Biomechanics of the Spine

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General Kinematics

- Curvature
  - Sagittal
  - Shape of vertebrae & disks, rib cage, inclination of sacral end plate
  - Developmental phenomenon, posture, rate of growth
  - Add flexibility & shock absorbing capability

- 6 degrees of freedom
  - Translation & Rotation
  - 3 orthogonal planes
  - Motion usually coupled

- Center of gravity – in front of 2nd sacral segment
ROM

- Facet joints & Intervertebral disks
- C spine
  - Flexion-extension predominates, midcervical
  - Axial rotation, upper cervical
  - Lateral bending
- T spine
  - Little motion, rib cage
- L spine
  - Lateral bending, mid portion
  - Flexion-extension, lumbosacral
  - Rotation, minimal
- Greater mobility at C & L spine > more stress > more clinical complaints
The Motion Segment

- **Functional Spinal Unit**
  - 2 adjacent vertebrae & intervening soft tissue

- **Anterior**
  - Vertebral body
  - Disk
  - ALL, PLL
    - Support, absorb impact, restrict vertical translation

- **Posterior**
  - Neural arch & its processes
  - Facet joint
The diagram illustrates the movement patterns of the cervical, thoracic, and lumbar vertebrae in relation to flexion/extension, lateral bending, and axial rotation.

- **Flexion/Extension (E)**: The vertebrae move in a forward and backward direction.
- **Lateral Bending (L)**: The vertebrae move side to side.
- **Axial Rotation (R)**: The vertebrae rotate around their own axis.

Each section (cervical, thoracic, lumbar) shows the movement patterns for these three types of movements, with arrows indicating the direction of motion.
Disk

- Major restraint to motion
- Viscoelastic behavior, demonstrates Creep & Hysteresis
- Avascular
  - End-plate microfractures > vascular ingrowth & granulation tissue > altered mechanical behavior
  - End-plates influence the nutrition; diffusion
- Lumbar FSU
  - Disk – 40% of torque resistance
  - Rest by posterior element and ligaments
- Diurnal change in height
  - 1% shorter at night; 2% for children; 0.5% for elderly
  - 50% of height lost during first 2 hours in upright
- Healthy disks creep slower
**Intradiscal Pressure**

- Compressive loads in vivo: 500N standing, 700N sitting
- Increased to 3000 to 6000N during lifting of moderate weights, decreases with load closer to body
- Estimate of $P = 1.5 \times$ compressive load divided by the cross sectional area
- Disk pressure is usually uniform
- Pressure lowest in supine position
- Disk usually does not fail, but end plates fracture
Annulus Fibrosus

- 90 collagen sheets
- Fibers of adjacent sheets 30° to each other
- Hyaline cartilage plates & bony ring epiphyses of vertebral bodies
- Vertical component – tension resistor during flex-ex & lateral bending
- Horizontal component – rotary stress
- Axial load – tensile stress
Nucleus Pulposus

- Eccentrically positioned posteriorly
- Young & healthy
  - 50% cross-sectional
  - 90% water, bound to proteoglycans
- Aging > dessication > increase viscosity > fissuring
- Pascal’s law
  - Fluid mass within closed container > local increase in pressure > transmit around entire side wall (annulus)
  - Young nucleus > even distribution of load
  - Old nucleus > undue concentration on vertebral body edges
- Small displacement w/ ROM, ball-bearing like
- Compressive stress predominates
Vertebral Body

- **Primary load-transmitting element, 80-90%**
- **Bone Mineral Content, Size**
  - Osteoporosis > loss of horizontal trabeculae
  - Increasing size from C to L spine
- **Compressive load > pressure higher in center of end plates than periphery**
- **In vivo, filled with blood > greater strength, hydraulic shock absorber**
- **Weaker anterior trabeculae, Wolff’s law**
Segment of Relative Weakness
Posterior Elements

- pedicles, lamina, facet joints, spinous & transverse processes
- Bony processes > lengthen moment arms of muscles
- Forces on processes > transmitted to Lamina
- Forces on posterior elements > transmitted to vertebral bodies from Pedicles
- Pars Interarticularis
  - Large bending forces; excessive extension
  - Thicker than rest of lamina
  - Common site of stress/fatigue fractures > weakens motion segment > spondylolysis
• **Facet Joints**
  - Major role in controlling motion
  - Resist torsion & shear, role in compression
  - Lumbar FSU – facets 40% torque resistance, 40% disk, 20% ligaments
  - Load sharing varies with flexion & extension
    - Seated position > decreased lumbar lordosis > increased intradiscal pressure & decreased load-bearing of the facets
  - Orientation of facets
    - C spine - 45° transverse, parallel frontal
    - T spine - 60° transverse, 20° frontal
    - L spine - 90° transverse, 45° frontal
  - Capsules lax > allow gliding
Ligaments

- Nonsegmental longitudinal (ALL, PLL, supraspinous)
- Segmental longitudinal (interspinous, intertransverse, ligamenta flava)
- Capsular ligaments
- Limit motion, provide stability/equilibrium
- ALL
  - Interlinked to disks
  - Resists extension
  - 2X tensile strength of PLL
- **PLL**
  - Narrow over vertebral bodies, flare out over disks; thin lateral extension
  - Resists flexion
  - Ossification > spinal stenosis

- **Ligamentum Flavum**
  - Elastic & strong
  - “shingled” configuration with laminae
  - Lengthen w/ flexion, shorten w/ extension
  - Loss of disk height or hyperextension > buckle into spinal canal

- **Interspinous & Supraspinous**
  - Resist flexion
  - Long moment arms
Cervical Spine

- Almost infinite number of head positions
- Spinous processes increase in length distally
- C 1-2 almost transverse, C 2- T 1 45º to transverse
- Occipitoatlantoaxial complex – specialized articulation, large ROM, no disk
  - 60% axial rotation – C 1-2, difficult for occipital condyles to slide on C 1, no loss w/ aging
  - Lateral bending – small, alar ligament
  - IAR – close to cord, rotate without impingement
- **C 3-7 - flex-ex predominates, lateral bending**
  - IAR – lower vertebra (flex-ex); upper vertebra (lateral bending)
  - Distinct coupling pattern – lateral bending & axial rotation, spinous process point opposite to lateral bend
  - Axial rotation – limited by uncinate processes & facets

- **Intradural sagittal diameter**
  - 2-3mm lower in extension
  - Posteroinferior margin of upper vertebra & ligamentum flavum
  - Cord thicker in extension > less play in ext
  - Canal widest at C 1-2, narrows at C 5
Thoracic Spine

- Rigid, transition between C & L regions
- Facet orientation changes, may be abrupt T 9-12
- Flex-ex – upper: 4º, middle: 6º, lower: 12º
- Lateral bending – upper: 6º, lower 2/3: 9º
- Axial rotation – upper 1/2: 8º, lower 3 segments: 2º each
- Upper & lower region – lateral bending & axial rotation strongly coupled
- Middle – variable coupled motion
Lumbar Spine

- **Flexion-Extension**
  - large, due to sizable disks & lack of facet restraint
  - IAR – posterior half of disk, moves w/ flex-ext
    - Centrode – path of moving IAR

- **Lateral bending** – IAR on left side of disk w/ right bend

- **Axial rotation** – IAR in posterior nucleus

- **Disk degeneration** – IAR spread out
- Sagittal plane translation
  - 2-3 mm, normal in symptom free pts
  - Up to 5 mm in L 3-4 & L4-5, 4 mm in L5-S1
- Lateral bending & axial rotation coupling
  - Spinous processes point in same direction as lateral bending
  - Opposite of cervical, upper thoracic, lumbosacral
Sacroiliac Region

- Poorly understood
- Partly synovial, partly syndesmotic
- Stiff, coarse interdigitating articular surfaces
- IAR scattered
- Complete ankylosis in up to 76% over age of 50
- Joint motion – overcome ligamentous resistance, 1 leg stance
Vertebral Muscles

- Spine buckles w/ small compressive forces without muscles
- Anterior, posterior, lateral
- Gross-function – span several motion segs
- Fine-function – span 1 or 2 segs
- Deep back muscles are major spine movers; many other groups
<table>
<thead>
<tr>
<th>Function</th>
<th>Muscles</th>
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<tbody>
<tr>
<td><strong>Anterior</strong></td>
<td></td>
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<tr>
<td>Muscles in front flex the spine.</td>
<td>Longus collis*</td>
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</tbody>
</table>
| If the muscle runs a little obliquely and contracts independently of the corresponding muscle on the opposite side, it rotates and bends the spine laterally, as well as flexes it. | Longus capitis  
Rectus capitis anterior  
Rectus capitis lateralis†  
Obliquus externus abdominis*  
Obliquus internus abdominis*  
Psoas major†  
Psoas minor†  
Iliacus  
Quadratus lumborum |
Posterior

Muscles in back extend the spine.

If the muscle runs a little obliquely and contracts independently of the corresponding muscle on the opposite side, it rotates and bends the spine laterally, as well as extends it.

Superficial stratum

Splenius capitis**
Splenius cervicis+
Erector spinae (sacrospinalis)
Iliocostalis**
Longissimus*
Spinalis**

Deep stratum

Semispinali
Thoracis*
Cervicis*
Capitis*
Multifidi*
Rotatores*
Interspinales
Intertransversaril*
**Lateral**

Muscles on the side bend the spine laterally

<table>
<thead>
<tr>
<th>Trapezius</th>
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<tbody>
<tr>
<td>Sternocleidomastoid*</td>
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<tr>
<td>Quadratus lumborum</td>
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<tr>
<td>Scalenus*</td>
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<tr>
<td>Anterior</td>
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<td>Medial</td>
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<td>Posterior</td>
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Little muscular activity to maintain upright position

- Spine in near equilibrium
- Cervical & lumbar curvatures
- Trunk relatively even in front & behind line of gravity

Flexion

- Anterior muscles initiate (isotonic) > anterior dysequilibrium > gravity takes over, controlled by extensors (eccentric)