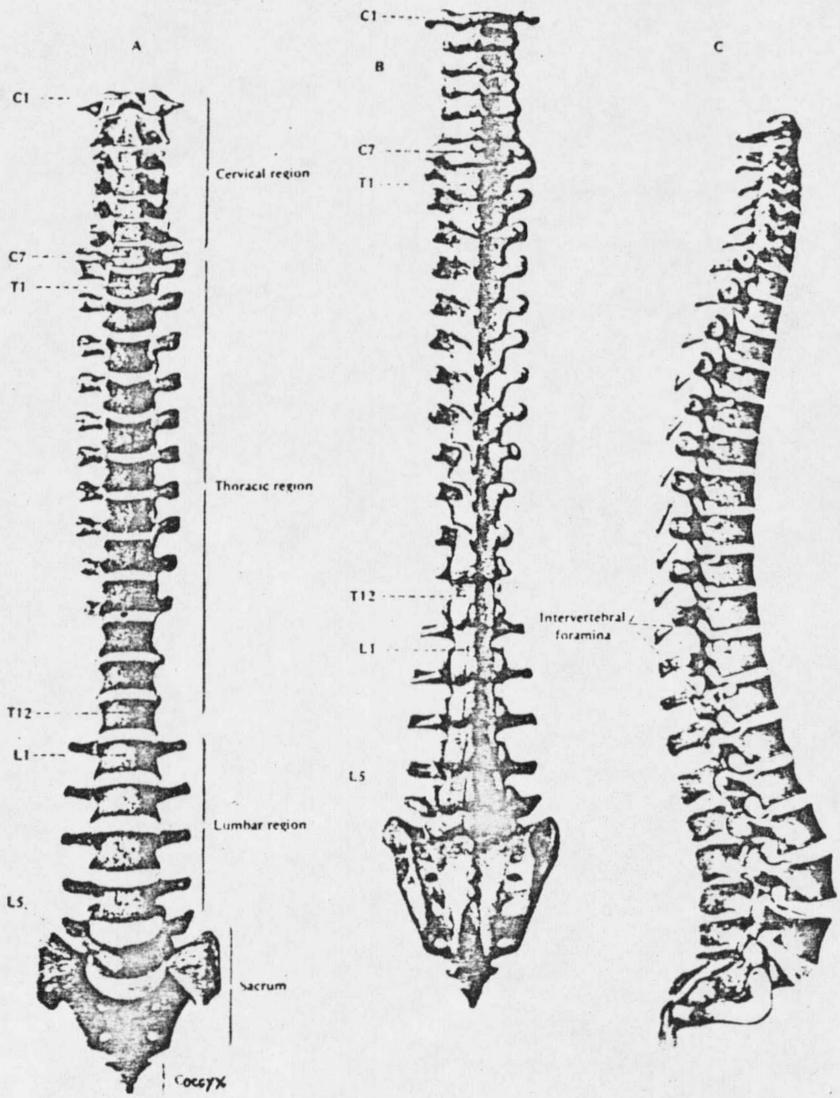
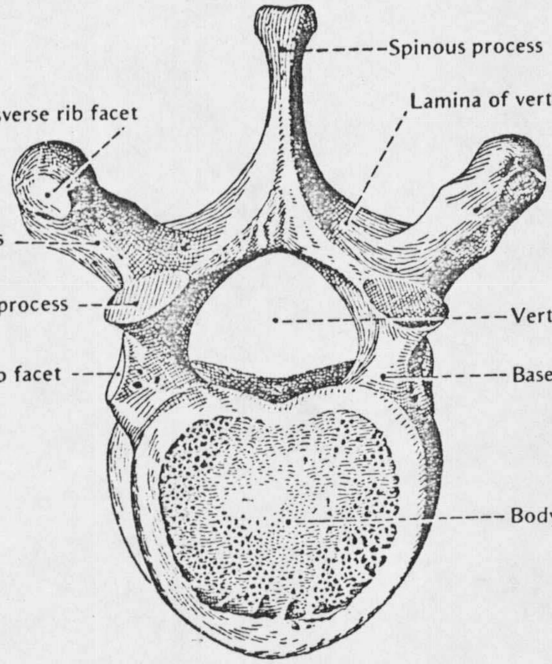


Figure 3-1.--The Vertebral Column. A: Anterior view. B: Posterior view. C: Lateral view. Source: B. R. Landau, Essential Human Anatomy and Physiology.

A typical vertebra (Figure 3-2) consists of a body with a vertebral arch attached to its posterior surface. This arch encloses an opening, the vertebral foramen, which contains the spinal cord. From the arch arise four processes for articulations and three processes primarily for attachments of ligaments and muscles. Those associated with articulation are the paired superior and inferior articular processes. The three remaining processes are the paired transverse processes which extend laterally and the single spinous process which protrudes posteriorly at an angle from the arch. Each body is connected to the adjacent vertebrae through fibrocartilage discs called intervertebral discs. The vertebral bodies increase in size as one proceeds from the top of the spine to the bottom.

All vertebrae in the spine are basically the same as that depicted by Figure 3-2 with the exception of the first and second cervical vertebrae. The first cervical (Figure 3-3), the Atlas, has no body. It is essentially a ring with two lateral masses. The superior articular processes are modified to a pair of large concave articular facets which the head rides on. The second cervical, the Axis (Figure 3-4) has a tooth-like process, the dens, which protrudes upward from its body. Ligaments hold the dens in place behind the anterior arch of the atlas such that it serves as the body of the atlas.

A



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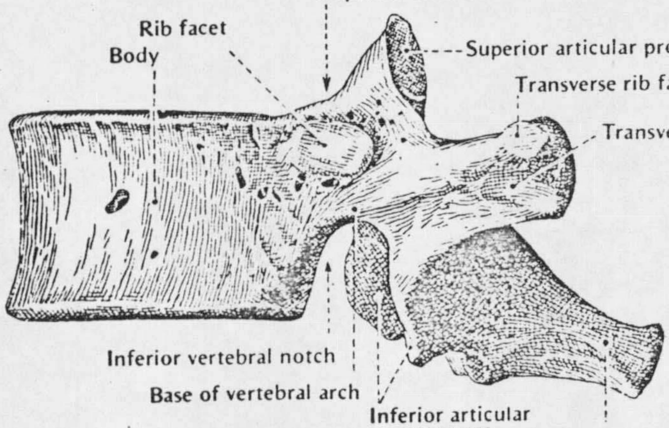

Figure 3-2.--The Structure of the Vertebrae, Illustrated by a typical thoracic vertebra. Source: B. R. Landau, Essential Human Anatomy and Physiology.

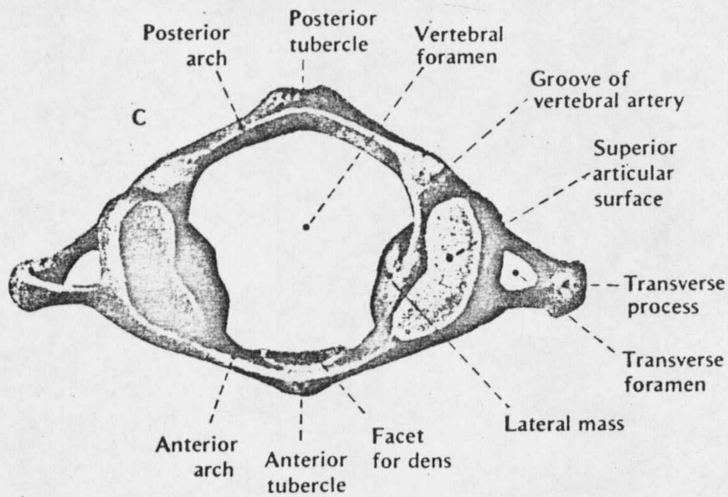

Figure 3-3.--Atlas, cranial view. Source: B. R. Landau, Essential Human Anatomy and Physiology.

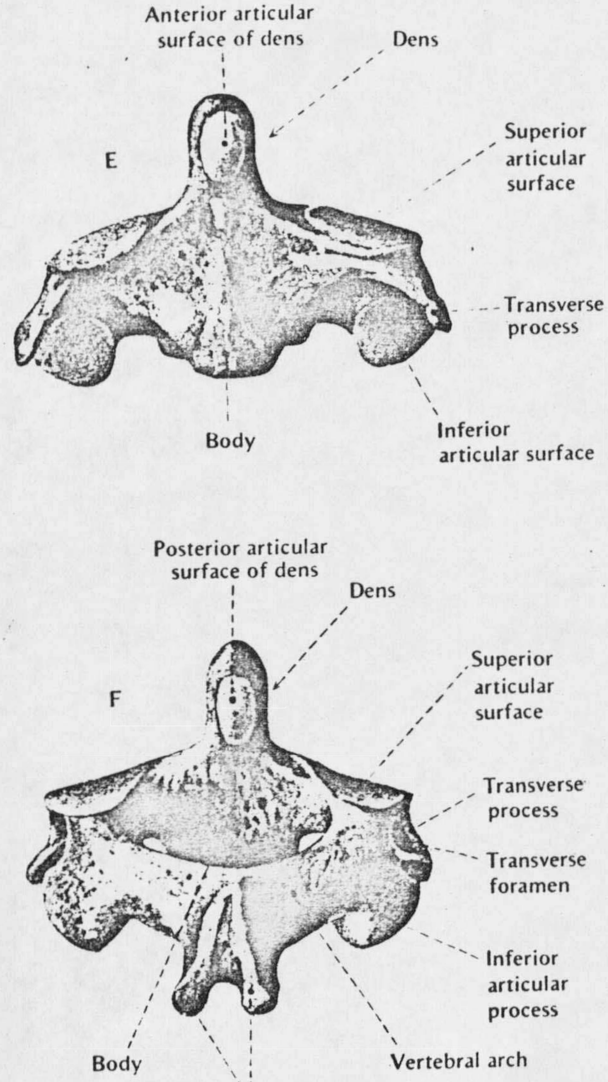

Figure 3-4.--Axis, ventral view and dorsal view. Source: B. R. Landau, Essential Human Anatomy and Physiology.

Bone is a connective tissue in which the intercellular substance consists of mineral deposits composed mainly of inorganic salts of calcium and phosphate complex. The cells and fibers are largely protein. Thus, bone is hard and rigid due to the minerals and tough due to the cells and fibers. The body of the vertebra is composed of an outer ring of dense material called compact bone, its center filled with cancallous bone. The articular surfaces and processes are basically shells of compact bone with cancellous material for cores much the same as the body. There is no marrow cavity in the vertebra.

The intervertebral disc is a fibrocartilage pad (Figure 3-5). Fibrocartilage is composed of collagen fibers and reinforcing ligaments which together assure strong union between bones. Collagen fibers are composed of fibers which are strong and inflexible. A gelatin type substance is intermingled with these fibers. Ligaments are much the same in composition. The intervertebral discs must support weight and absorb shock; therefore, its structure includes a mass of fibrogelatinous pulp (nucleus pulposus) at the core as a shock absorber. Around the core are wrapped concentric rings of fibers (annulus fibrosus). Under sudden severe pressure, the nucleus pulposus may break through the annulus fibrosus and cause pressure on nerves or may burst through into the body of the vertebra. The intervertebral disc is much more flexible than the vertebra and the vertebra is virtually a rigid body relative to the intervertebral disc.

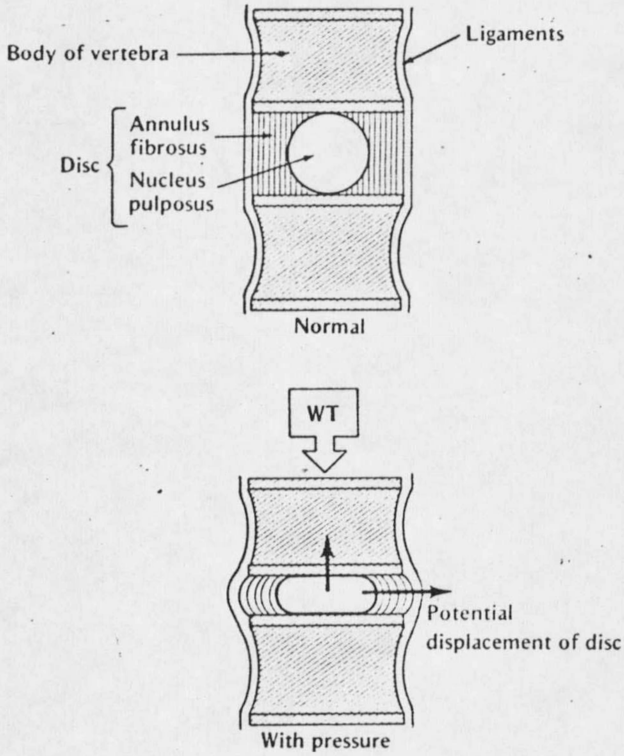

Figure 3-5.--Schematic of intervertebral disc. Source: B. R. Landau, Essential Human Anatomy and Physiology.

Ligaments, Muscles, and Connective Tissue

In addition to the intervertebral discs, the vertebrae are connected by several muscles and ligaments. The posterior vertebral muscles are divided into two groups referred to as superficial and deep muscles. These muscles are all located below the massive back muscles associated with the upper trunk. The superficial muscles insert several segments above their origins and act over several joints while the deep muscles generally insert on the segments directly above their origins. Table 3-1 lists the muscles associated with the spine and their functions. Figure 3-6 shows the superficial muscles of the back and Figure 3-7 shows the deep muscles of the back.

The ligaments which connect adjacent vertebrae are shown in Figure 3-8. The intertransverse ligaments firmly bond the transverse processes of adjacent vertebrae together. The supraspinous ligament does the same for the spinous processes of adjacent vertebrae. A collagen tissue (not shown in Figure 3-8) connects the inferior and superior processes of adjacent vertebrae.

Ribs

The ribs articulate posteriorly with the twelve thoracic vertebrae The first seven ribs attach to the sternum through the costal cartilages. The next three are attached to the cartilage of the rib above it and are thus indirectly attached to the sternum. The final two ribs have no anterior articulation and are called floating ribs. Each rib has a round head that connects to the rib facets on the bodies of two vertebrae and a tubercle that connects with the rib facet on the transverse process of one of the vertebrae. The connective tissue is collagen and though the ribs move with their respective vertebrae, they are somewhat free to rotate about their connection points like ball and socket joints.

TABLE 3-1

Muscle	Origin	Insertion	Action
Superficial muscles of the back			
Splenius capitis	lower half of ligamentum nuche and transverse processes of seventh cervical and first four thoracic vertebrae	mastoid process and occipital bone	singly--abducts and rotates both--extends head and cervical region
cervicis	spinous process of third to sixth thoracic vertebrae	transverse processes of first three cervical vertebrae	
Erector spinal iliocostalis lumborum dorsi cervicis	laterally--angle of ribs and or pelvic girdle	angle of rib, or cervical vertebrae six segments above	extends vertebral column
longissimus dorsi cervicis capitis	medially--transverse processes of lumbar, thoracic, and cervical vertebrae	transverse processes of vertebrae six segments above	all extend and abduct the vertebral column, but only capitis acts on the head
spinalis dorsi cervicis	medially--spinous processes of thoracic and lowest cervical vertebrae	spinous processes six segments above	extends vertebral column

TABLE 3-1 Continued

Muscle	Origin	Insertion	Action
Deep muscles of the back			
Semispinalis dorsi cervicis capitis	transverse processes of thoracic and seventh cervical vertebrae	spinous processes six segments above and occipital bone (capitis)	extends and rotates vertebral column and head (capitis)
Multifidus	pelvic girdle, lumbar vertebrae, transverse processes of thoracic and lower cervical vertebrae	spinous processes three segments above	extends vertebral column; each side may abduct and rotate
Rotatores	transverse processes of all vertebrae	spinous process of vertebrae above	extends and rotates vertebral column
Interspinales	spinous processes, especially in cervical and lumbar regions	spinous process of vertebrae above	extends
Intertransversarii	transverse rpocesses, especially lumbar and cervical regions	transverse processes of vertebrae above	extends and abducts

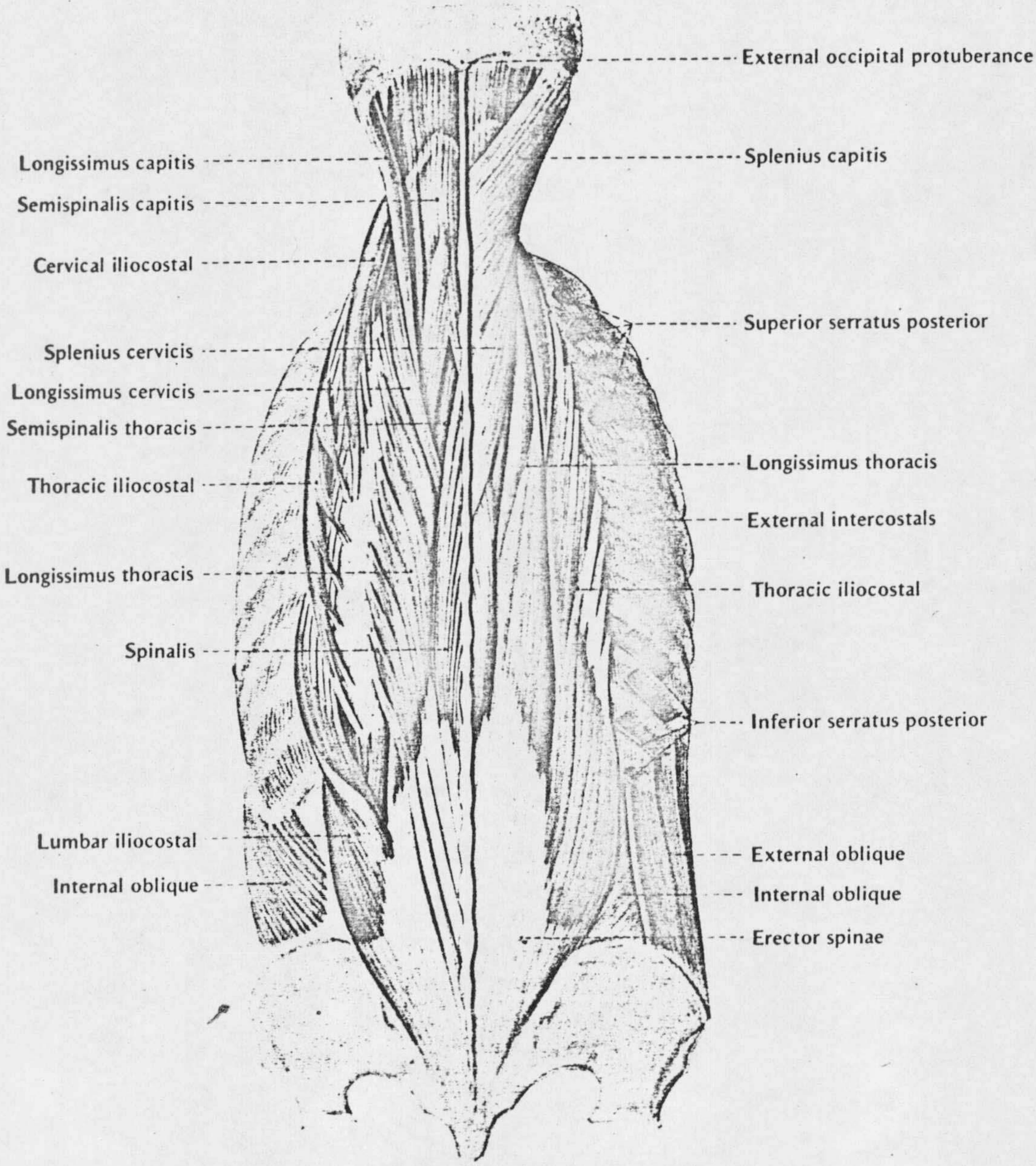

Figure 3-6.--Superficial muscles of the back. Source: B. R. Landau, Essential Human Anatomy and Physiology.

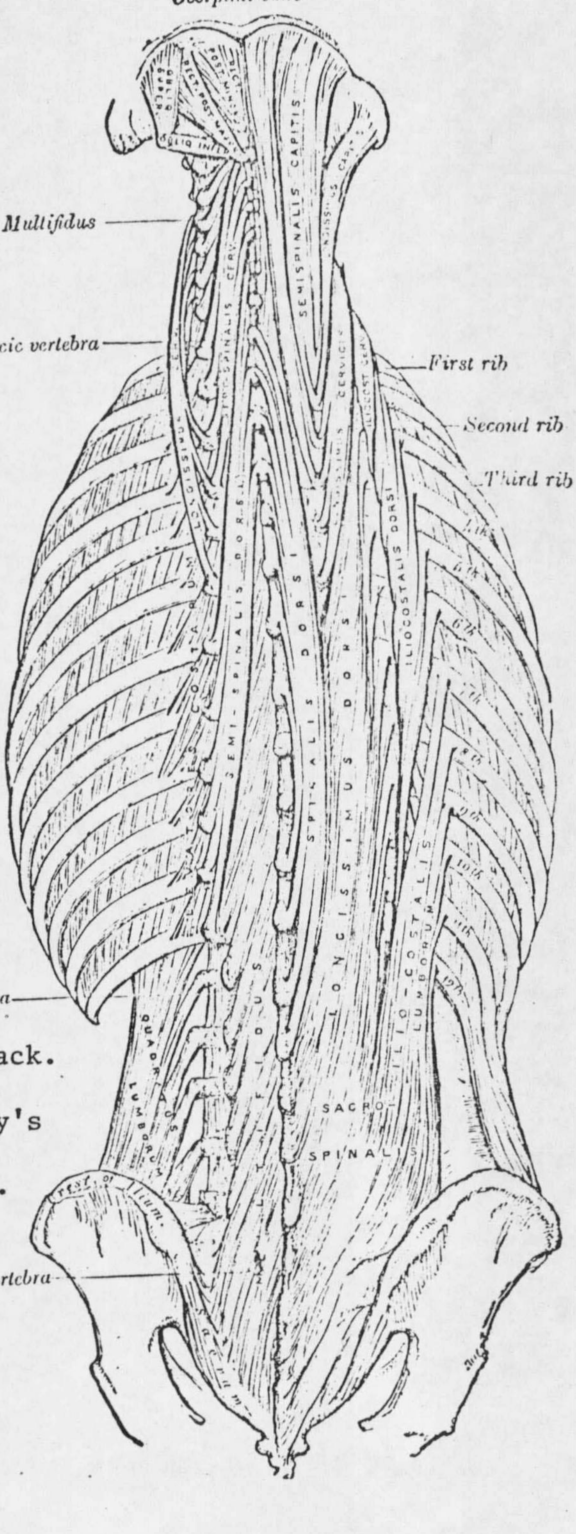

Figure 3-7.--Deep muscles of the back.

Source: H. Gray, Gray's Anatomy, 25th Edition.

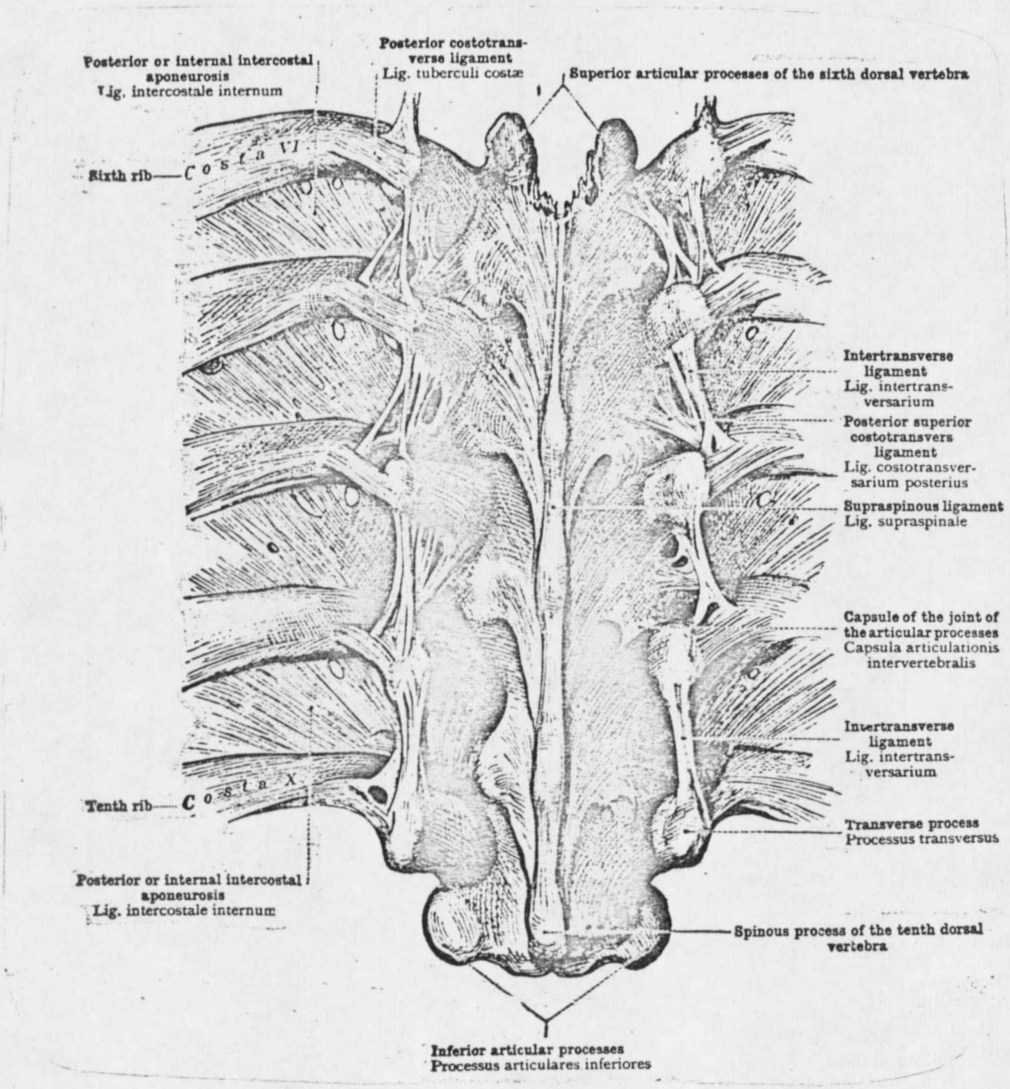

Figure 3-8.--Costovertebral articulations. Source: C. Toldt, M.D., An Atlas of Human Anatomy, Vol. 1, Second Edition.

Other Considerations

On the anterior side of the vertebrae lie several muscles and the internal organs of the human body. The digestive organs lie in front of the lumbar and middle to lower thoracic regions. The lungs lie in front of the upper thoracic region. Though these organs are very soft, they do constrain somewhat the position and movement of the spine.

Other bones are connected indirectly to the spine through attached bones such as the scapula (shoulder blade), clavicle (collar bone), and illium (pelvis). Assumptions were made to limit model complexity introduced by these bones.

CHAPTER IV

MODELING THE SPINE SYSTEM

The model was constructed such that consideration of medical benefits of geometric changes, material property variations, bone fusions, and Harrigan rod implants could be determined.

The Model

The spine was modeled as a series of rigid bodies (vertebrae) connected by finite beam elements (intervertebral discs) and four springs representing various ligaments and muscles. This is shown schematically in Figure 4-1 below.

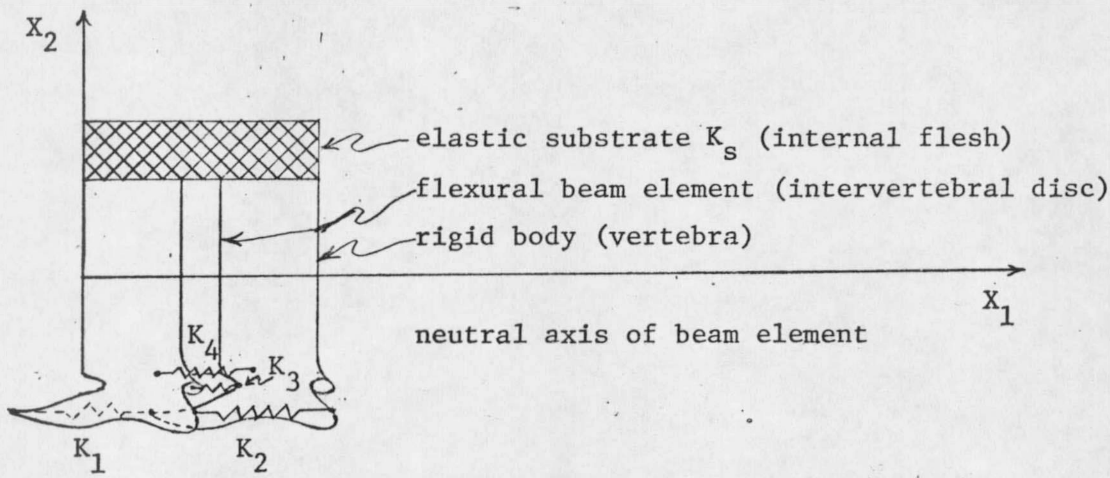

Figure 4-1.--Modeling concepts of vertebral column.

The elastic substrate K_s in Figure 4-1 represents the internal organs and flesh that the vertebral column contacts on its anterior side.

The elongation of each of the springs was dependent on the motion of the intervertebral discs and the geometry of the configuration. The first spring, with stiffness K_1, represents the muscles and ligaments that connect one spinous process of one vertebra to the spinous process of the next vertebra. The second spring, with stiffness K_2, represents the muscles on each side of the spinous process that connect one transverse process of one vertebra to the transverse process of the next vertebra. The third spring, with stiffness K_3, represents the collagen fiber between the inferior and superior articular processes of adjacent vertebrae. The final spring, with stiffness K_4, simulates bone grafted onto the vertebral column for corrective purposes. The muscles that run along the back connecting the vertebrae are treated as if they are segmented muscles connecting one vertebra to another rather than several. Thus, their stiffening effects are incorporated in springs 1, 2, and 3.

The ribs were modeled as curved beam elements with each rib divided into three sections each of constant curvature as shown in Figure 4-2. This was done consistant with the rib geometry defined by Schultz, et. al. [13]. Dimensions of ribs not listed by Schultz were obtained by interpolating between values available. Section OA was assumed to be curved such that it connected perpendicular to the vertebra at O. Point A corresponded to the average data point of Schultz's work. The curvature of DL was set such that its center of curvature was on the X_3 axis as seen in Figure 4-2. A spring, with stiffness K_r, was attached