SPINE AND INTERVERTEBRAL DISK BIOMECHANICS
ANATOMY

[Image of vertebral column diagram with labeled parts such as "Superior articular process," "Transverse process," etc.]
ANATOMY

Body of vertebra
Intraarticular ligament
Intervertebral foramen
Sup. costotransverse ligament
Lat. costotransverse ligament
Intervertebral disc
Head of rib
Tubercle of rib
Frontal (right) and left lateral (left) views of the human spine.
Normal variation in shape of the spine
(data for 18 subjects between the ages 10-18 years)
Normal direction of load on human vertebrate
ANATOMY

Nucleus pulposus

Lamellae of annulus fibrosus

Annulus fibrosus
ANATOMY

- Nucleus pulposus
- Lamellae of annulus fibrosus
- Annulus fibrosus
BIOCHEMICAL COMPOSITION

- Collagen
  - tensile strength
  - 70% dry weight of outer annulus
  - <20% dry weight of nucleus in young

- Proteoglycans
  - stiffness, resistance to compression, and viscoelasticity
  - ~3% dry weight of outer annulus
  - 50% dry weight of nucleus of young
Load Support in the Disc

- **Pressurization of the NP**
- **Axial Compressive Stress**
- **Circumferential Tensile Stress**
- **Radial Compressive Stress**
SPINE MECHANICS

[Graph showing various mechanical properties of the spine, including rotation, translation, and moment.]
**Average stiffness values (N/mm and Nm/deg) for the adult human spine**

<table>
<thead>
<tr>
<th>Spine level</th>
<th>Comp</th>
<th>Shear (ant/post)</th>
<th>Lat</th>
<th>Bending (flex/ext)</th>
<th>Lat</th>
<th>Axial torsion</th>
<th>Reference</th>
</tr>
</thead>
<tbody>
<tr>
<td>C00-C1</td>
<td>—</td>
<td>—</td>
<td>—</td>
<td>0.04/0.02</td>
<td>0.09</td>
<td>0.06</td>
<td>100</td>
</tr>
<tr>
<td>C1-2</td>
<td>—</td>
<td>—</td>
<td>—</td>
<td>0.06/0.05</td>
<td>0.09</td>
<td>0.07</td>
<td>100</td>
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<tr>
<td>C2-7</td>
<td>1317</td>
<td>125/55</td>
<td>33</td>
<td>0.4/0.7</td>
<td>0.7</td>
<td>1.2</td>
<td>168</td>
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<tr>
<td>T1-12</td>
<td>1250</td>
<td>86/87</td>
<td>101</td>
<td>2.7/3.3</td>
<td>3.0</td>
<td>2.6</td>
<td>195</td>
</tr>
<tr>
<td>L1-5</td>
<td>667</td>
<td>145/143</td>
<td>132</td>
<td>1.4/2.9</td>
<td>1.6</td>
<td>6.9</td>
<td>34, 237</td>
</tr>
<tr>
<td>L5-S1</td>
<td>1000</td>
<td>78/72</td>
<td>97</td>
<td>2.1/3.0</td>
<td>3.6</td>
<td>4.6</td>
<td>159</td>
</tr>
</tbody>
</table>
Spine Biomechanics
muscle moment arm (~4 to 5 cm)
muscle contraction
ROM

muscle contraction
Principle of Moments

\[ F \times l = f \times L \]
M = 10BW
Ax = CCW moment
By = CW moment

x, y are moment arms
LIFTING A LEVER
MECHANICS OF LEVER

\[ F = \frac{30}{3} F_{\text{HAND}} \]
MECHANICAL ANALYSIS
NEWTON’S THIRD LAW

F_{\text{HAND}}
MOMENTS ABOUT SPINE

$$M_{\text{EXTERNAL}} = 12 \cdot F_{\text{HAND}}$$

$$M_{\text{INTERNAL}} = 2 \cdot F_{\text{MUSCLE}}$$
FORCE MULTIPLIER

\[ M_{\text{INTERNAL}} = M_{\text{EXTERNAL}} \]

\[ F_{\text{MUSCLE}} = \frac{12}{2} \times F_{\text{HAND}} \]

\[ F_{\text{MUSCLE}} = 6 \times F_{\text{HAND}} \]
SPINAL LOADING

- Lifting carbon pieces out of smelter electrochemical cell
- Pieces weigh 890 N (200 lbs)
- **3327 N (748 lbs) lumbar compression**
Graphical Analysis
ELECTROMYOGRAPHY
If you lift a weight, which of the following methods is best?

A?

B?

Why?
INTER-DISCAL PRESSURE
DISK DEGENERATION
DEGENERATION THEORIES

- Reduced nutrient transport
- Decreased viable cells
- Cell senescence
- Apoptotic debris
- Loss of proteoglycans
- Fatigue failure of matrix
- MMP degradation of matrix
Degenerative Cascade

Tissue Adaptation

Degenerative Changes

Altered Mechanical Environment

Altered Material Properties & Composition
Healthy

Degenerated
AGING EFFECTS

• Anatomic
  • Loss of disk height
  • Protrusion of central disk into body
  • Bulging or buckling of annulus

• Biochemical
  • Fewer viable cells in nucleus
  • Decreased proteoglycans and water in nucleus
  • Collagen increases in nucleus
DEGENERATION AND AGE
NUCLEUS PROPERTIES

Iatridis, J.C. et al. (1997) JOR 15:318-322
Lumbar Stabilization

Lumbar Instability
- Uncontrolled movements
- Osteoarthritic proliferations
- Low Back Pain

Bodybuilding
- Spinal Bracing
- Fixing Implants
- Lumbar Fusion
- Arthrodesis = surgical fixation of a joint
- Stiffer arthrodesis = better healing environment
Stiffness of Implanted Lumbar

Stiffness = \frac{\text{Load}}{\Delta d}

- **Stiffness** → quality index of arthrodesis
- **Instability** → a lack of stability or the loss of stiffness
Free Body Diagrams
Free-Body Diagram for a Simple Weight Holding Task
### Mean (SD) coordinates of vertebral body centers in healthy individuals

| Level | $x$ (cm)       | $y$ (cm)       | $\theta$ ($^\circ$)
|-------|----------------|----------------|----------------
| T1    | 0.80 (0.22)    | 40.13 (0.15)   | 26.85 (7.75)   |
| T2    | 0.0            | 38.47          | 26.85 (6.12)   |
| T3    | -0.77 (0.17)   | 36.78 (0.11)   | 24.03 (5.13)   |
| T4    | -1.46 (0.33)   | 35.01 (0.19)   | 20.03 (4.97)   |
| T5    | -2.01 (0.44)   | 33.11 (0.34)   | 15.35 (4.33)   |
| T6    | -2.36 (0.49)   | 31.17 (0.33)   | 9.39 (3.41)    |
| T7    | -2.52 (0.59)   | 29.15 (0.39)   | 3.82 (3.98)    |
| T8    | -2.49 (0.64)   | 27.07 (0.41)   | -2.40 (4.03)   |
| T9    | -2.32 (0.75)   | 24.90 (0.38)   | -6.57 (4.54)   |
| T10   | 1.86 (0.89)    | 22.64 (0.40)   | -8.95 (5.19)   |
| T11   | 1.31 (1.02)    | 20.25 (0.37)   | -11.22 (5.49)  |
| T12   | -0.60 (1.22)   | 17.72 (0.31)   | -12.33 (5.76)  |
| L1    | 0.24 (1.40)    | 14.99 (0.35)   | -13.40 (4.94)  |
| L2    | 1.22 (1.50)    | 12.10 (0.40)   | -13.43 (4.65)  |
| L3    | 2.11 (1.45)    | 8.96 (0.44)    | -8.18 (4.42)   |
| L4    | 2.51 (1.18)    | 5.46 (0.47)    | 2.07 (7.57)    |
| L5    | 1.99 (0.69)    | 2.48 (0.40)    | 19.13 (11.00)  |
| S1    | 0.0            | 0.0            | 42.46 (10.57)  |

$^a\theta$ is the inclination of the upper endplate with the $x$ axis, which is horizontal; a positive angle denotes an inclination below the horizontal. Data from Ashton-Miller and Skogland (24).
### Average segmental range of motion (°) at each spine level\(^\text{a}\)

<table>
<thead>
<tr>
<th>Level</th>
<th>Flexion</th>
<th>Flexion/Extension</th>
<th>Extension</th>
<th>Lateral bending</th>
<th>Torsion</th>
</tr>
</thead>
<tbody>
<tr>
<td>Occ−C1</td>
<td>13(^b)</td>
<td>13(^b)</td>
<td>8(^b)</td>
<td>0</td>
<td>47</td>
</tr>
<tr>
<td>C1−2</td>
<td>10(^b)</td>
<td>9</td>
<td>0(^b)</td>
<td>9</td>
<td></td>
</tr>
<tr>
<td>C2−3</td>
<td>8</td>
<td>3</td>
<td>10(^b)</td>
<td>11</td>
<td></td>
</tr>
<tr>
<td>C3−4</td>
<td>7</td>
<td>9</td>
<td>11</td>
<td>12</td>
<td></td>
</tr>
<tr>
<td>C4−5</td>
<td>10</td>
<td>8</td>
<td>13</td>
<td>12</td>
<td></td>
</tr>
<tr>
<td>C5−6</td>
<td>10</td>
<td>11</td>
<td>15</td>
<td>10</td>
<td></td>
</tr>
<tr>
<td>C6−7</td>
<td>13</td>
<td>5</td>
<td>12</td>
<td>9</td>
<td></td>
</tr>
<tr>
<td>C7−T1</td>
<td>6</td>
<td>4</td>
<td>14</td>
<td>8</td>
<td></td>
</tr>
<tr>
<td>T1−2</td>
<td>5</td>
<td>3</td>
<td>2</td>
<td>9</td>
<td></td>
</tr>
<tr>
<td>T2−3</td>
<td>4</td>
<td></td>
<td>3</td>
<td>8</td>
<td></td>
</tr>
<tr>
<td>T3−4</td>
<td>5</td>
<td></td>
<td>4</td>
<td>8</td>
<td></td>
</tr>
<tr>
<td>T4−5</td>
<td>4</td>
<td></td>
<td>2</td>
<td>8</td>
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<tr>
<td>T5−6</td>
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<td>8</td>
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<tr>
<td>T6−7</td>
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<td>3</td>
<td>8</td>
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<tr>
<td>T7−8</td>
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</tr>
<tr>
<td>T8−9</td>
<td>4</td>
<td></td>
<td>2</td>
<td>7</td>
<td></td>
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<tr>
<td>T9−10</td>
<td>3</td>
<td></td>
<td>2</td>
<td>4</td>
<td></td>
</tr>
<tr>
<td>T10−11</td>
<td>4</td>
<td></td>
<td>3</td>
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</tr>
<tr>
<td>T11−12</td>
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<td></td>
<td>3</td>
<td>2</td>
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</tr>
<tr>
<td>T12−L1</td>
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<td></td>
<td>3</td>
<td>2</td>
<td></td>
</tr>
<tr>
<td>L1−2</td>
<td>8</td>
<td>5</td>
<td>6</td>
<td>1</td>
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</tr>
<tr>
<td>L2−3</td>
<td>10</td>
<td>3</td>
<td>6</td>
<td>1</td>
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<tr>
<td>L3−4</td>
<td>12</td>
<td>1</td>
<td>6</td>
<td>2</td>
<td></td>
</tr>
<tr>
<td>L4−5</td>
<td>13</td>
<td>2</td>
<td>3</td>
<td>2</td>
<td></td>
</tr>
<tr>
<td>L5−S1</td>
<td>9</td>
<td>5</td>
<td>1</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

\(^a\)Cervical and thoracic data from ref. 291. Cervical data from ref. 132 unless otherwise specified. Thoracic data from ref. 29. Values are total flexion/extension values. Lumbar data from refs. 204, 206.

\(^b\)Data from ref. 291, p.65.
Schematic Representation of the Lumbar-Trunk

[Image of a schematic representation of the lumbar-trunk with various forces and moments labeled.]
Data incorporated into the ten single equivalent muscle L-3 cross-sectional model

<table>
<thead>
<tr>
<th>Muscle</th>
<th>Symbol</th>
<th>Line of action</th>
<th>Area ratio per side&lt;sup&gt;a&lt;/sup&gt;</th>
<th>Anteroposterior offset ratio&lt;sup&gt;b&lt;/sup&gt;</th>
<th>Lateral offset ratio&lt;sup&gt;c&lt;/sup&gt;</th>
</tr>
</thead>
<tbody>
<tr>
<td>Rectus abdominis</td>
<td>R</td>
<td>Longitudinal</td>
<td>0.0060</td>
<td>0.540</td>
<td>0.121</td>
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<tr>
<td>Internal oblique abdominals</td>
<td>I</td>
<td>Inclined 45° to longitudinal, in sagittal plane</td>
<td>0.0166</td>
<td>0.189</td>
<td>0.453</td>
</tr>
<tr>
<td>External oblique abdominals</td>
<td>X</td>
<td>Inclined 45° to longitudinal, in sagittal plane</td>
<td>0.0148</td>
<td>0.189</td>
<td>0.453</td>
</tr>
<tr>
<td>Erector spinae</td>
<td>E</td>
<td>Longitudinal</td>
<td>0.0389</td>
<td>0.220</td>
<td>0.179</td>
</tr>
<tr>
<td>Latissimus dorsi</td>
<td>L</td>
<td>Inclined 45° to longitudinal, in frontal plane</td>
<td>0.0037</td>
<td>0.276</td>
<td>0.211</td>
</tr>
</tbody>
</table>

<sup>a</sup>In ratio to trunk width times trunk depth.

<sup>b</sup>From vertebral body center, in ratio to trunk depth.

<sup>c</sup>From vertebral body center, in ratio to trunk width.

The vertebral body center lies in the midsagittal plane at 0.66 times the trunk depth from the anterior-most edge of the cross section.
The equations of equilibrium that govern the ten-muscle cross-sectional model of Fig.7* 

Equations of force equilibrium:
\[ F_x = S_x + (L_x - L) \leftrightarrow \sin \gamma \]
\[ F_y = S_y = (h + I) \leftrightarrow \sin \beta - (X_t + X_r) \leftrightarrow \sin \delta \]
\[ F_z = (E + E_t) + (R_t + R_r) + (L_t + L_r) \leftrightarrow \cos \gamma + (h + I) \leftrightarrow \cos \beta + (X_t + X_r) \leftrightarrow \cos \delta - C \]

Equations of moment equilibrium:
\[ M_x = (R_t + R_r) \leftrightarrow y_1 + [(h + I) \leftrightarrow \cos \beta + (X_t + X_r) \leftrightarrow \cos \delta] \leftrightarrow y_0 - (E + E_t) \leftrightarrow y_r - (L_t + L_r) \leftrightarrow \cos \gamma \leftrightarrow Y_1 \]
\[ M_y = (R - R_t) \leftrightarrow x_t + [(h - I) \leftrightarrow \cos \beta + (X_t - X_r) \leftrightarrow \cos \delta] \leftrightarrow x_0 + (E - E_t) \leftrightarrow x_r + (L_t + L_r) \leftrightarrow \cos \gamma \leftrightarrow X_1 \]
\[ M_z = [(h - I) \leftrightarrow \sin \beta + (X_t - X_r) \leftrightarrow \sin \delta] \leftrightarrow x_0 + (L_t - L_r) \leftrightarrow \sin \gamma \leftrightarrow Y_1 \]

*F_x, F_y, F_z are the net reaction force components.
M_x, M_y, M_z are the net reaction moment components.
C, S_x, S_y are the motion segment compression and shear forces.
E, L, R, h, X_t are the forces in the left-side erector spinae, latissimus dorsi, rectus abdominis, and internal and external oblique muscles.
E, L, R, h, X_t are the corresponding right-side muscle forces.
\( \beta, \delta, \gamma \) are the angles shown in Fig. 7.
\( x_0, x_1, x_r, x_t \) are the positive distances from the y axis for the corresponding muscles.
\( y_0, y, y_t, y_r \) are the corresponding distances from the x axis.
An example of a deformable element model that incorporates 119 rigid elements and 503 deformable elements. This model was used to study how the configuration of the rib cage might be altered by deformities that occur in the spine as scoliosis progresses (66).
The forces on the back

This is about 10 x body weight!

\[ T_{total} = T_{vertebrae} - T_1 - T_2 \]

900 N

6 cm

400 N

30 cm

40 cm

8000 N !!!

2

1

\[ \tau \]
Competition Lifts - the clean and jerk

Technique is designed to overcome relative weakness of our arms.

In all positions, elbows and shoulders are almost directly above or below the bar, thus creating small moments.
The moments that gravitational forces produce at L5-S1 depend on their moment arms. These depend on:

- the size of the mass that the woman lifts, or the mass' distance from the woman's body.

- She can minimize flexor moments on L5-S1 if she holds the mass so that its center of gravity is close to her body as she lifts it.

The woman’s lifting posture:

- She can minimize flexor moments on L5-S1 if she bends her knees to lift rather than lifting with straight knees (Nordin & Frankel, 1989, Fig.10-22)
Vertebral fractures

- Difficult to study
  - Definition is controversial
  - Many do not come to clinical attention
  - Slow vs. acute onset
  - The event that causes the fracture is often unknown

- Poor understanding of the relationship between spinal loading and vertebral fragility
Factor of risk for vertebral fracture (L2)
Bending forwards 90° with 10 kg weight in hands

** P<0.005 for age-regressions
† p<0.01 for comparison of age-related change in M and W

FE MODEL OF THE INTACT SEGMENT

Vertebral bodies

Intervertebral disc

Interspinous ligament
Supraspinous ligament
Flaval ligament

Facet Joints
Capsular ligaments

Anterior longitudinal ligament
Posterior longitudinal ligament

FE MODEL OF THE IMPLANTED SEGMENT

Bryan Prosthesis
Upper Extremity Biomechanics
GLENOHUMERAL LOADING

- **Method**
  - Isometric arm abduction
  - Muscle force proportional to EMG
- **Results**
  - Max = 0.89 x BW
  - Max at 90° abduction

Biomechanics

- Throwing a baseball is an unnatural movement
- Excessively high forces are generated at the elbow and shoulder
- Throwing requires flexibility, strength, coordination
Biomechanics

- Phases of throwing:
  - Windup
  - Cocking
  - Acceleration
  - Deceleration
  - Follow-through
Biomechanics

Fig. 1
The 4 phases of throwing
Biomechanics

- Windup
  - Body placed in good starting position
  - Gains momentum in forward direction
  - Lasts 0.5 to 1.0 seconds
  - Minimal muscle activity
Biomechanics

- Cocking
  - Begins with front foot contact
  - Ends with shoulder in maximal external rotation (MER)
  - Elbow flexed, forearm supinated
  - Lasts 0.1 to 0.15 seconds
  - Deltoid, rotator cuff, medial and lateral elbow musculature highly active during cocking phase
Biomechanics

- Acceleration
  - Begins with MER
  - Ends with ball release
  - Arm moves to a position of internal rotation and adduction at the shoulder and extension at the elbow
  - Lasts a few hundredths of a second
  - Large valgus and extension forces generated at the elbow
Biomechanics

- Deceleration/Follow-through
  - Begins with maximal internal rotation (MIR)
  - Ends with foot contact
  - Follow-through is complete when pitcher achieves a balanced position and is ready to resume play