

Morphological and Kinematic Aspects of Human Spine – As Design Inputs for Developing Spinal Implants

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Abstract

In present time, pain and stiffness in the cervical region of spine has become quite a common phenomena owing to the urbanized lifestyle of people which involves watching television or working on desktop computer for long hours without changing sitting postures. This pain and stiffness most often results from degeneration which takes place in the spinal discs which are located in between the vertebrae. However, the concept of establishing spinal pain as being caused by Degenerative Disc Disease is still problematic and unclear. Result of analysis on an anatomically accurate and validated intact finite element model of the spine indicated that the strain energy density and stress (internal responses) in the bony vertebra adjacent to the degenerated disc increased. During last few decades, biomedical engineers have been closely working with physicians for developing effective biomechanical techniques for relieving such pain. With conventional methods of spinal arthrodesis, the adjacent-segment ROM was significantly increased but with cervical disc arthroplasty, it has been reported to be preserved at the preoperative level. Artificial inter-vertebral disc has been in use for almost two decades in mainly European and some Asian countries. However, insertion of artificial cervical disc also has many technical issues and is not without risk. Complications, including the need for re-surgery, device migration and physiological bodily response to the wear debris of the implant have been reported. An in-depth knowledge about the morphological and kinematic aspects of the spine is very much essential for designing and developing any such instrumentation. These include: - (a) shape and dimensions of bone vertebrae, (b) type and estimated values of loads to which the implants will be subjected, (c) motion patterns of vertebrae at the location where degeneration has taken place. Lastly, the choice of available materials that can be safely used for developing such implants is to be finalized. After these design inputs are obtained, computational stress analysis for bone and implants and also tribological characterization is to be done for investigating the wear rate of different combinations of materials in contact – that are planned for use as implants.

Keywords: Cervical spine; Anatomy; Morphology; Kinematics; Vertebra; Disc; Degenerative disc disease; Arthrodesis; Arthroplasty; Artificial inter-vertebral disc

Introduction

Human spine is a complex, and remarkable, mechanical structure. It serves to protect the spinal cord and nerve roots and provides an incredible amount of flexibility to the trunk. It also transmits the weight of the upper body to the pelvis and is subjected to internal forces exceeding many times the entire body weight. But at the same time, the spine is also sometimes the cause of great pain and worry which is commonly known as back pain. The probable causes of such back pain and their clinical remedies have been investigated by physicians during last few decades. Of late, biomedical engineers have also joined hands with physicians for developing effective biomechanical techniques for relieving the suffering patients from such pain. It is imperative that an in-depth knowledge about the structure and functions of the spine is very much essential for designing and developing any such instrumentation. Figure 1 shows the views of Human Spine from front, back and side and shows its different segments. While the cause of such back pain have been understood through clinical studies [1,2] during past few decades, but there is difference of opinion among experts regarding the remedial measures needed to relieve such pain. The two main cause of back pain have been identified as injury and degeneration. While spinal injury asks for immediate surgical intervention in most cases, degeneration of spinal discs is a slower process but if not detected earlier, this may also result in surgery. Also, such disc degeneration problem which is known as Degenerative Disc Disease (DDD) is one of the major problems in Human Spine that have most commonly been observed by clinicians throughout the world. All the possible kinds of DDD reported so far are shown in Figure 2. It is generally caused by aging or by prolonged load on spine without changing the posture.

According to clinical findings [3], 60 percent of people over age 40 suffer from some degree of disc degeneration. Spondylosis is a term referring to degenerative osteoarthritis of the joints between the centre of the spinal vertebrae and/or neural foraminae. When space between two adjacent vertebrae becomes narrow, compression of a nerve root emerging from the spinal cord may result in radiculopathy (sensory and motor disturbances, such as severe pain in the neck, shoulder, arm, back, and/or leg, accompanied by muscle weakness). Generally disc degeneration problem initiates Spondylosis which is a stage of severe pain and immediate surgical implantation becomes mandatory. To design and develop such implants (as biomechanical remedies to spinal problems), the biomechanics of the spine (especially kinematic aspects) needs to be understood by the engineers in close association with clinicians.

Spinal Anatomy and Movements

The spine is an assemblage of many discrete bony elements, called vertebrae, which are held together by passive ligamentous restraints. In between the vertebrae, there are intervertebral discs. Two vertebrae and

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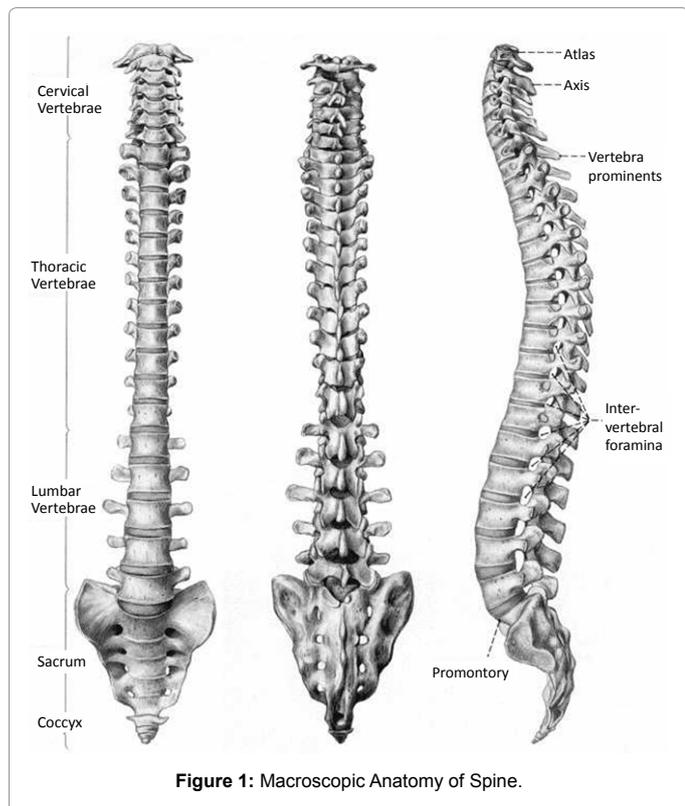


Figure 1: Macroscopic Anatomy of Spine.

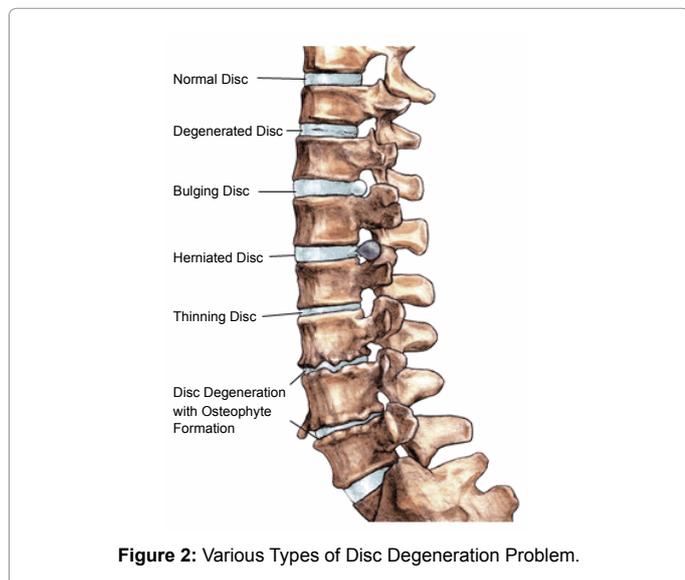


Figure 2: Various Types of Disc Degeneration Problem.

an intervertebral disc, taken together, form an articulating joint. These joints are also known as Functional Spine Units or FSUs. Movement of such FSUs is achieved by muscular activation. Based on the bone structure and kinematic functions, spine is broadly divided into five regions: the cervical spine, the thoracic spine, the lumbar spine, the sacrum, and the coccyx (as shown in Figure 1). Each of these five regions has different anatomical characteristics as well as load bearing capacity.

The junctions between the broad regions, i.e., the cervicothoracic, thoracolumbar, and lumbosacral junctions, frequently are sites for degenerative changes over the long term, most likely due to the abrupt

change in “stiffness” that occurs at these junctions [1,2]. Let us consider the cervicothoracic (C-T) junction. The C-spine essentially is free to rotate about the C-T junction due to the relative immobility of the trunk during head movement. The C-spine thus acts as a cantilever beam with the “fixed end” at the C-T junction, the location of the highest stresses.

Human spine possesses three movements viz (i) flexion/extension in the sagittal or lateral plane (ii) lateral bending in the coronal or frontal plane and (iii) axial rotation in the transverse or axial plane. Thus, the spine is said to possess six (6) degrees of freedom. A functional spinal unit (FSU) is comprised of a superior vertebra-intervertebral disc-inferior vertebra osteoligamentous unit. A FSU, therefore, possesses 6 DOF as well and is the basic unit of study of the spine.

Anatomy of Vertebra

Each vertebra shares common morphologic characteristics - an anterior vertebral body (or centrum) and the posterior neural arch, as shown in Figure 3. The superior and inferior surfaces of the vertebral bodies transition to cartilaginous endplates to which the intervertebral discs are affixed. The neural arch begins bilaterally with the pedicles which are bony beams whose axes are oriented anteroposteriorly and mediolaterally. The pedicles form a junction with the laminae, which extend around the spinal canal, the superior and inferior facets, and the transverse processes. The articulating facets serve to limit motion and transmit direct compressive forces and bearing compressive forces from bending and rotation.

Biomechanics of Spine

The spine is a mechanical structure. The vertebrae articulate with each other in a controlled manner through a complex of levers (vertebrae), pivots (facets and discs), passive restraints (ligaments), and activations (muscles). The long, slender, ligamentous bony structure is markedly stiffened by the rib cage. Although the spine has some inherent ligamentous stability, the major portion of the mechanical stability is due to the highly developed, dynamic neuromuscular control system. The spine structure is designed to protect the spinal cord, which lies at its center. The spine has three fundamental biomechanical functions. Firstly, it transfers the weights and the resultant bending moments of the head, trunk, and any weights being lifted to the pelvis. Secondly, it allows sufficient physiologic motions between these three body parts. Finally, and most important, it protects the delicate spinal cord from potentially damaging forces and motions produced by both physiologic movements and trauma. These functions are accomplished through the highly specialized mechanical properties of the normal spinal anatomy [1,2].

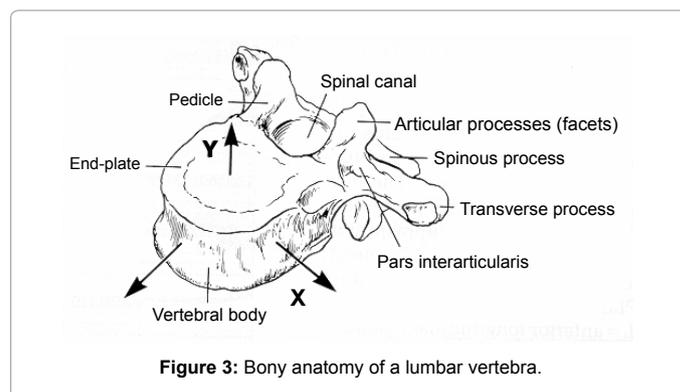


Figure 3: Bony anatomy of a lumbar vertebra.

Kinematic Aspects

Kinematics is the study of motion of bodies. The motion patterns of the spine are complex. Normal patterns are characterized by parameters common across regions of the spine. If a load (moment or force) is applied to a FSU or a multilevel spinal unit (MSU), the unit first displaces from a neutral position to a position where an appreciable resistance is first encountered, as shown in Figure 4. The initial lax region of the motion is termed the neutral zone (NZ). The presence of a NZ allows the spine to undergo relatively large motions with very little muscular effort; enlargement of a NZ can indicate an abnormal structural change and be a cause for concern [3]. Next to NZ, a region of stiffening is encountered, termed the elastic zone (EZ). The displacement at the largest applied load or at the limit of motion for an activity is termed the Range of Motion (RoM). These 3 parameters have been effective in characterizing the complex nonlinear load-displacement relation of spinal units. It is to be noted that this nonlinear relation is similar to practically every biologic tissue. Also to be noted that the spine as a structure displays viscoelastic characteristics due to the viscoelastic nature of its constituents.

Other kinematic terms relevant to the study of spinal kinematics are flexion, extension, lateral bending, and axial rotation. Flexion refers to bending forward about an axis perpendicular to the sagittal plane; extension refers to bending backward about that axis. Together, flexion-extension is referred to as sagittal bending. Lateral bending refers to bending to either side and can be either left or right lateral bending. Axial torsion refers to turning the head, for example, and also can be either left or right, as shown in Figure 5 and 6.

Still more kinematic terms relevant to the study of spinal kinematics are motion pattern, coupling, instantaneous axis of rotation, and instability. Motion pattern refers to the displacement path a vertebral body follows under load. If a bead is considered on a straight rod, then on pushing, it moves down the rod along a straight path. When the rod is bent, on pushing the bead, it now moves along the curved

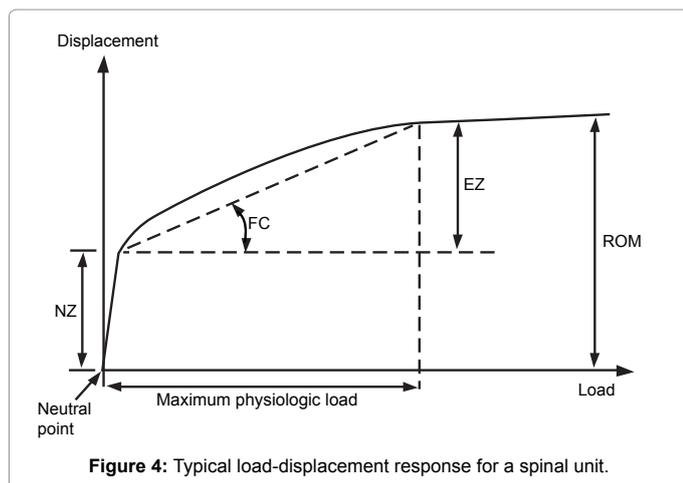


Figure 4: Typical load-displacement response for a spinal unit.

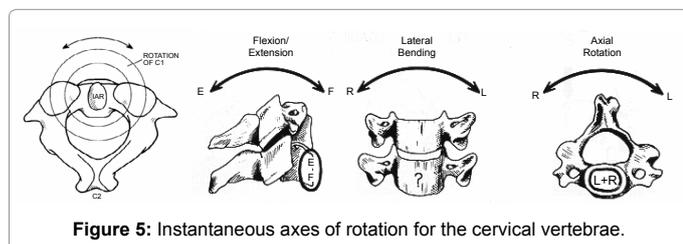


Figure 5: Instantaneous axes of rotation for the cervical vertebrae.

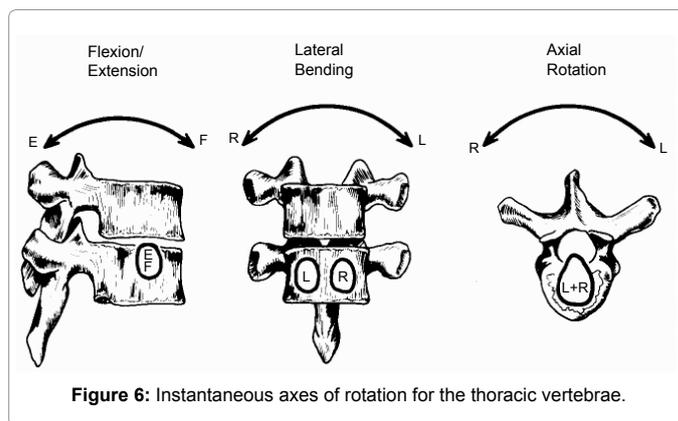


Figure 6: Instantaneous axes of rotation for the thoracic vertebrae.

rod: the motion pattern of the bead has changed. For the spine, when motion patterns deviate from “normal,” this can be an indication of an abnormality. Coupling refers to motion about or along axes secondary to those of the axis of applied load. For example, in the middle and lower cervical spine, left lateral bending produces a concomitant left axial torsion due to the orientation of the articulating surfaces of the facets. Coupling motions can change with abnormalities also. Taken together, abnormal motion patterns and coupling can be an indication for clinical instability, which ultimately must be treated in some manner [3]. The instantaneous axis of rotation (IAR) is an axis about which a vertebral rotates at some instant of time. For normal spinal units, the IAR for each of the rotary modes (flexion, extension, lateral bending, and axial torsion) is confined to a relatively small area somewhere within the spinal unit.

Biomechanical Remedies to Spinal Problems

Surgical implantation is the most common form of Biomechanical remedy to Spinal problems. The two main surgical approaches are Spinal Fusion Surgery or Arthrodesis and Spinal Arthroplasty. Arthrodesis is simpler of the two. It is a proven technique to restore vertebral alignment and to stabilize the damaged portion of the spine by supporting plates. It prevents the spine from undergoing further damage or degeneration. On the other hand, Spinal Arthroplasty involves restoration of motion by implanting artificial inter-vertebral discs in place of degenerated discs. This method is not yet fully proven but it promises a better life after operation since almost full functionality of the damaged portion of the spine is restored [4].

Important Design Inputs for Developing Spinal Implants

There are few design inputs which are required to be studied and understood clearly for designing spinal implants that can solve the spinal malfunction satisfactorily after their implantation surgery [5]. First of all, shape and geometrical dimensions of bone vertebrae are to be studied [6]. Secondly type of loads to which the implants will be subjected and their estimated values are to be derived. After this, motions of vertebrae are to be studied at the location where the damage has taken place and implantation is to be done. This range of motion is expected to be restored after implantation surgery. Lastly, the choice of available materials that can be safely used for developing such implants is to be finalized. After these design inputs are gathered and studied, stress analysis has to be taken up for bone and implants. Also, tribological characterization is to be done for investigating the wear rate of different combinations of materials in contact – that are planned for use as implants.

Concluding Remarks

The concept of establishing spinal pain as being caused by Degenerative Disc Disease is still problematic and unclear. Result of analysis on an anatomically accurate and validated intact finite element model of the spine indicated that the strain energy density and stress (internal responses) in the bony vertebra adjacent to the degenerated disc increased. With conventional methods of spinal arthrodesis, the adjacent-segment ROM was significantly increased [7] but with cervical disc arthroplasty, it has been reported to be preserved at the preoperative level. Investigative study about disc degeneration, in general and then about the presently practiced disc regeneration processes, have shown that only dynamic stabilization systems currently offer the potential of a mechanical approach to intervertebral disc regeneration, when it is used either with pedicle screws or with an inter-spinous device. Artificial intervertebral disc has been in use for almost two decades in mainly European and some Asian countries [8,9]. However, insertion of artificial cervical disc also has many technical issues and is not without risk. Complications, including the need for re-surgery, device migration and physiological bodily response to the wear debris of the implant have been reported [10]. Due to lack of published data on direct comparison of disc prosthesis vis-a-vis discectomy with or without fusion, the safety and efficacy of artificial disc still cannot be established. It is expected that, in near future, short-term randomized controlled trial data will be available. As such, at present, artificial intervertebral disc should be considered as still at an experimental stage.

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