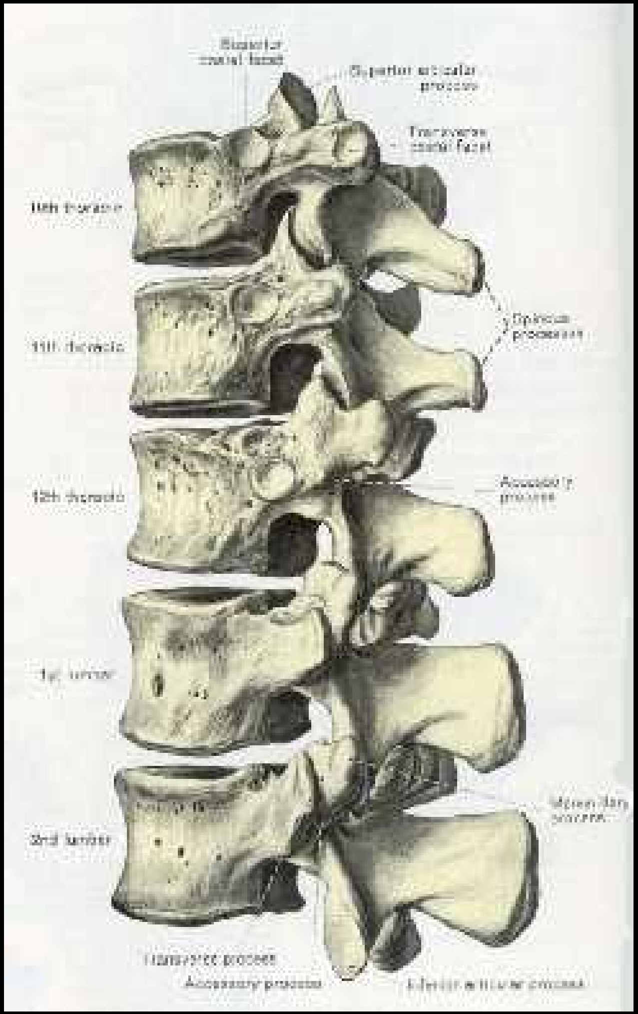
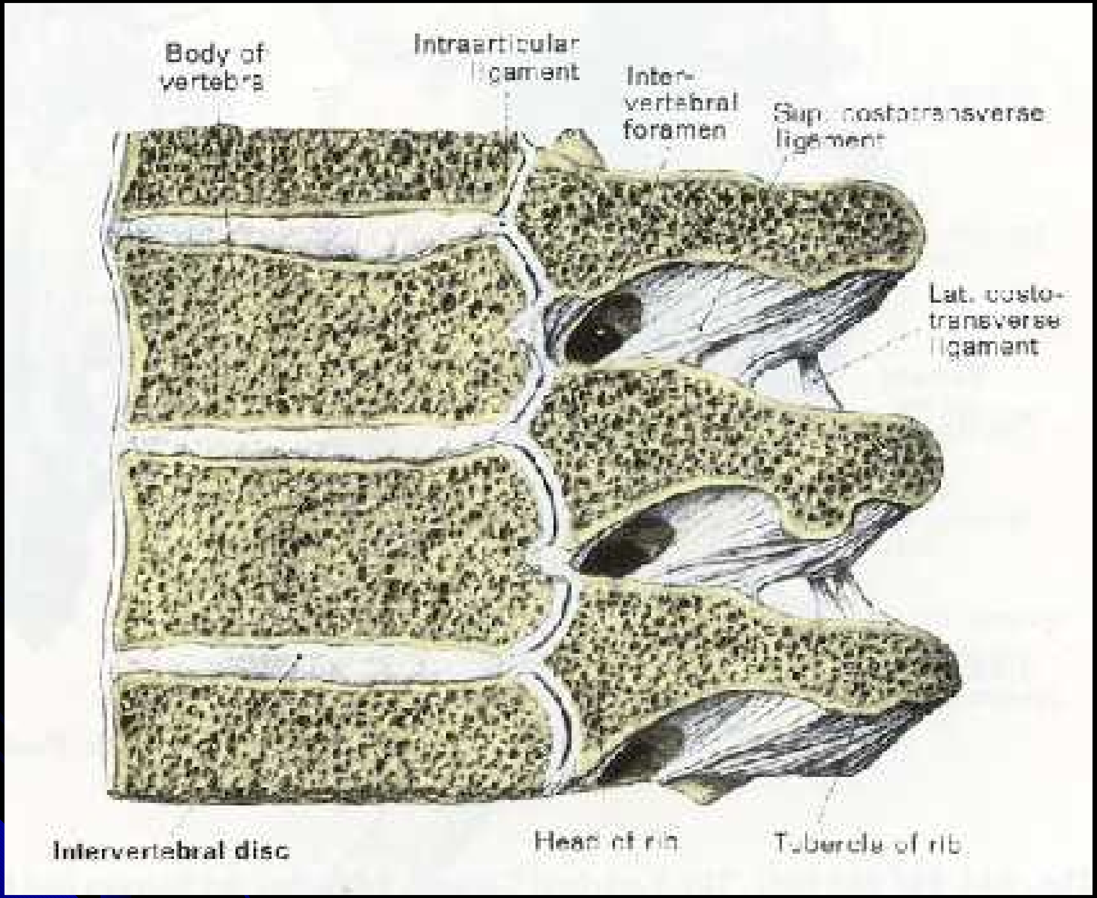
# SPINE AND INTERVERTEBRAL DISK BIOMECHANICS

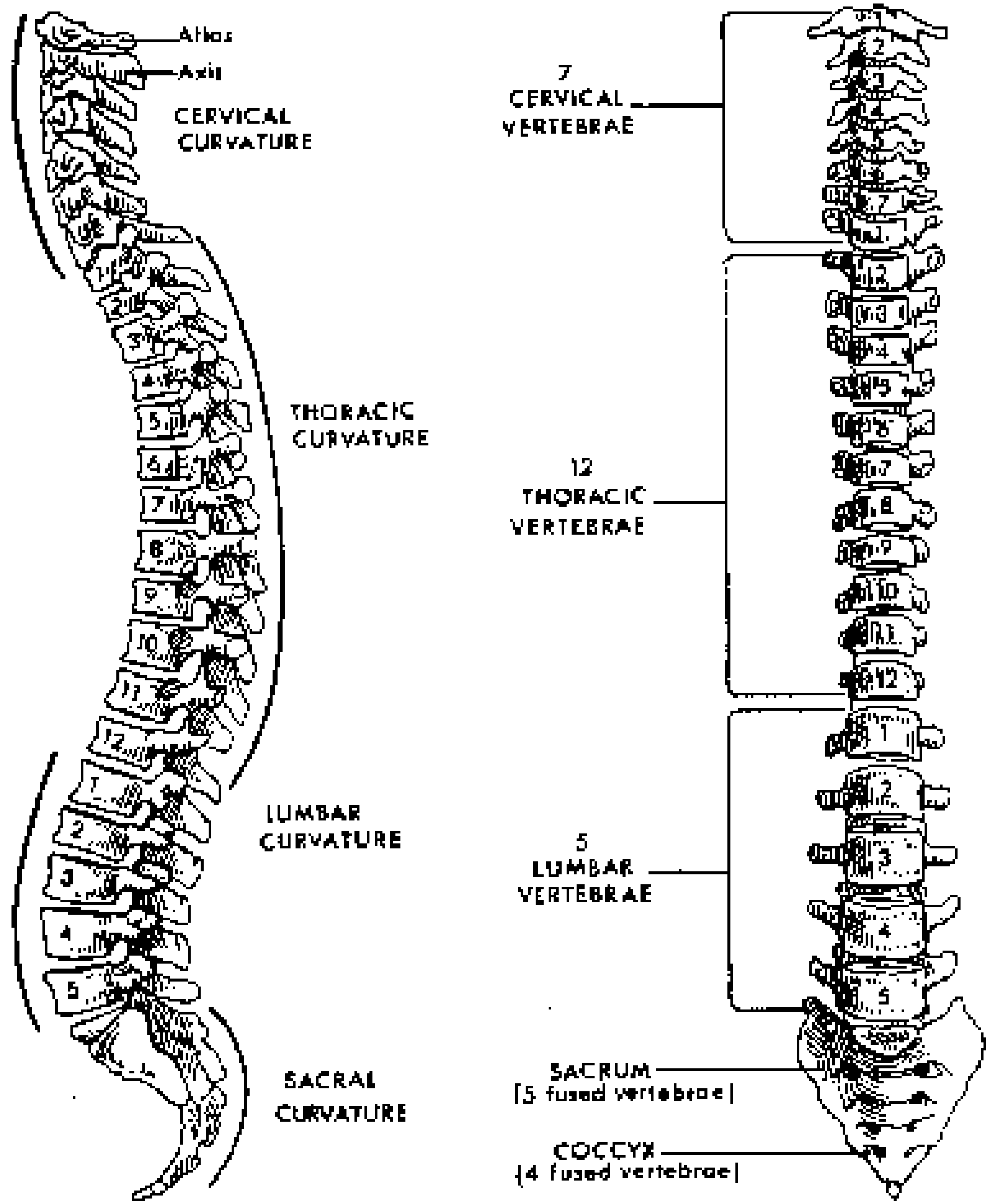
# ANATOMY


Superior articular process
Transverse costal facet
11th thoracic
Spinous processes
12th thoracic
Accessory process
2nd lumbar
Transverse process
Accessory process
Inferior articular process

# ANATOMY



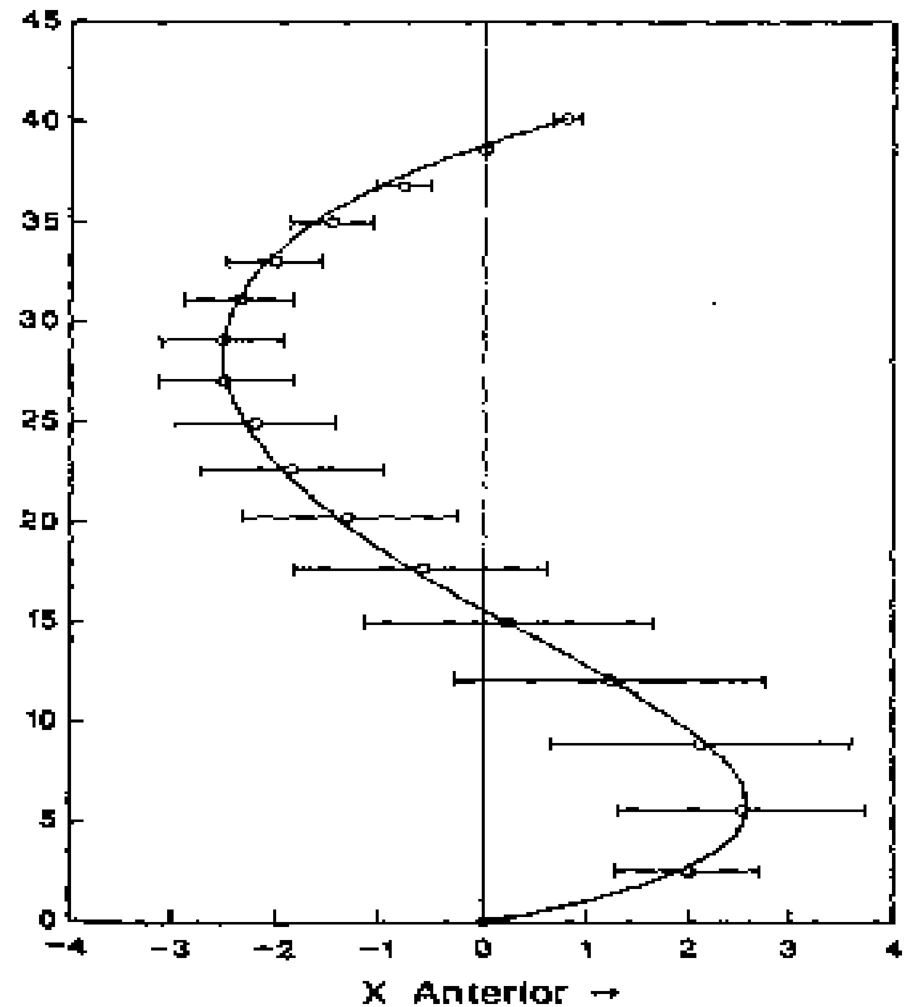
Body of vertebra
Intraarticular ligament
Inter-vertebral foramen
Sup. costotransverse ligament
Lat. costo-transverse ligament
Intervertebral disc
Head of rib
Tubercle of rib



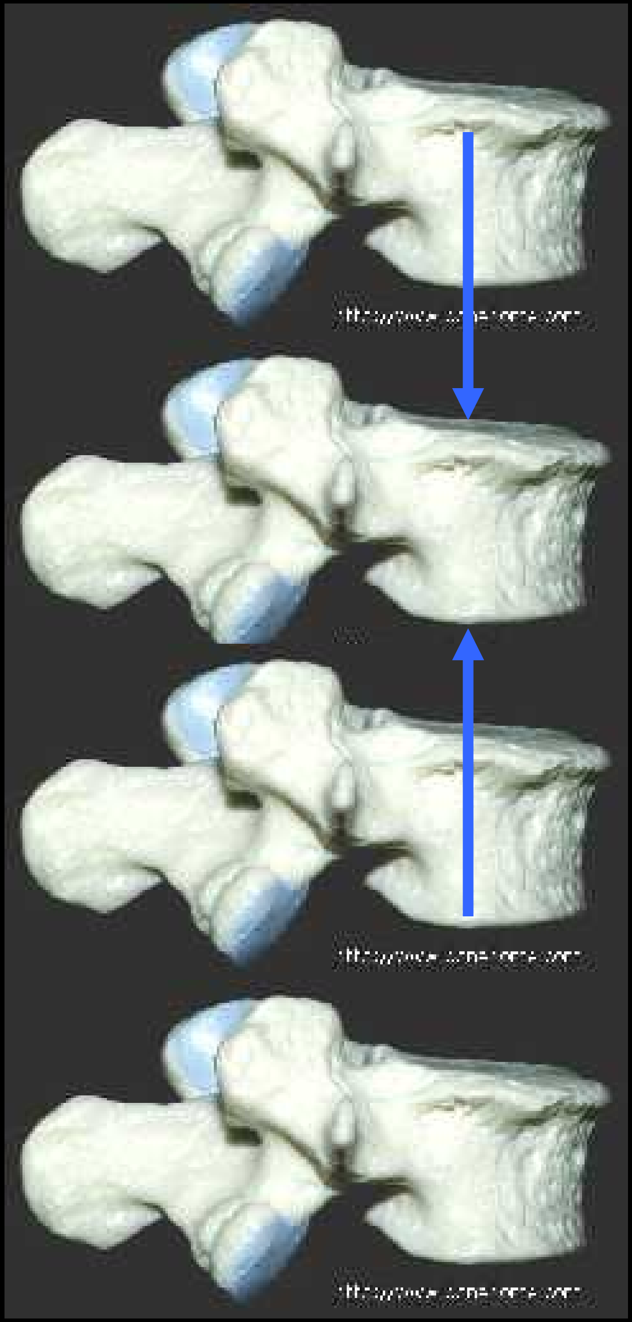

Frontal *(right)* and left lateral *(left)* views of the human spine.

# Normal variation in shape of the spine

(data for 18 subjects between the ages 10-18 years)



# Normal direction of load on human vertebrate



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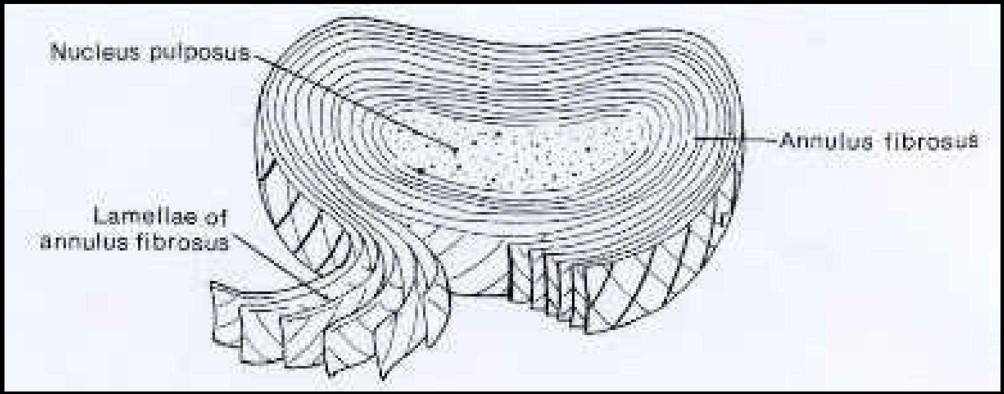
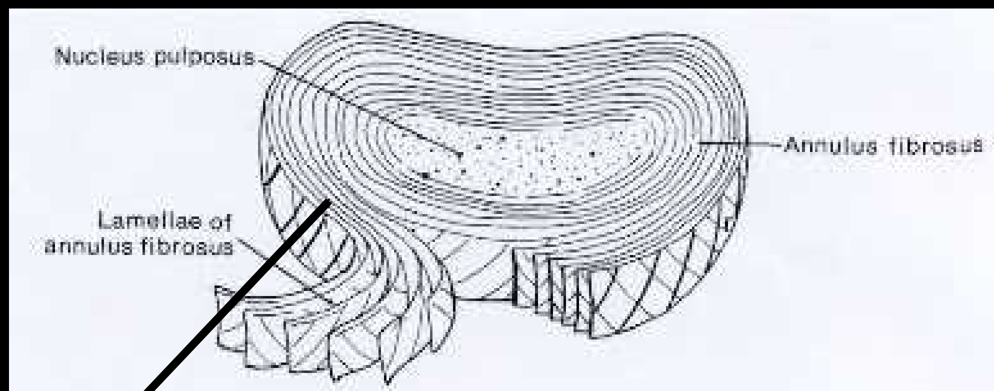
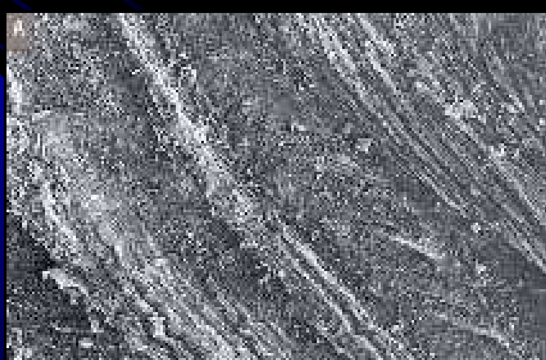


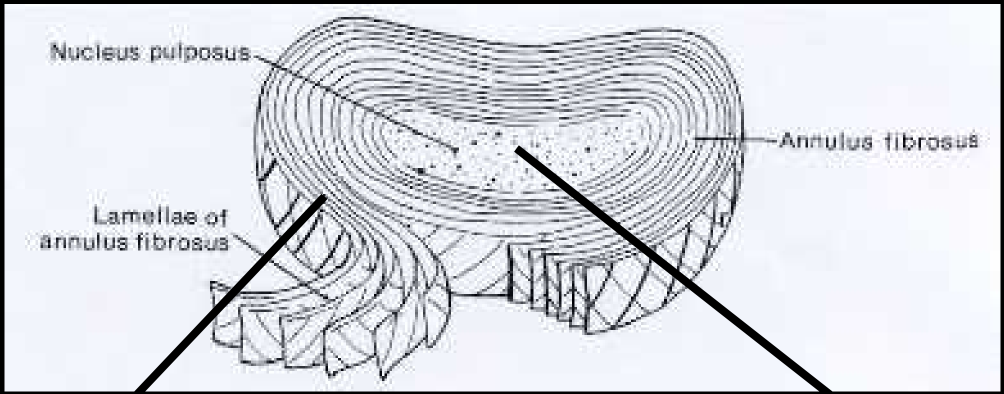
Nucleus pulposus
Annulus fibrosus
Lamellae of
annulus fibrosus

# ANATOMY


Nucleus pulposus
Annulus fibrosus
Lamellae of
annulus fibrosus



# ANATOMY



Nucleus pulposus
Annulus fibrosus
Lamellae of
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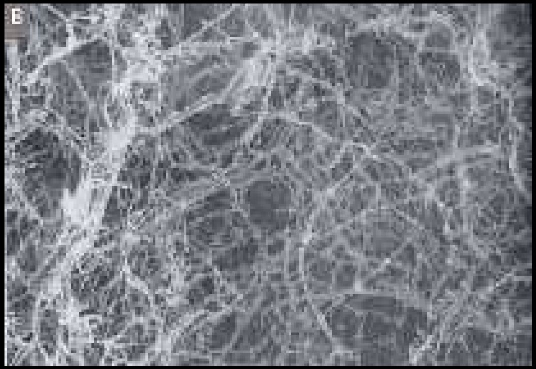
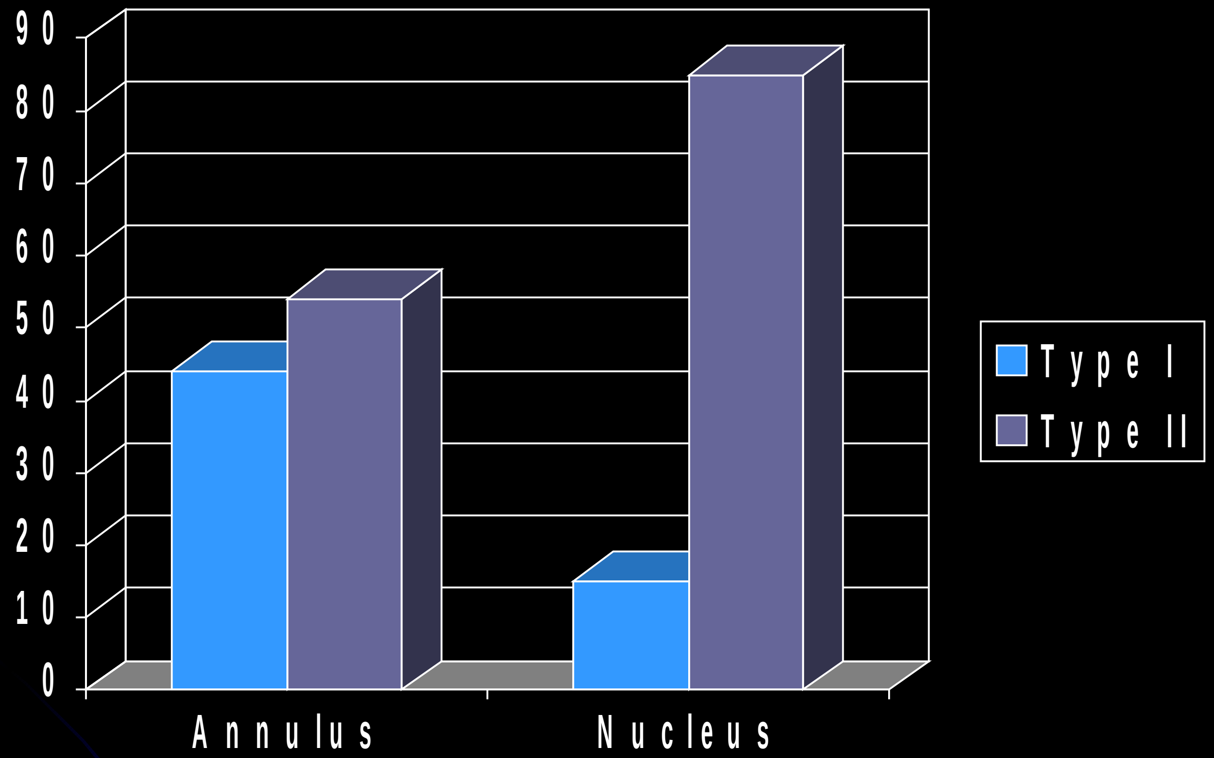


# BIOCHEMICAL COMPOSITION

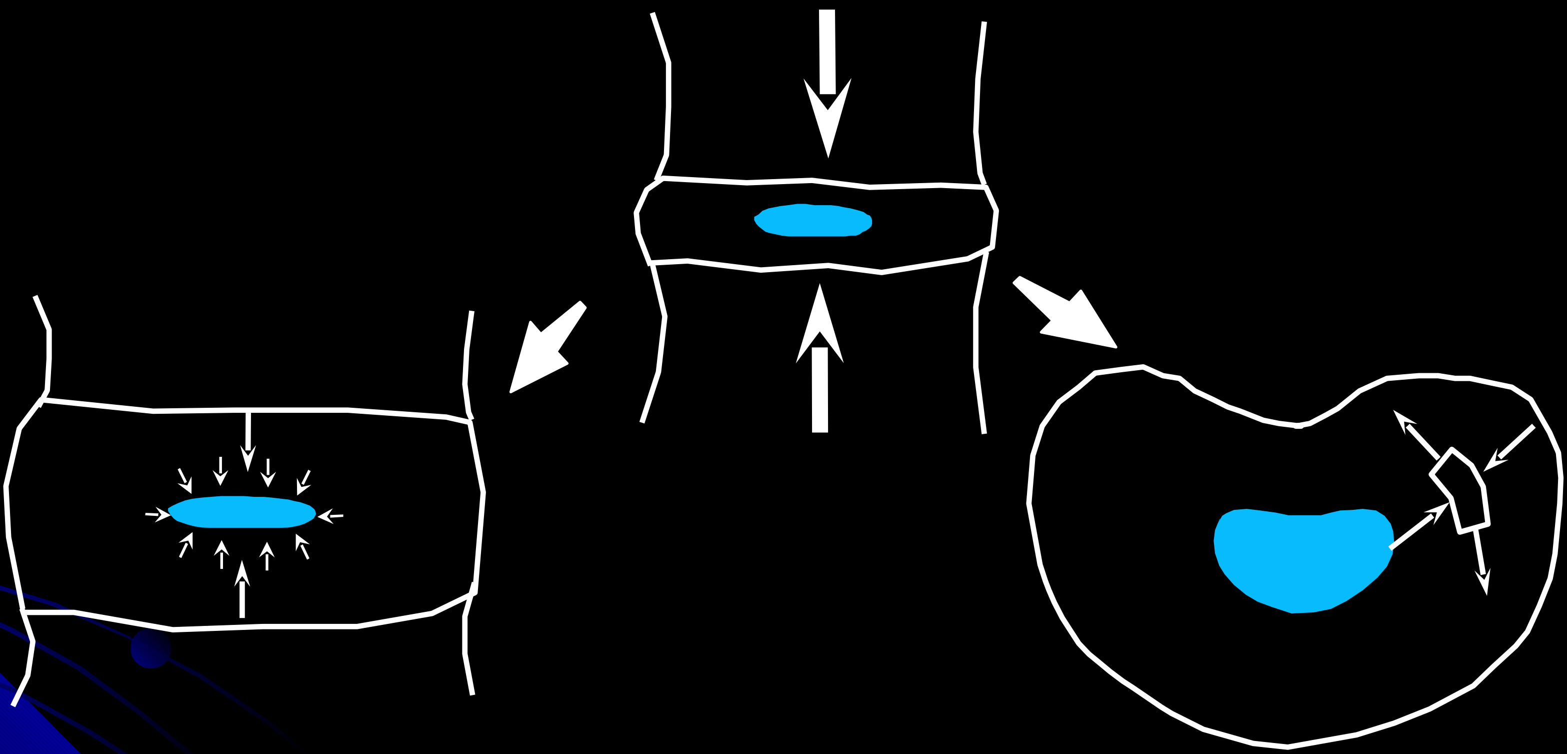
- Collagen
  - tensile strength
  - 70% dry weight of outer annulus
  - <20% dry weight of nucleus in young
- Proteoglycans
  - stiffness, resistance to compression, and viscoelasticity
  - ~3% dry weight of outer annulus
  - 50% dry weight of nucleus of young

# COLLAGEN




Eyre, D.R. and Muir, H. (1977) *Biochimica et Biophysica Acta* 492:29-42

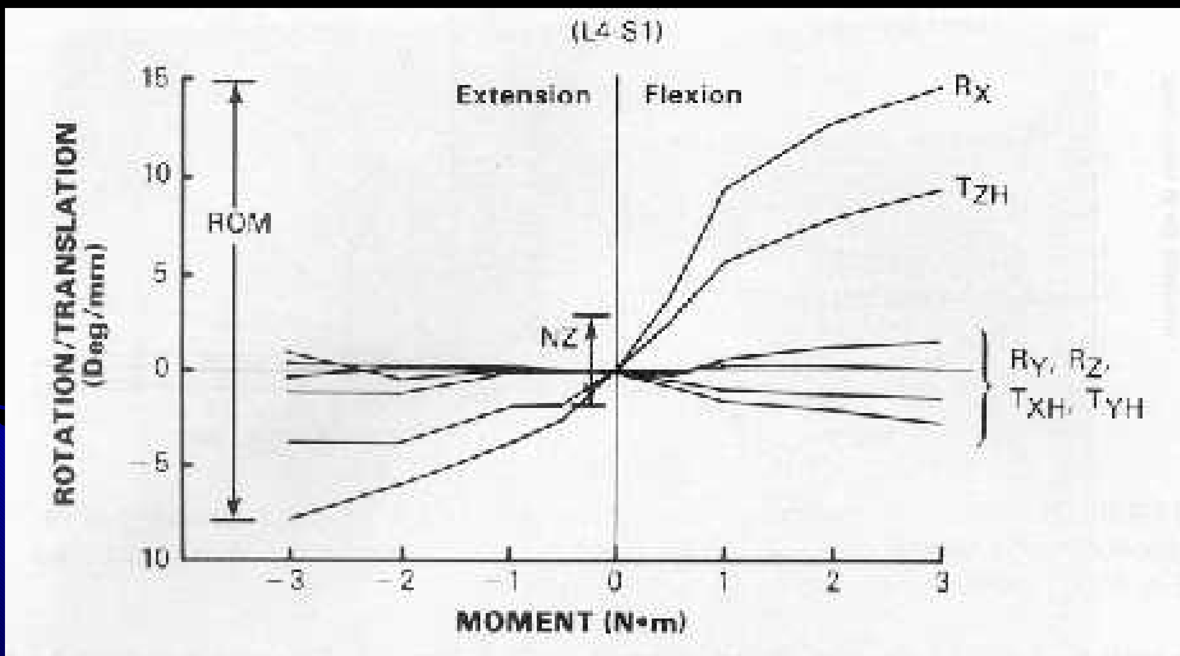
# Load Support in the Disc



**pressurization** of the NP
axial **compressive** stress

circumferential **tensile** stress
radial **compressive** stress

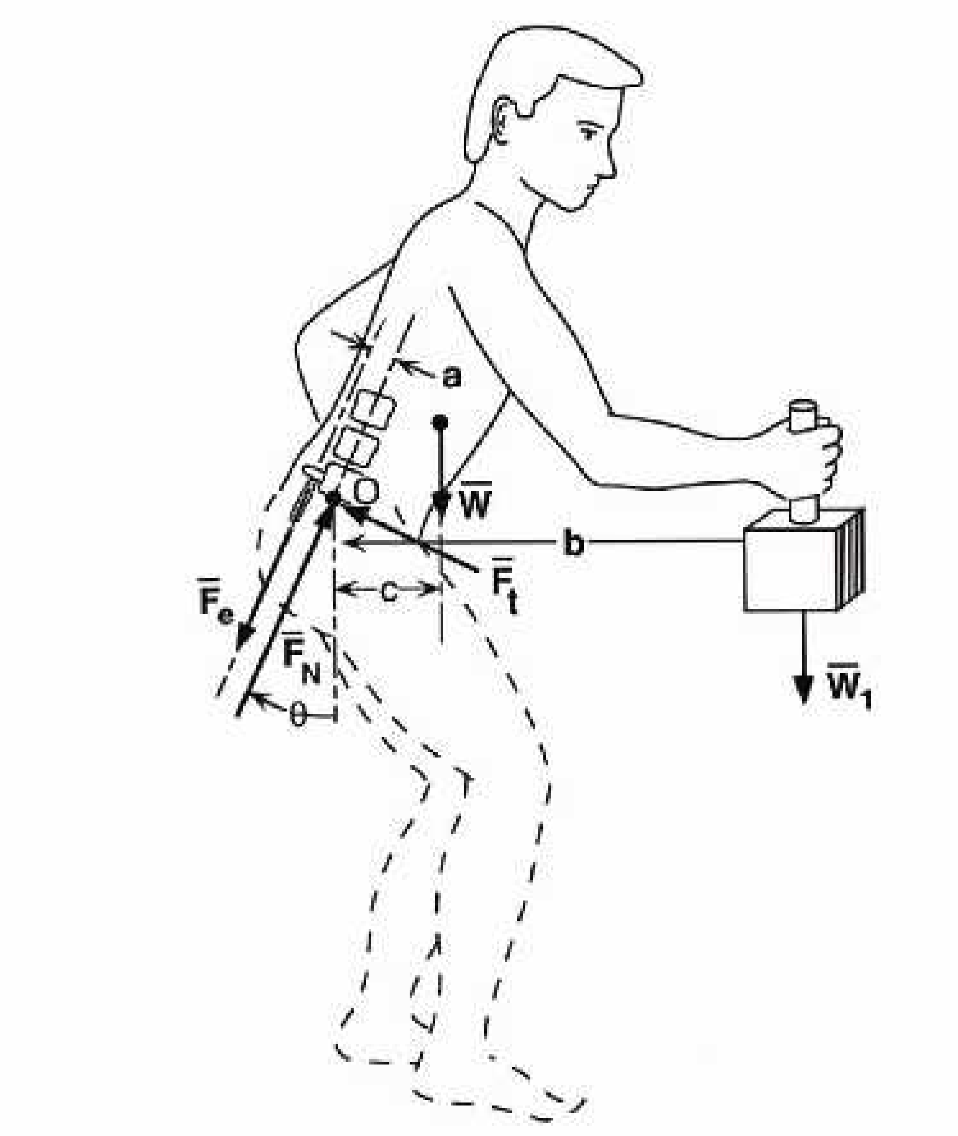
# SPINE MECHANICS

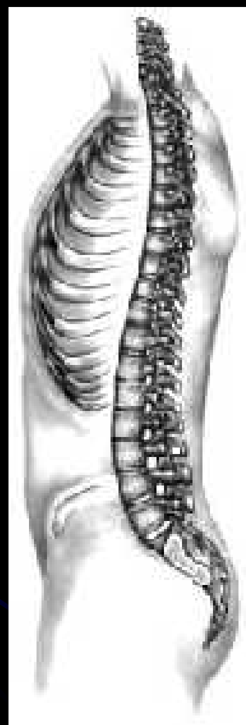


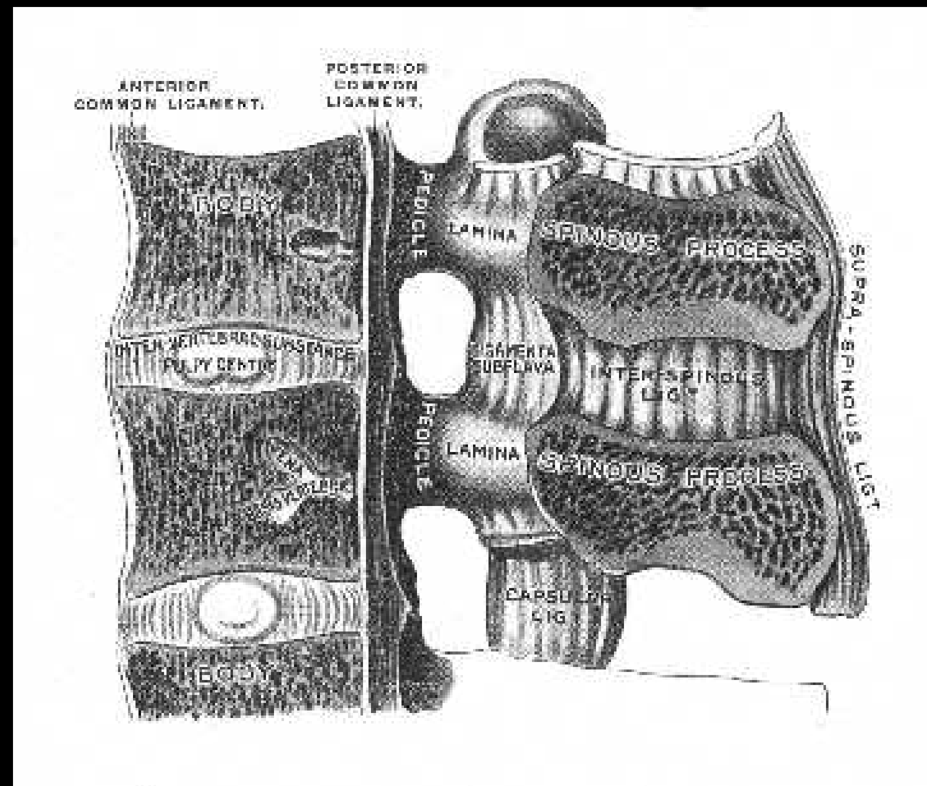

*Average stiffness values (N/mm and Nm/deg) for the adult human spine*

| Spine level | Comp | Shear (ant/post) | Lat | Bending (flex/ext) | Lat | Axial torsion | Reference |
|---|---|---|---|---|---|---|---|
| Occ–C1 | — | — | — | 0.04/0.02 | 0.09 | 0.06 | 100 |
| C1–2 | — | — | — | 0.06/0.05 | 0.09 | 0.07 | 100 |
| C2–7 | 1317 | 125/55 | 33 | 0.4/0.7 | 0.7 | 1.2 | 168 |
| T1–12 | 1250 | 86/87 | 101 | 2.7/3.3 | 3.0 | 2.6 | 195 |
| L1–5 | 667 | 145/143 | 132 | 1.4/2.9 | 1.6 | 6.9 | 34, 237 |
| L5–S1 | 1000 | 78/72 | 97 | 2.1/3.0 | 3.6 | 4.6 | 159 |

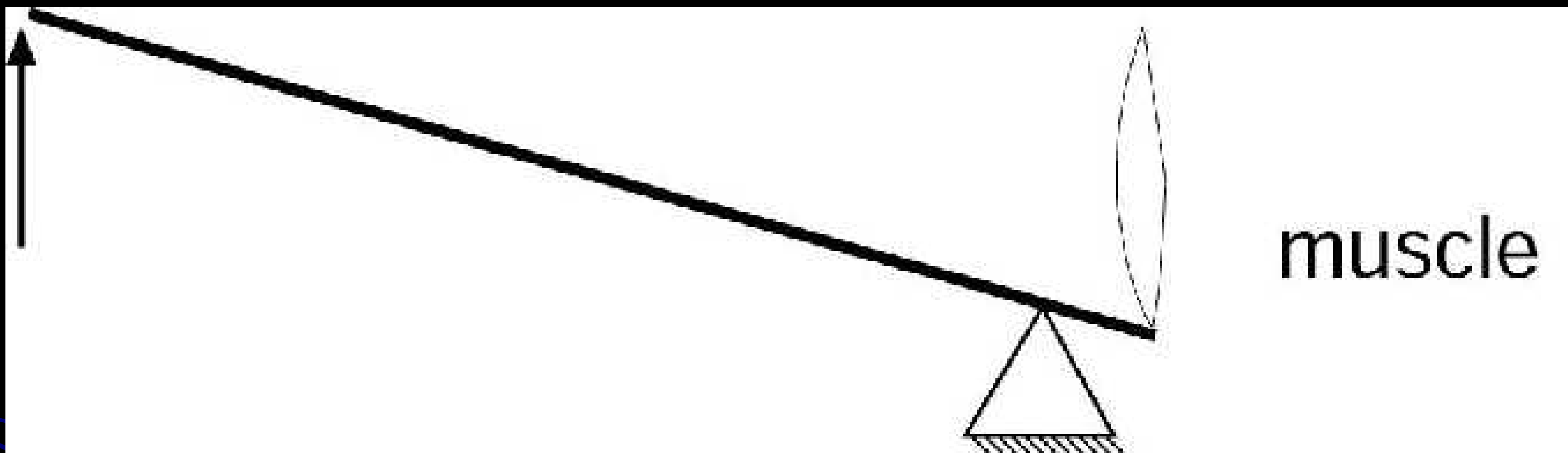
# Spine Biomechanics

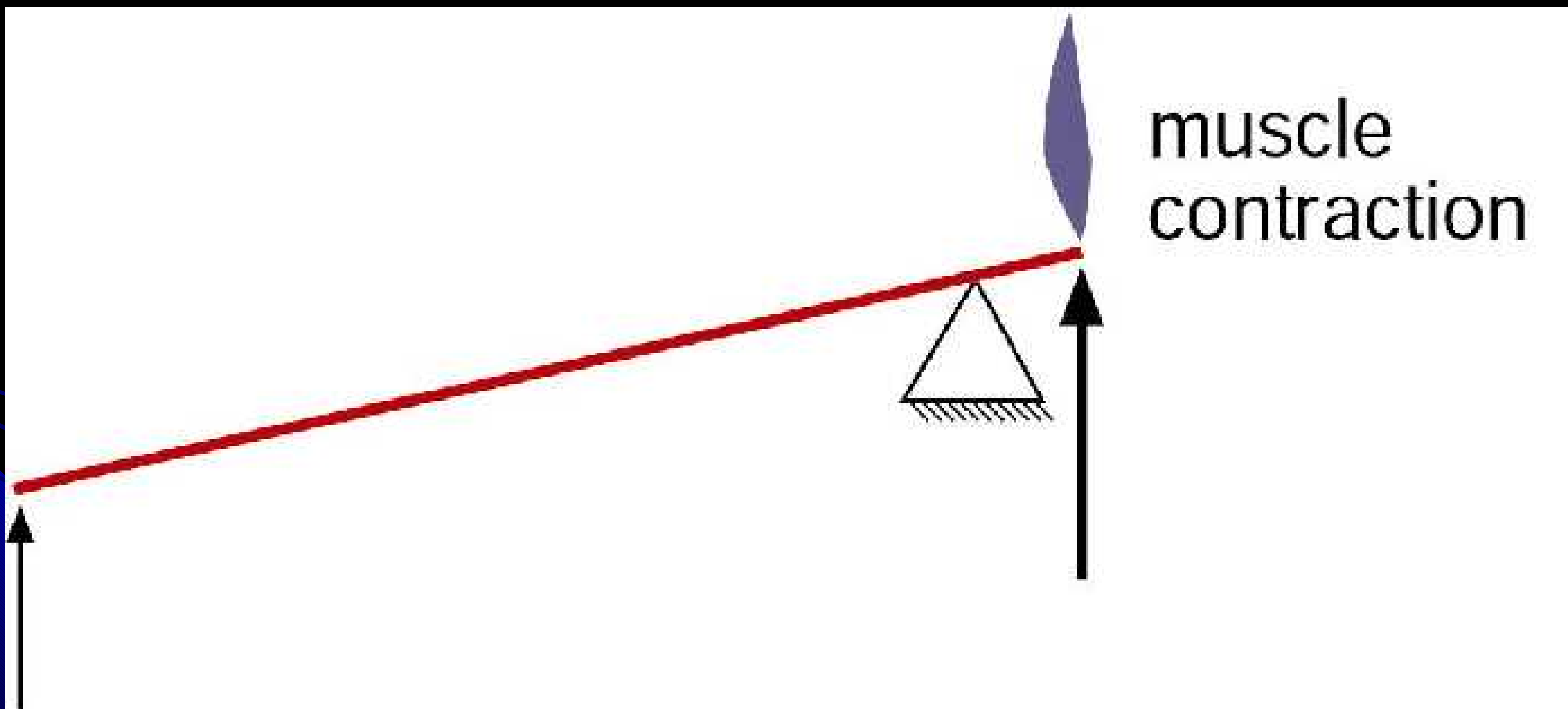




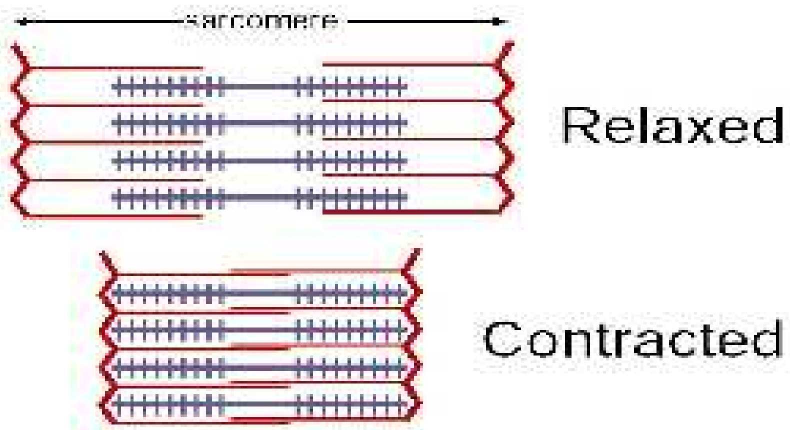


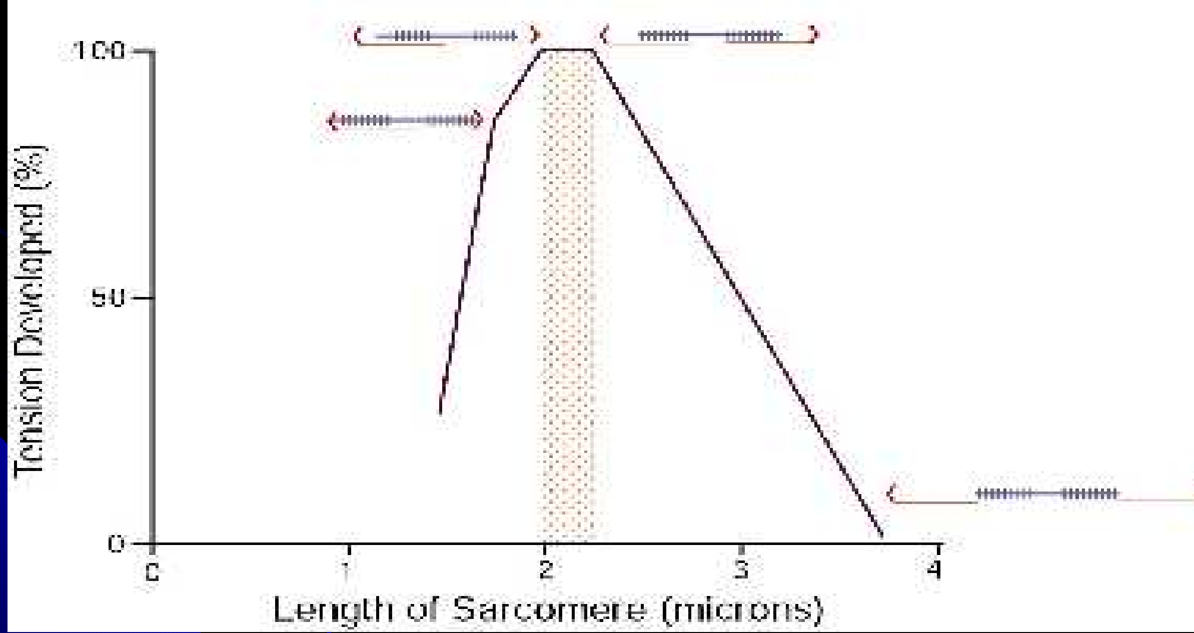

muscle moment arm (~4 to 5 cm)

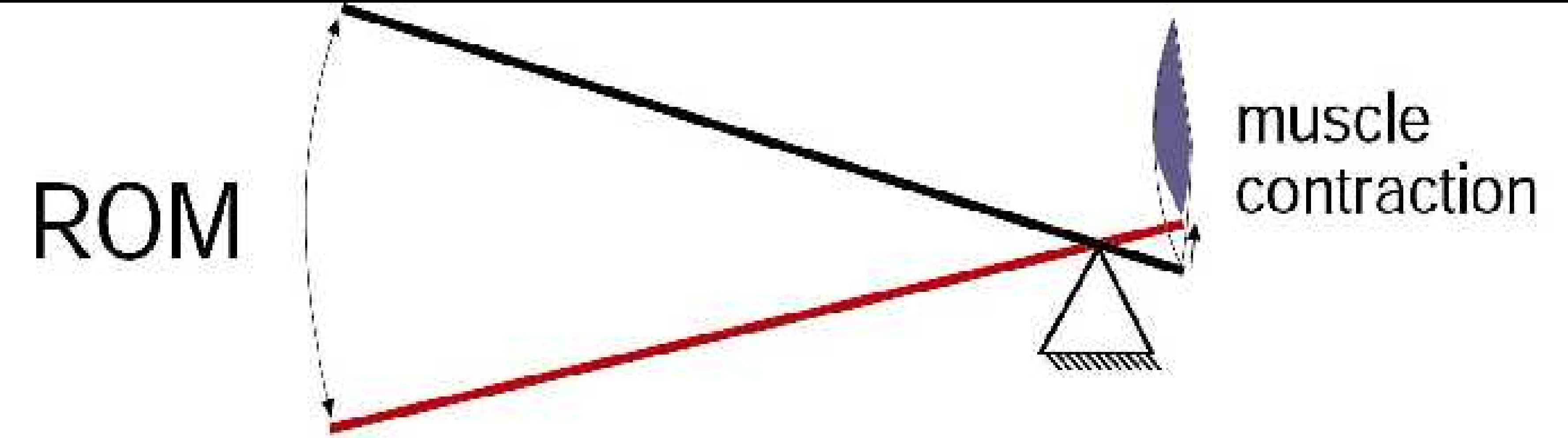

muscle


muscle
contraction

# Sliding Filaments

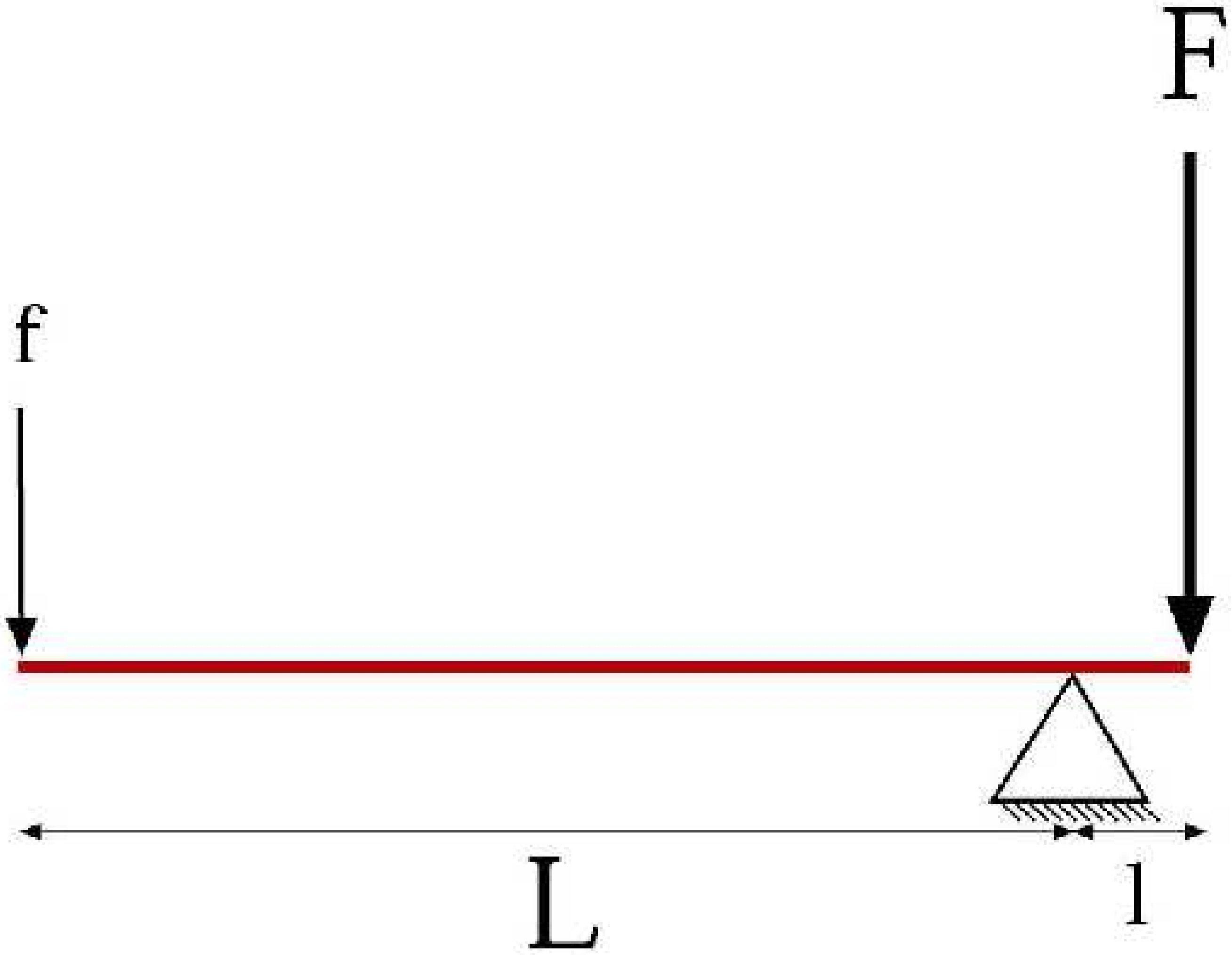


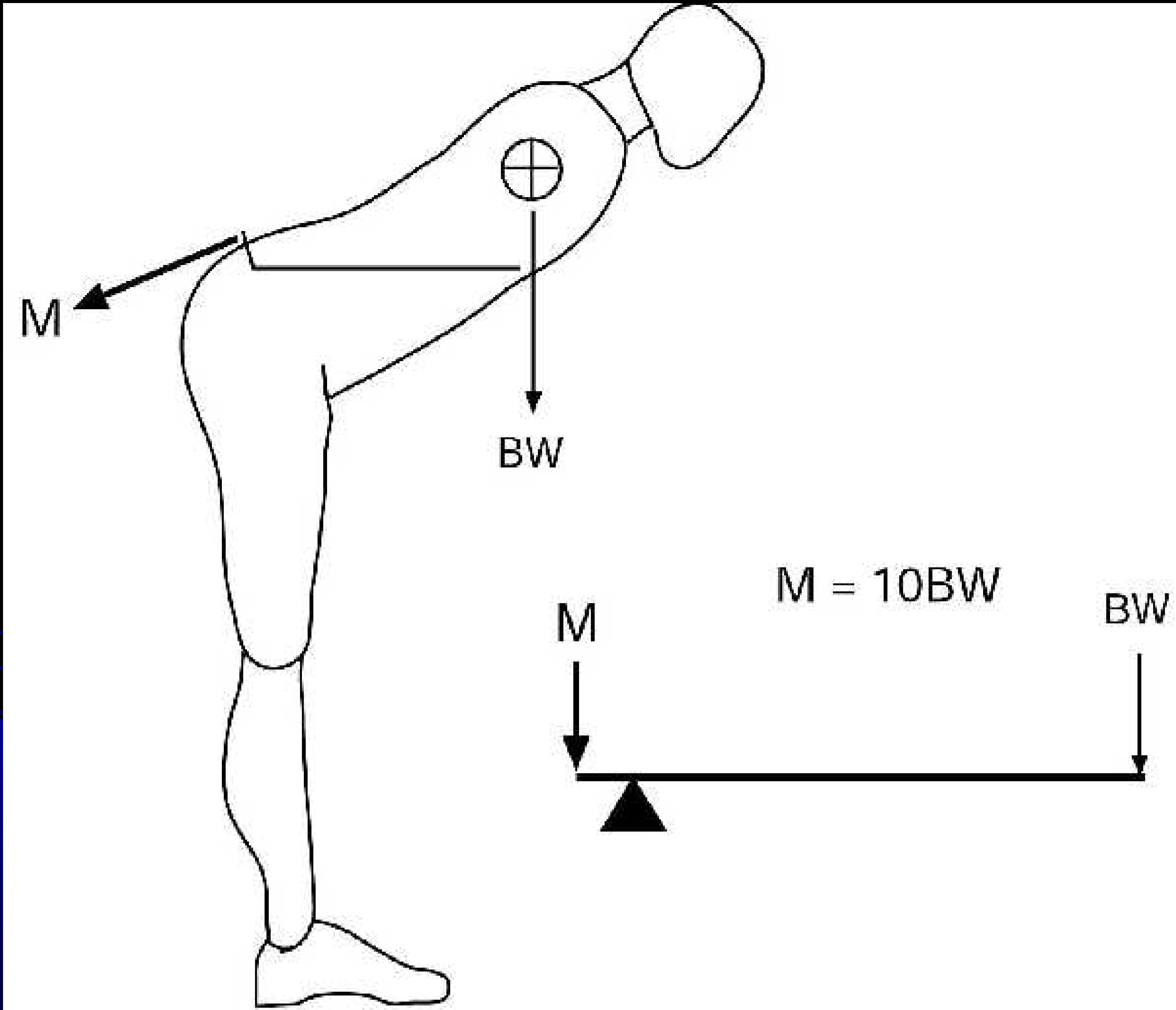



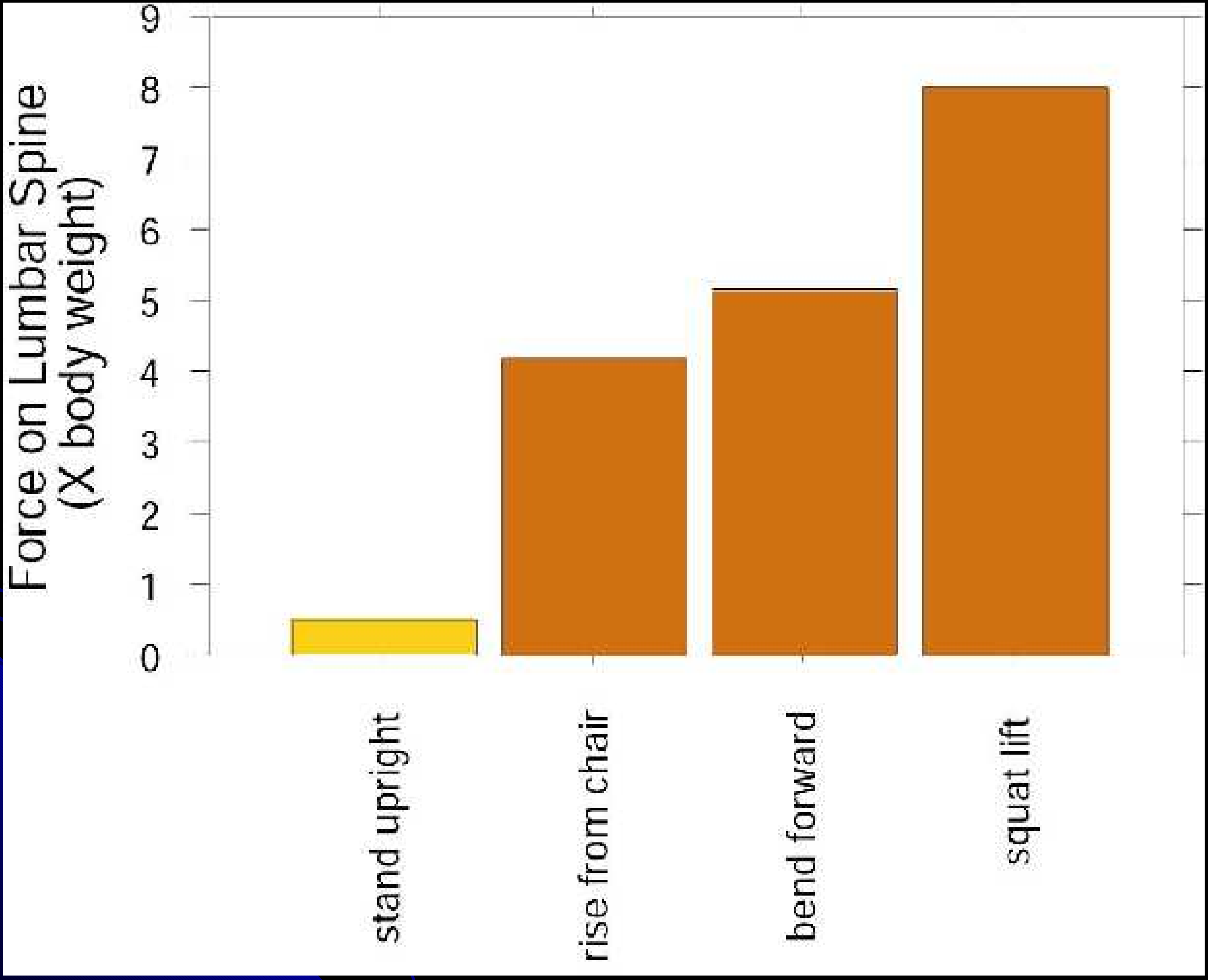

ROM
muscle
contraction

# Principle of Moments

$$F*l = f*L$$

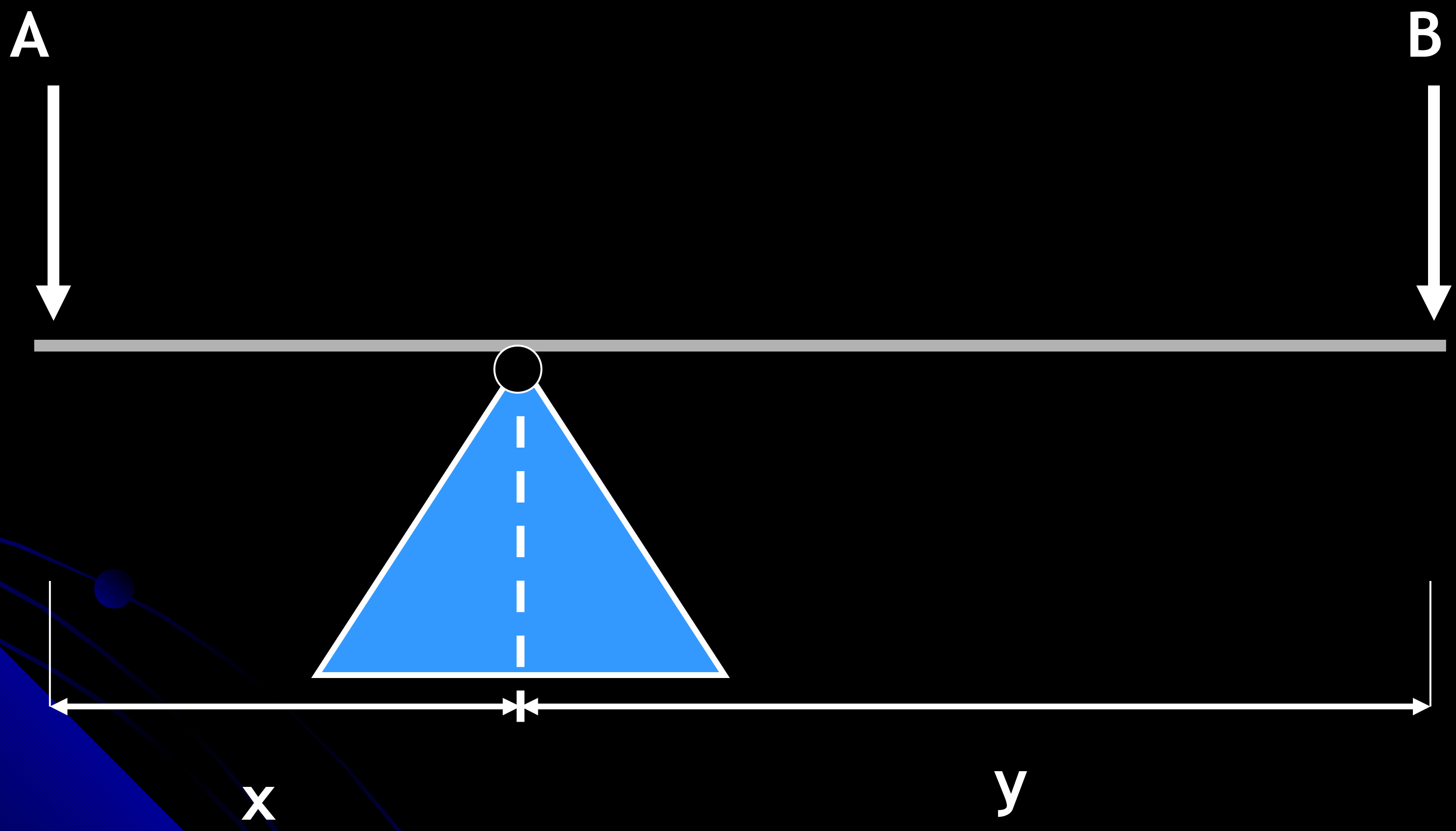



M
BW
M = 10BW
M
BW


Force on Lumbar Spine
(X body weight)
0
1
2
3
4
5
6
7
8
9
stand upright
rise from chair
bend forward
squat lift

Ax = CCW moment

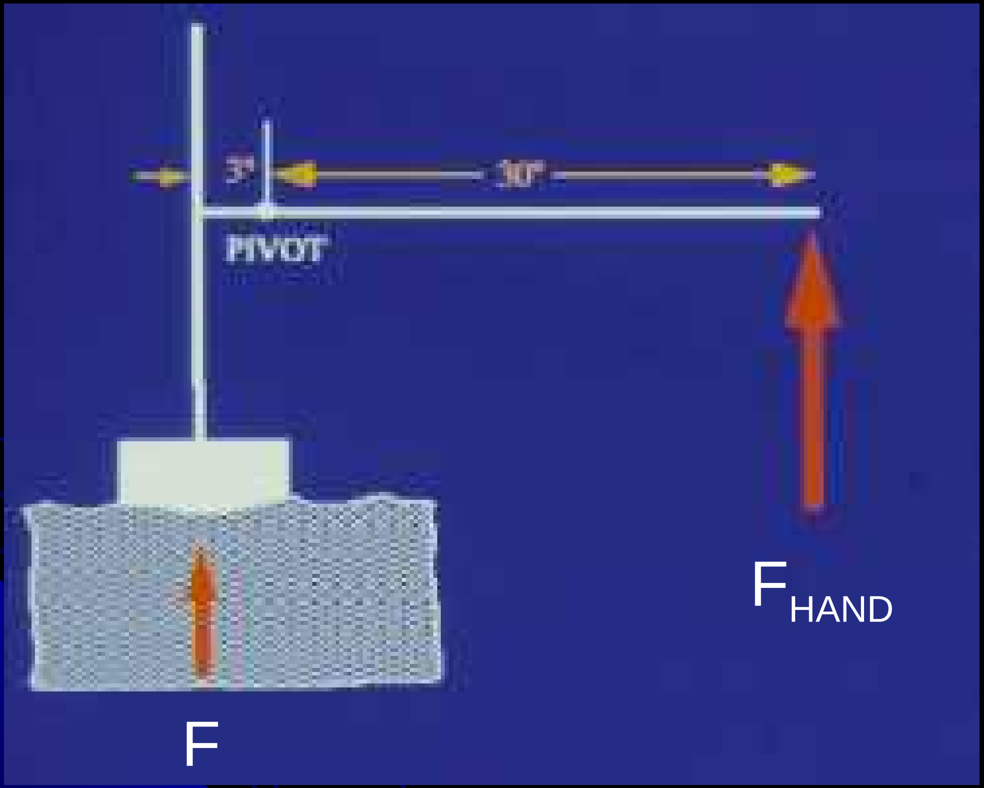
By = CW moment




x, y are moment arms

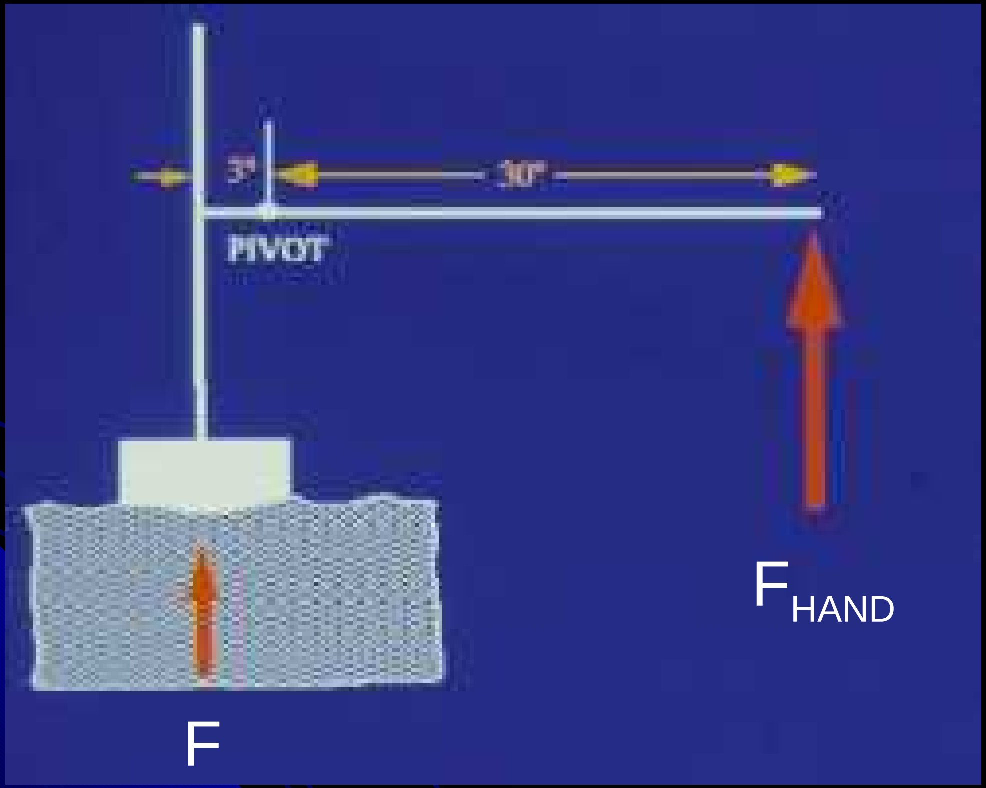
# LIFTING A LEVER

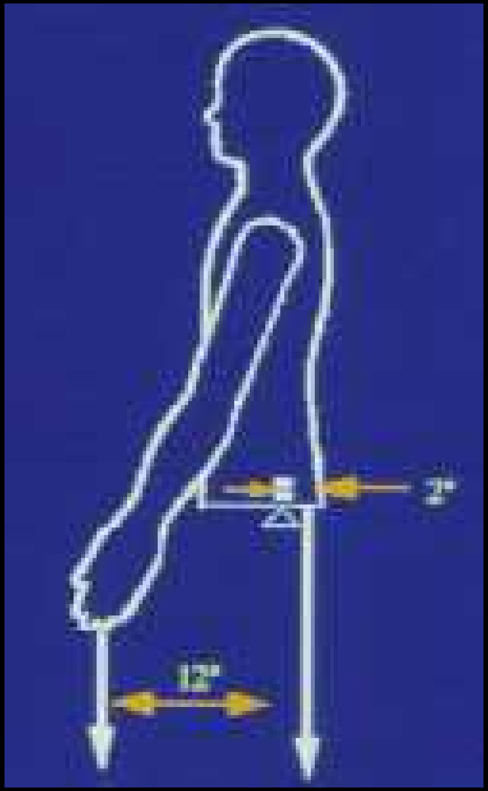
# MECHANICS OF LEVER



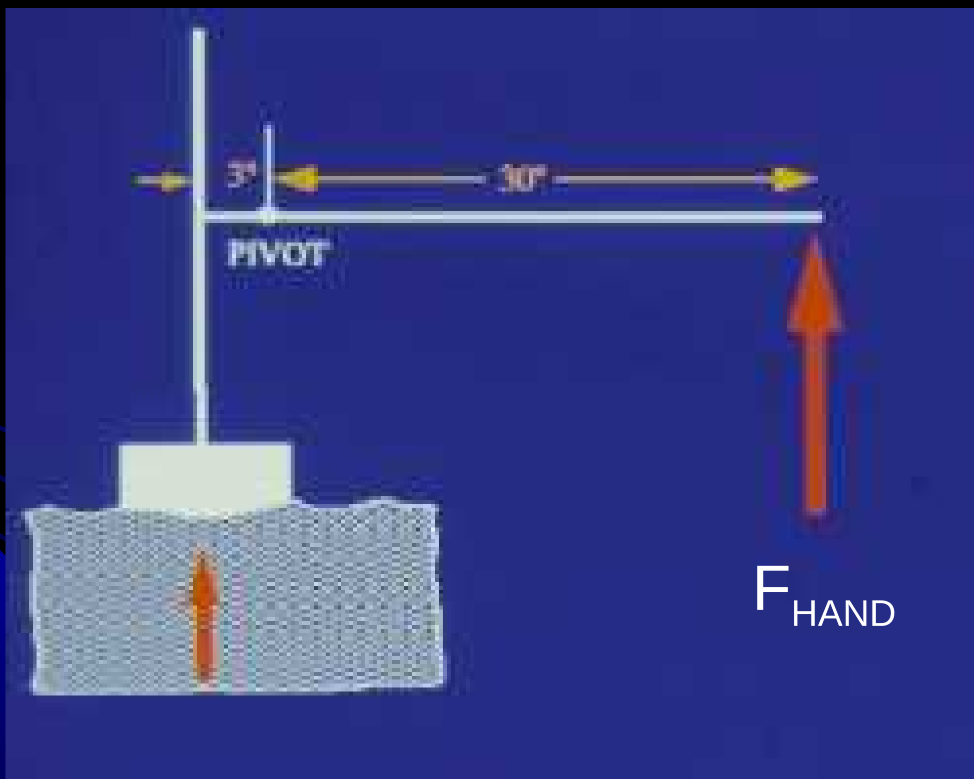

$$F = \frac{30}{3} F_{HAND}$$

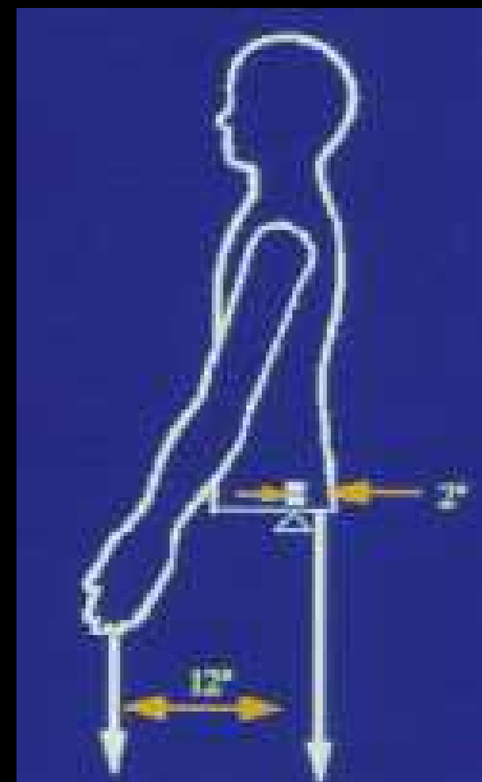
# MECHANICAL ANALYSIS



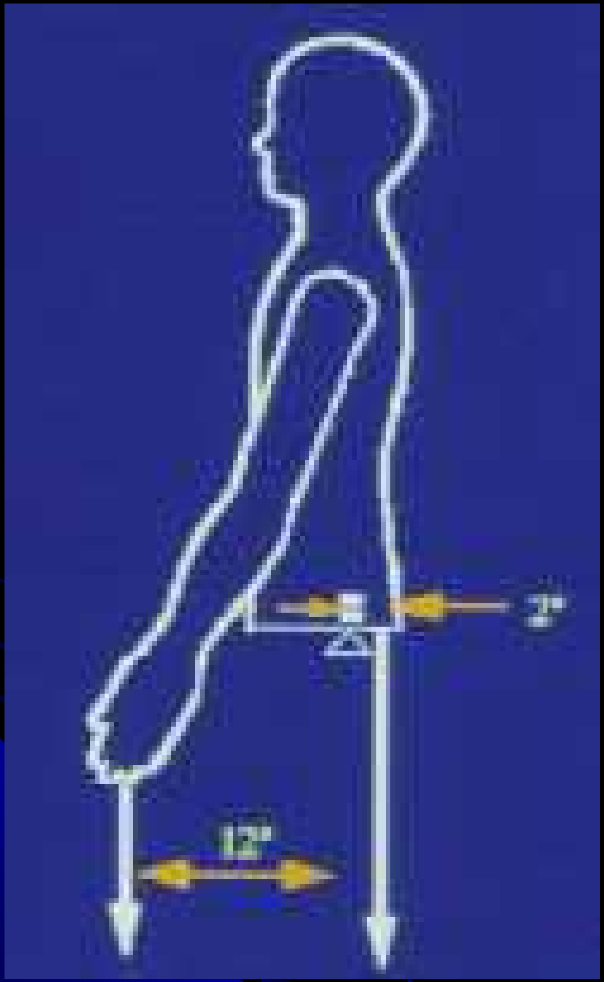
# NEWTON'S THIRD LAW




$F_{HAND}$

# MOMENTS ABOUT SPINE

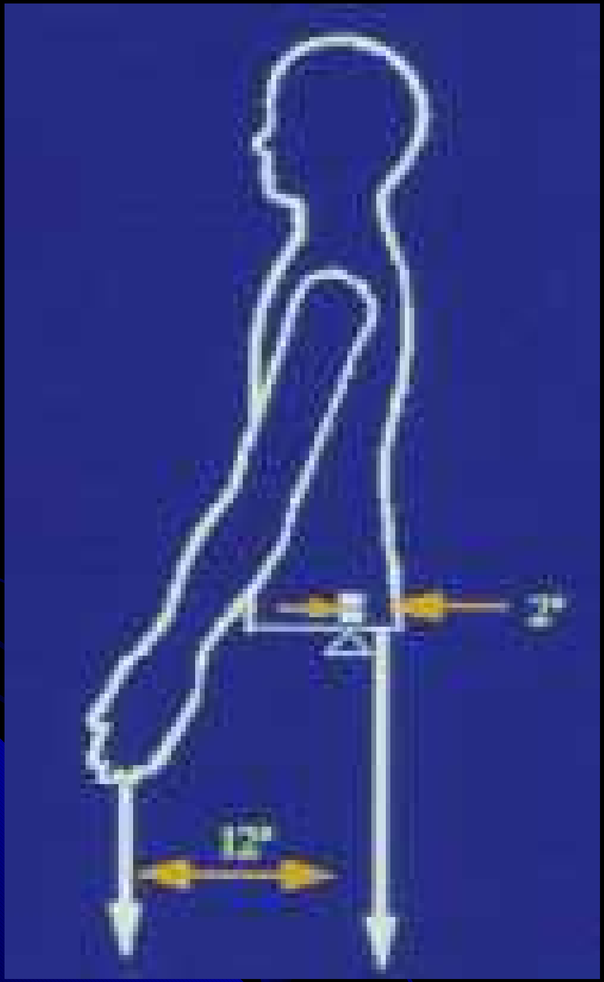



$F_{HAND}$ $F_{MUSCLE}$

$M_{EXTERNAL}=12*F_{HAND}$

$M_{INTERNAL}=2*F_{MUSCLE}$

# FORCE MULTIPLIER




$F_{HAND}$ $F_{MUSCLE}$

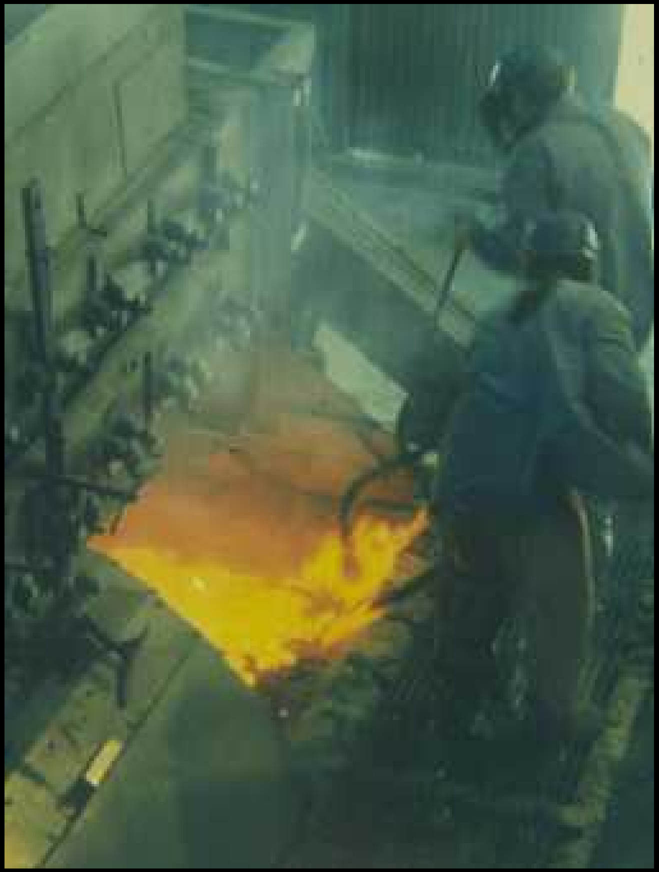
$$M_{INTERNAL} = M_{EXTERNAL}$$

$$F_{MUSCLE} = \frac{12}{2} F_{HAND}$$

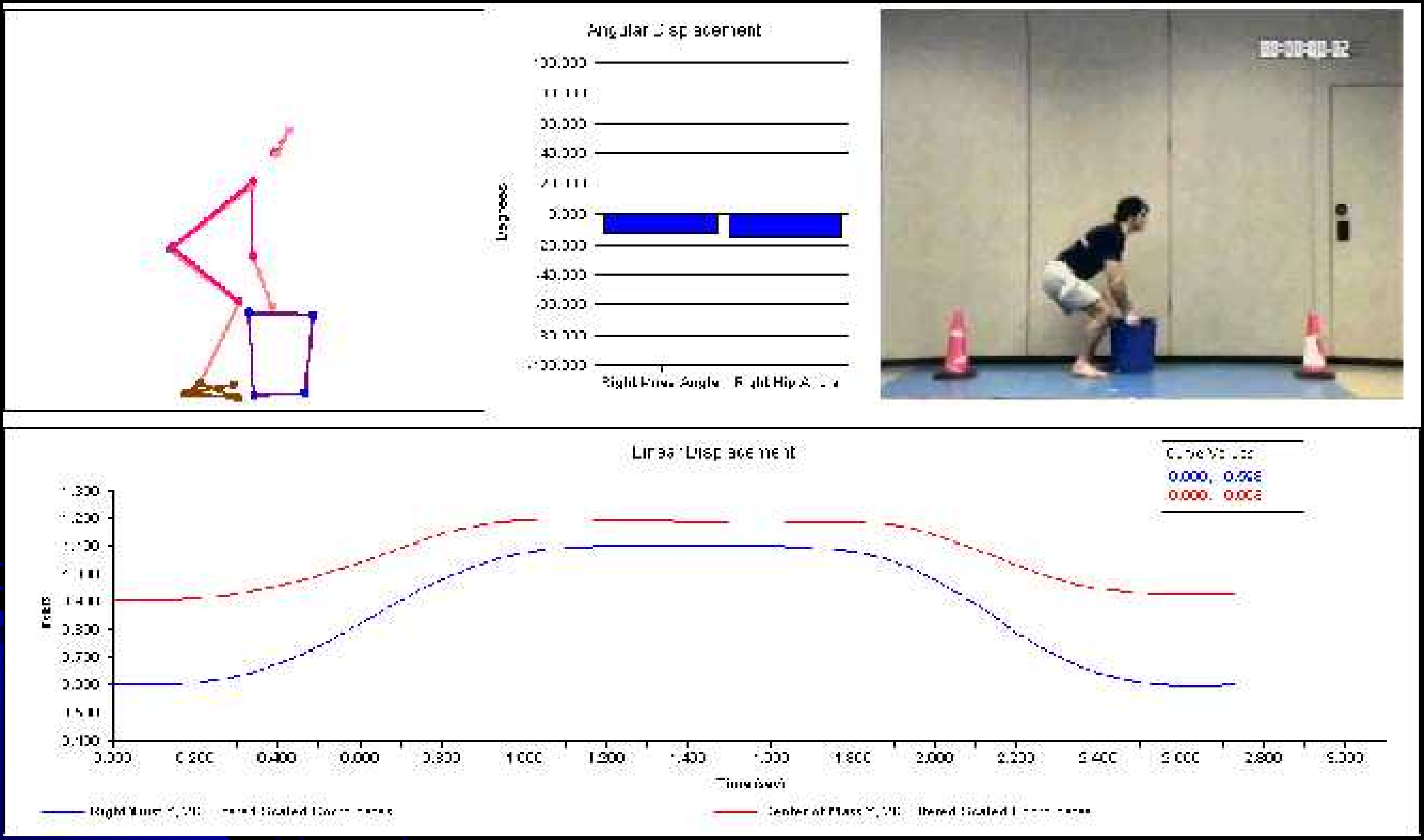
$$F_{MUSCLE} = 6\ F_{HAND}$$

# 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

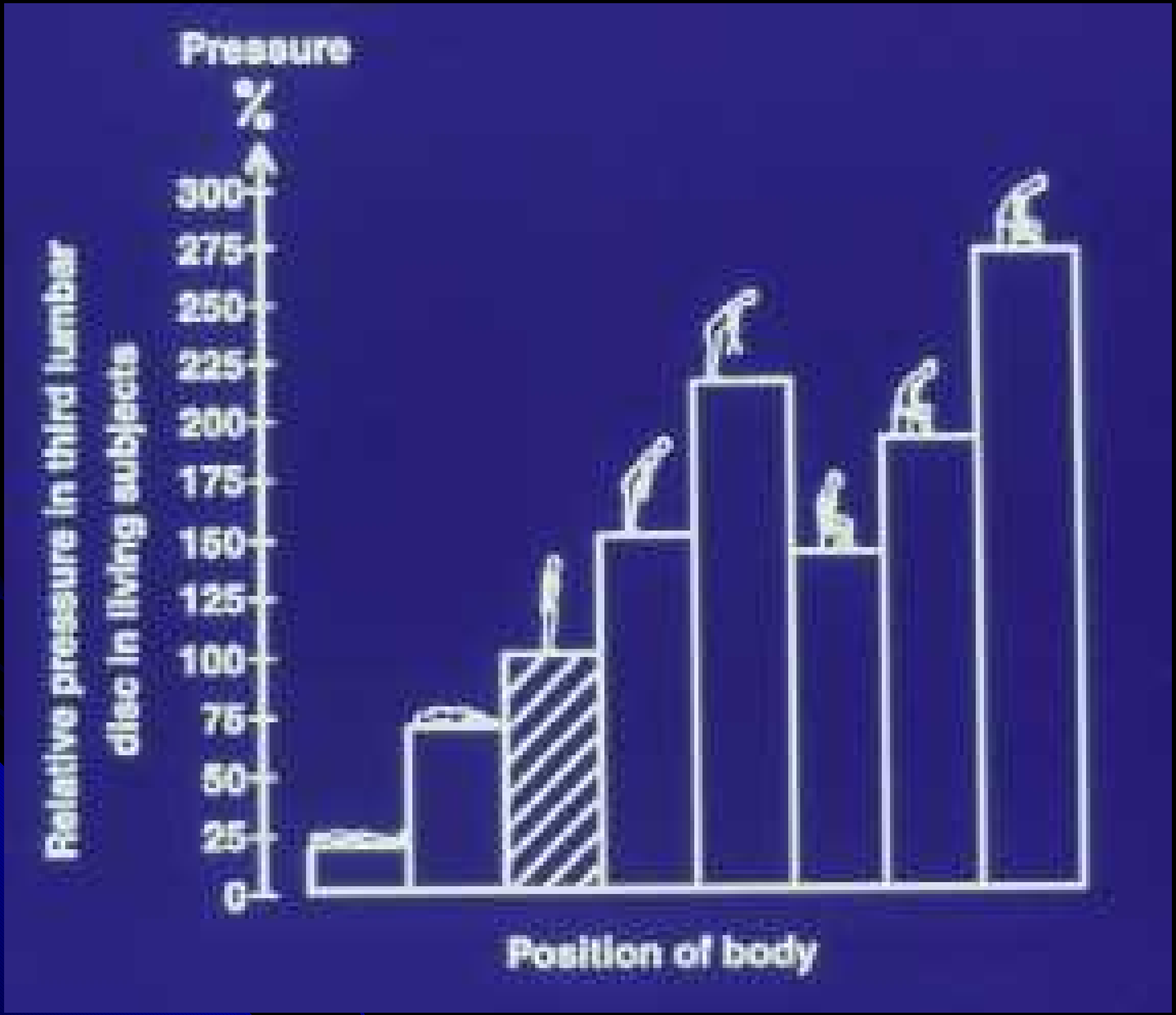
If you lift a weight, which of the following methods is best ?

**A?**

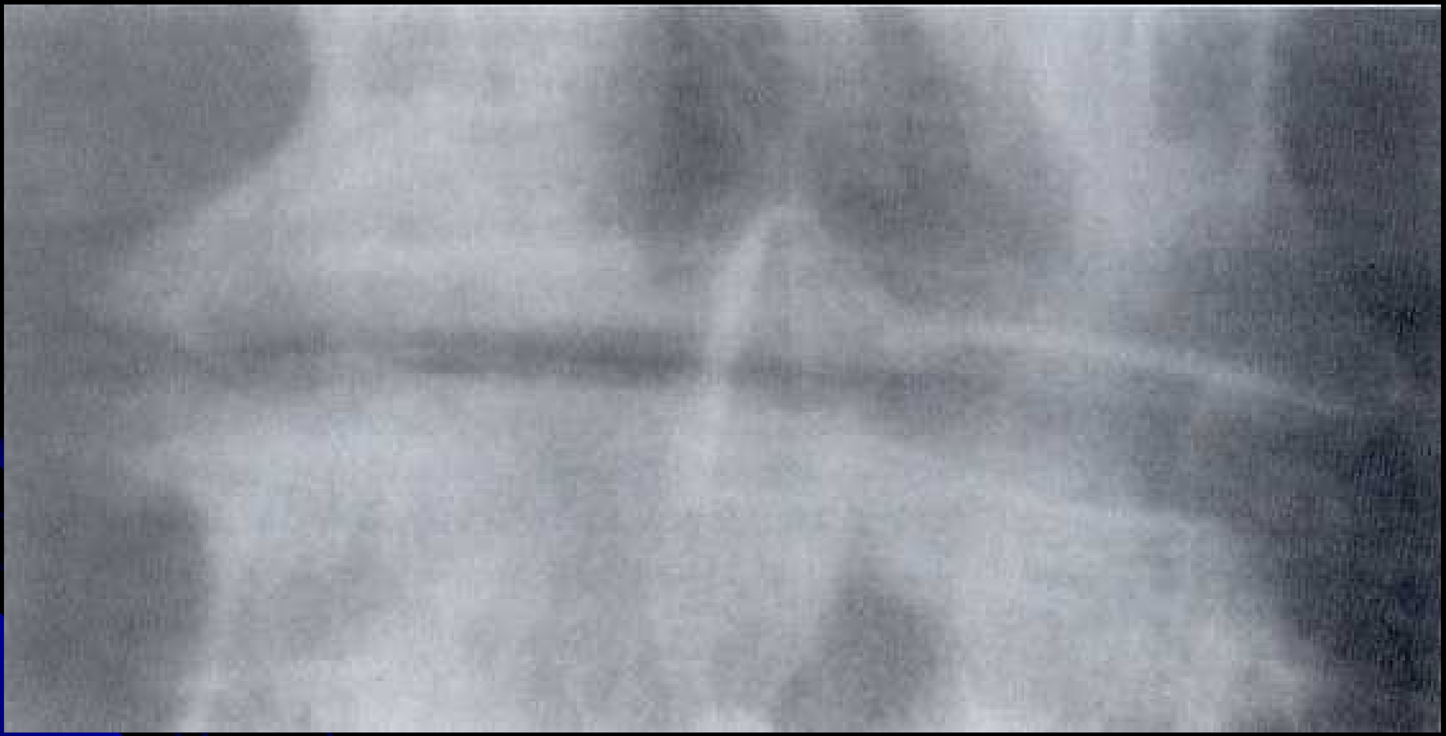
**B?**

Why?

# INTER-DISCAL PRESSURE



# DISK DEGENERATION



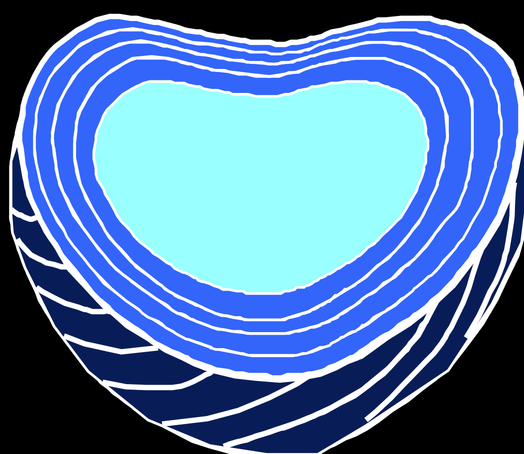
# DEGENERATION THEORIES

- 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 Material Properties & Composition

Altered Mechanical Environment

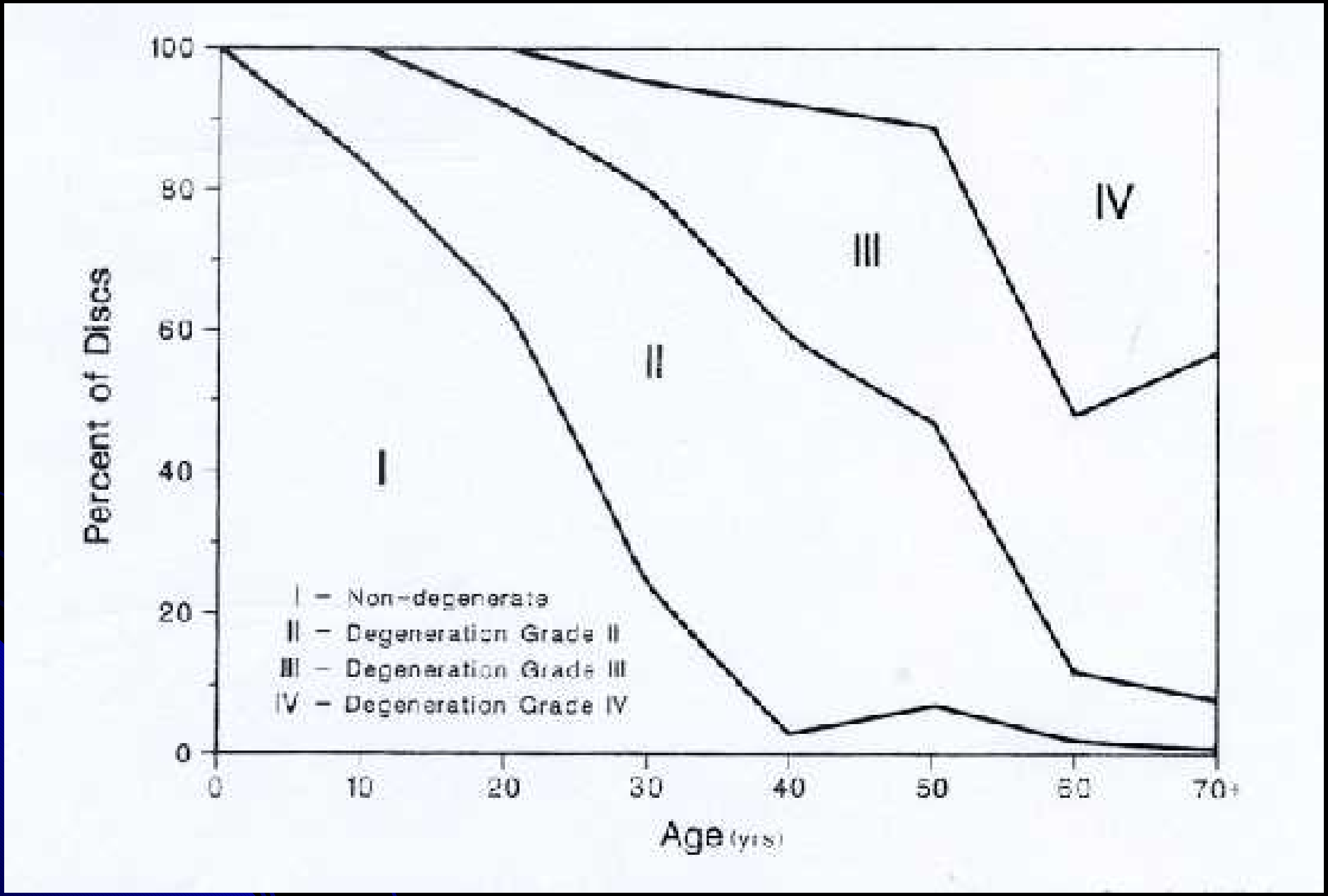

Healthy
Degenerated

# AGING EFFECTS

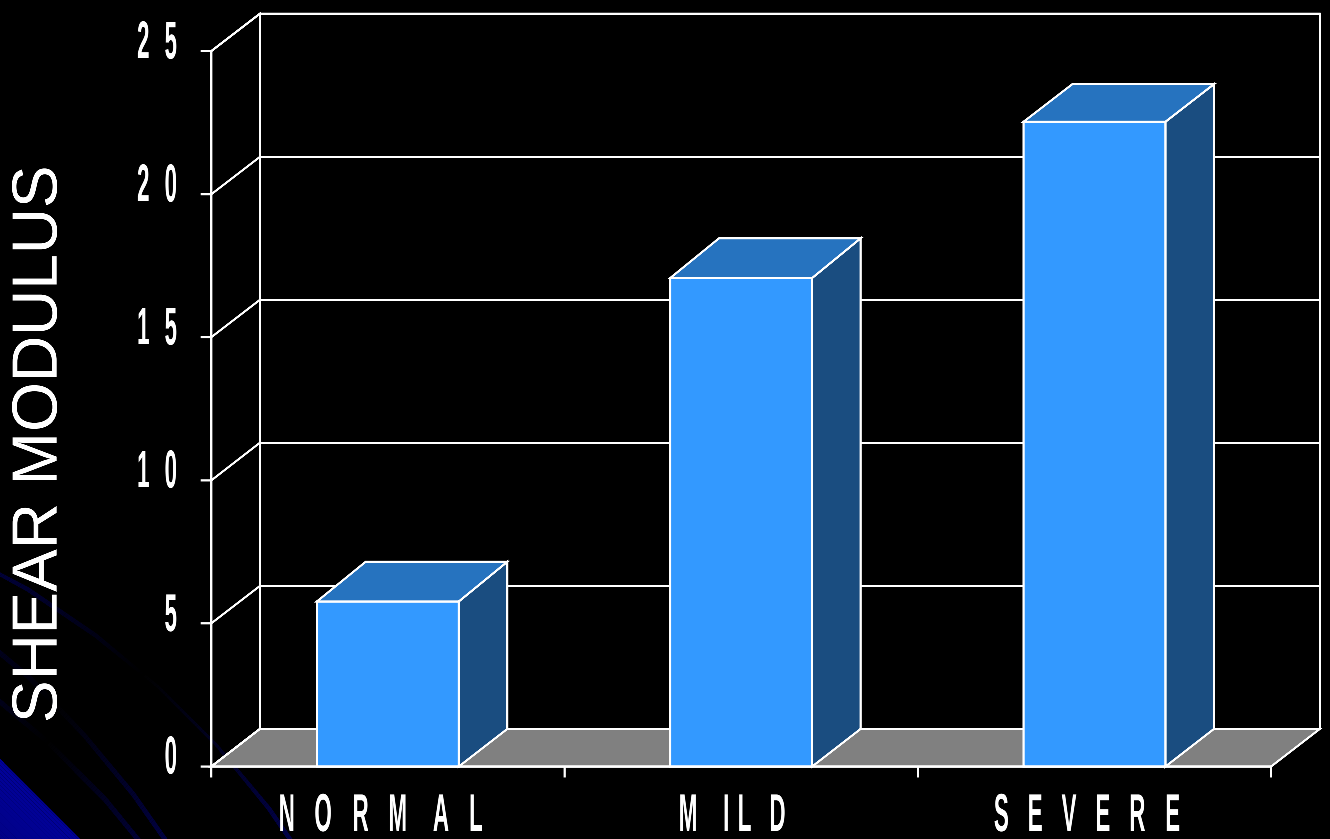
- Anatomic
  - Loss of disk height
  - Protrusion of central disk into body
  - Bulging or buckling of annulus

- Biochemical
  - Fewer viable cells in nucleus
  - Decreased proteoglycans and water in nucleus
  - Collagen increases in nucleus

# DEGENERATION AND AGE

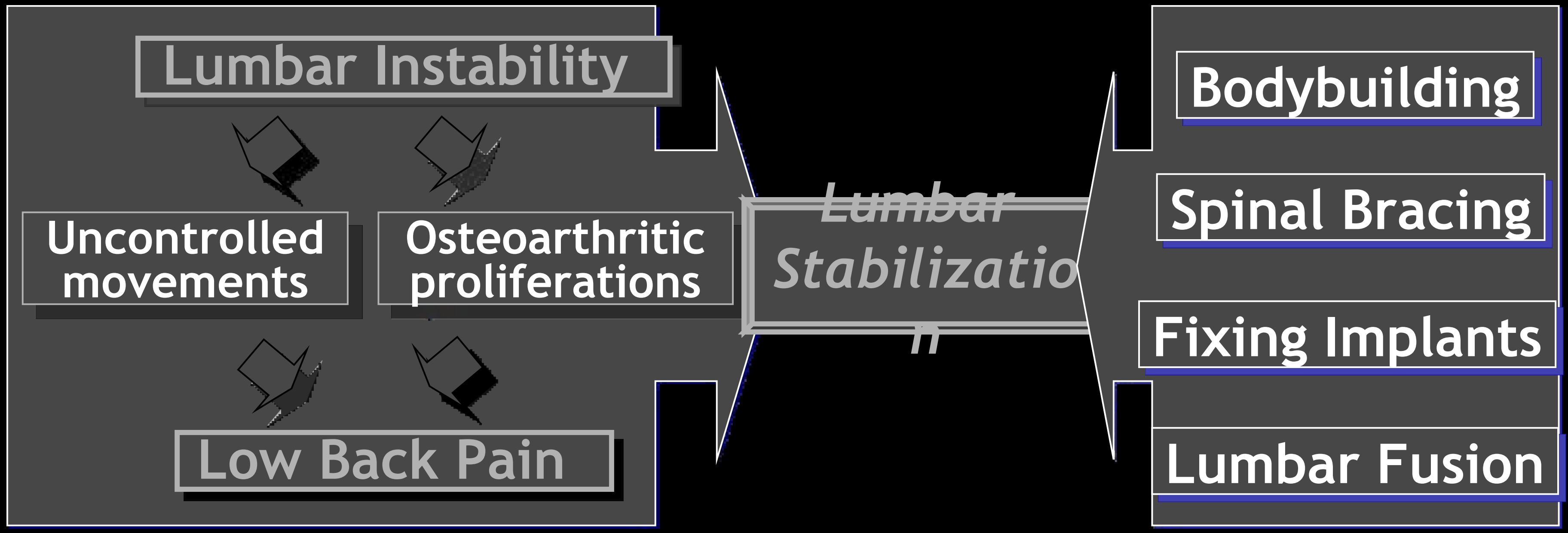


# NUCLEUS PROPERTIES

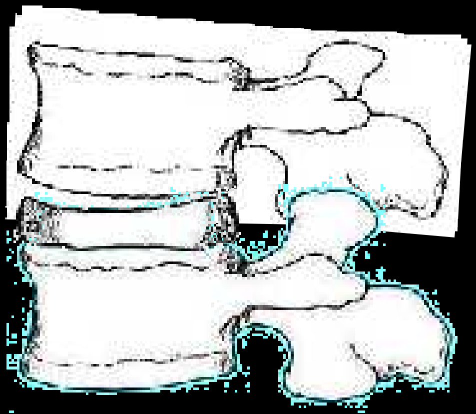
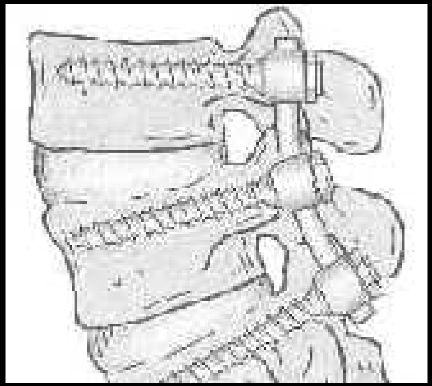
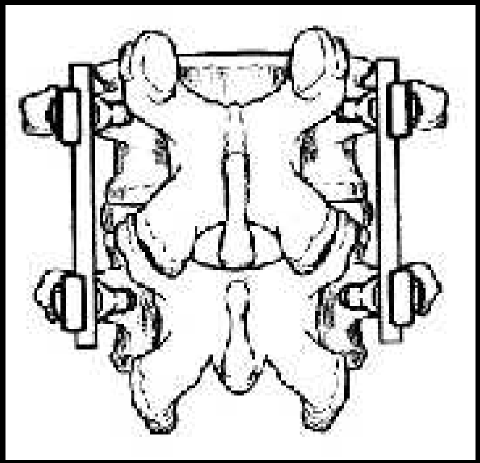


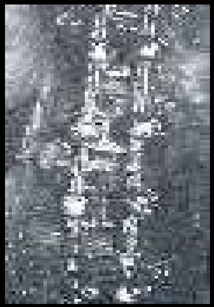
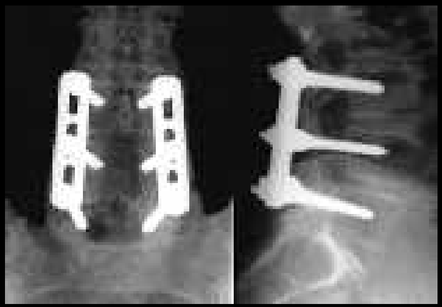

Iatridis, J.C. *et al*. (1997) *JOR* 15:318-322

# Lumbar Stabilization



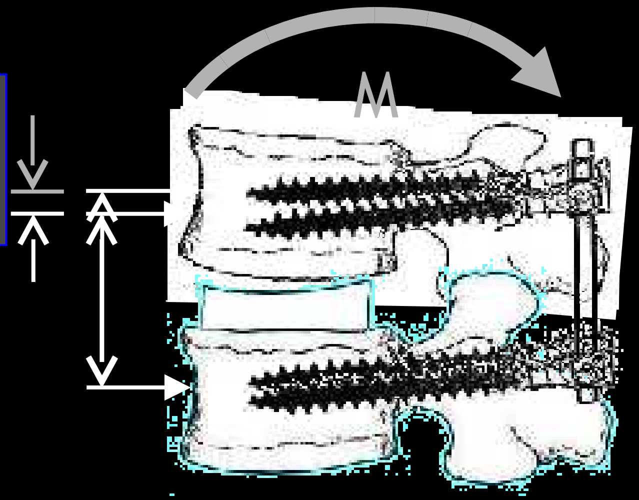
- Arthrodesis = surgical fixation of a joint
- Stiffer arthrodesis = better healing environment


# Stiffness of Implanted Lumbar

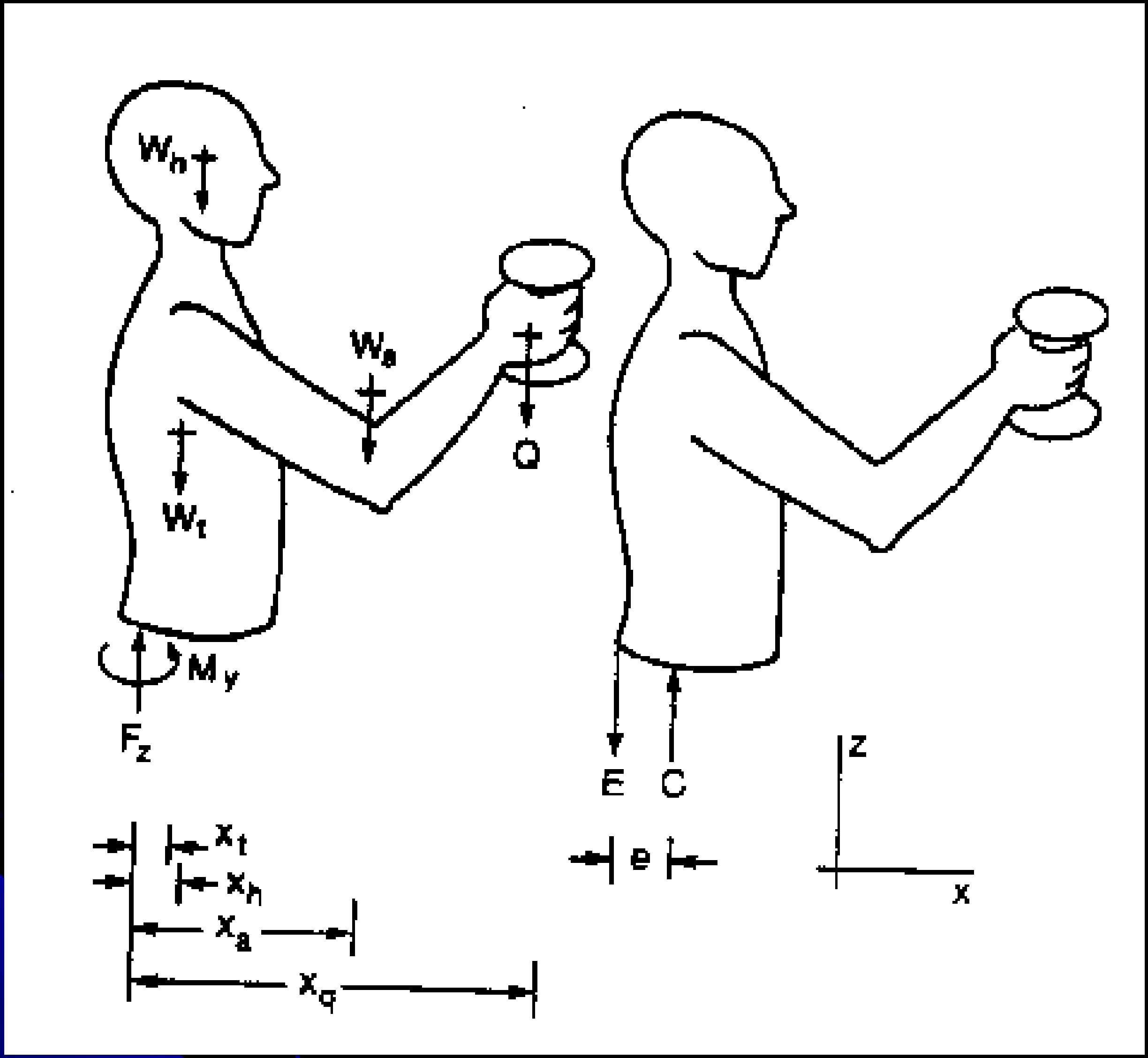
$$\text{Stiffness} = \frac{\text{Load}}{\Delta d}$$




- 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) | θ (°)[a] |
|---|---|---|---|
| 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) | −8.16 (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]θ 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).

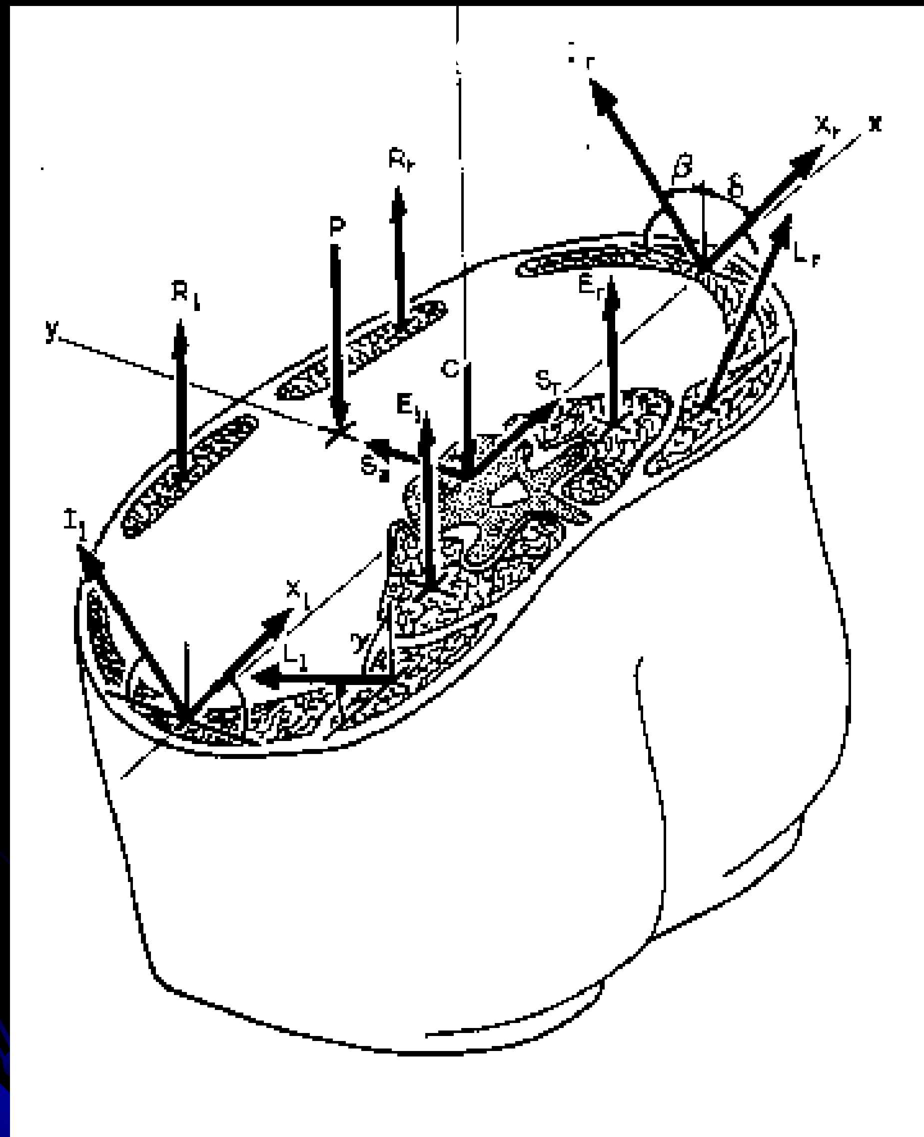
*Average segmental range of motion (°) at each spine level[a]*

| Level | Flexion | Flexion/ Extension | Extension | Lateral bending | Torsion |
|---|---|---|---|---|---|
| Occ–C1 | 13[b] | | 13[b] | 8[b] | 0 |
| C1–2 | 10[b] | | 9 | 0[b] | 47 |
| C2–3 | 8 | | 3 | 10[b] | 9 |
| C3–4 | 7 | | 9 | 11 | 11 |
| C4–5 | 10 | | 8 | 13 | 12 |
| C5–6 | 10 | | 11 | 15 | 10 |
| C6–7 | 13 | | 5 | 12 | 9 |
| C7–T1 | 6 | | 4 | 14 | 8 |
| T1–2 | 5 | | 3 | 2 | 9 |
| T2–3 | | 4 | | 3 | 8 |
| T3–4 | | 5 | | 4 | 8 |
| T4–5 | | 4 | | 2 | 8 |
| T5–6 | | 5 | | 2 | 8 |
| T6–7 | | 5 | | 3 | 8 |
| T7–8 | | 5 | | 2 | 8 |
| T8–9 | | 4 | | 2 | 7 |
| T9–10 | | 3 | | 2 | 4 |
| T10–11 | | 4 | | 3 | 2 |
| T11–12 | | 4 | | 3 | 2 |
| T12–L1 | | 5 | | 3 | 2 |
| L1–2 | 8 | | 5 | 6 | 1 |
| L2–3 | 10 | | 3 | 6 | 1 |
| L3–4 | 12 | | 1 | 6 | 2 |
| L4–5 | 13 | | 2 | 3 | 2 |
| L5–S1 | 9 | | 5 | 1 | 1 |

[a]Cervical and thoracic data from ref. 291. Cervical data from ref. 132 unless otherwise specified. Thoracic data from ref. 28. 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



. *Data incorporated into the ten single equivalent muscle L-3 cross-sectional model*

| Muscle | Symbol | Line of action | Area ratio per side[a] | Location of centroid: Anteroposterior offset ratio[b] | Location of centroid: Lateral offset ratio[c] |
|---|---|---|---|---|---|
| Rectus abdominis | R | Longitudinal | 0.0060 | 0.540 | 0.121 |
| Internal oblique abdominals | I | Inclined 45° to longitudinal, in sagittal plane | 0.0168 | 0.189 | 0.453 |
| External oblique abdominals | X | Inclined 45° to longitudinal, in sagittal plane | 0.0148 | 0.189 | 0.453 |
| Erector spinae | E | Longitudinal | 0.0389 | 0.220 | 0.179 |
| Latissimus dorsi | L | Inclined 45° to longitudinal, in frontal plane | 0.0037 | 0.276 | 0.211 |

[a]In ratio to trunk width times trunk depth.
[b]From vertebral body center, in ratio to trunk depth.
[c]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*[a]

Equations of force equilibrium:

$$F_x = S_r + (L_r - L_l) \leftrightarrow \sin\gamma$$

$$F_y = S_a = (I_l + I_r) \leftrightarrow \sin\beta - (X_l + X_r) \leftrightarrow \sin\delta$$

$$F_z = (E_l + E_r) + (R_l + R_r) + (L_l + L_r) \leftrightarrow \cos\gamma + (I_l + I_r) \leftrightarrow \cos\beta + (X_l + X_r) \leftrightarrow \cos\delta - C$$

Equations of moment equilibrium:

$$M_x = (R_l + R_r) \leftrightarrow y_r + [(I_l + I_r) \leftrightarrow \cos\beta + (X_l + X_r) \leftrightarrow \cos\delta] \leftrightarrow y_o - (E_l + E_r) \leftrightarrow y_e - (L_l + L_r) \leftrightarrow \cos\gamma \leftrightarrow y_l$$

$$M_y = (R_l - R_r) \leftrightarrow x_r + [(I_l - I_r) \leftrightarrow \cos\beta + (X_l - X_r) \leftrightarrow \cos\delta] \leftrightarrow x_o + (E_l - E_r) \leftrightarrow x_e + (L_l + L_r) \leftrightarrow \cos\gamma \leftrightarrow x_l$$

$$M_z = [(I_r - I_l) \leftrightarrow \sin\beta + (X_l - X_r) \leftrightarrow \sin\delta] \leftrightarrow x_o + (L_r - L_l) \leftrightarrow \sin\gamma \leftrightarrow y_l$$

[a] $F_x$, $F_y$, $F_z$ are the net reaction force components.

$M_x$, $M_y$, $M_z$ are the net reaction moment components.

$C$, $S_a$, $S_r$ are the motion segment compression and shear forces.

$E_l$, $L_l$, $R_l$, $I_l$, $X_l$ are the forces in the left-side erector spinae, latissimus dorsi, rectus abdominis, and internal and external oblique muscles.

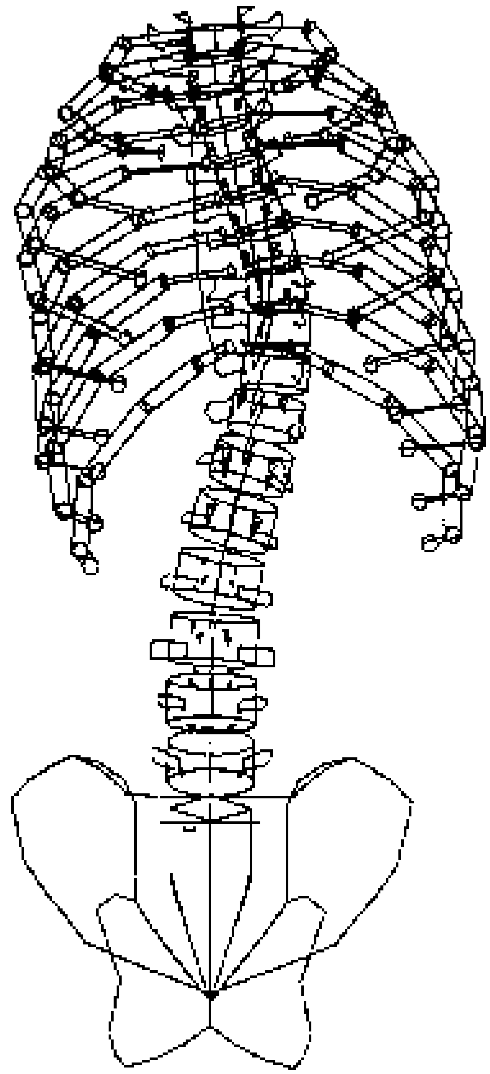
$E_r$, $L_r$, $R_r$, $I_r$, $X_r$ are the corresponding right-side muscle forces.

$\beta$, $\delta$, $\gamma$ are the angles shown in Fig. 7.

$x_e$, $x_l$, $x_r$, $x_o$ are the positive distances from the *y* axis for the corresponding muscles.

$y_e$, $y_l$, $y_r$, $y_o$ are the corresponding distances from the *x* axis.

# Deformable Element Model of the Spine

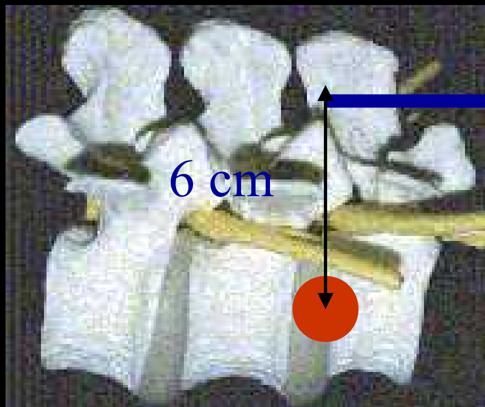


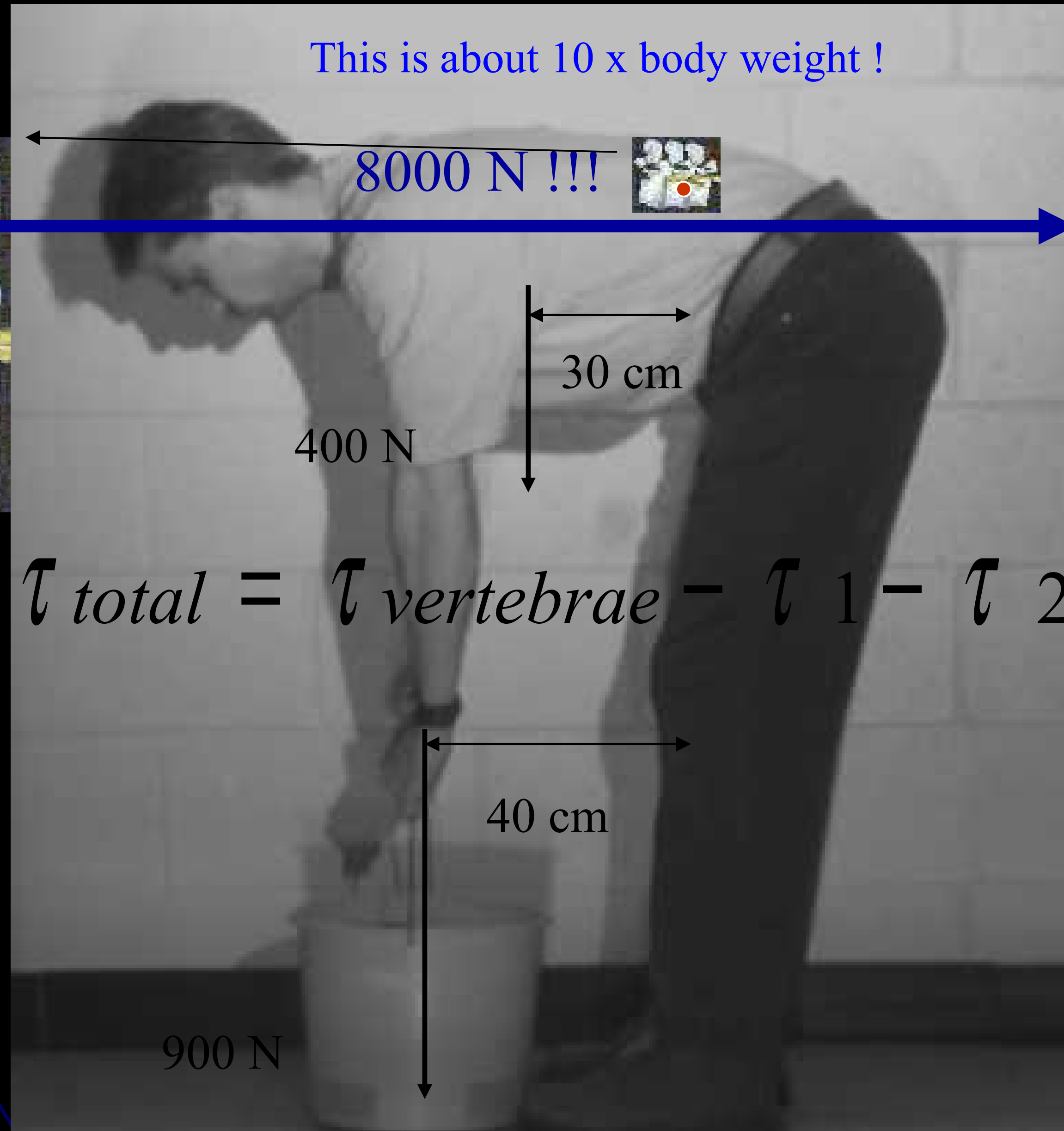
An example of a deformable element model that incorporates 119 rigid elements and 503 deformable elements. This model was used to study how the configuration of the rib cage might be altered by deformities that occur in the spine as scoliosis progresses (66).

A

B

# The forces on the back

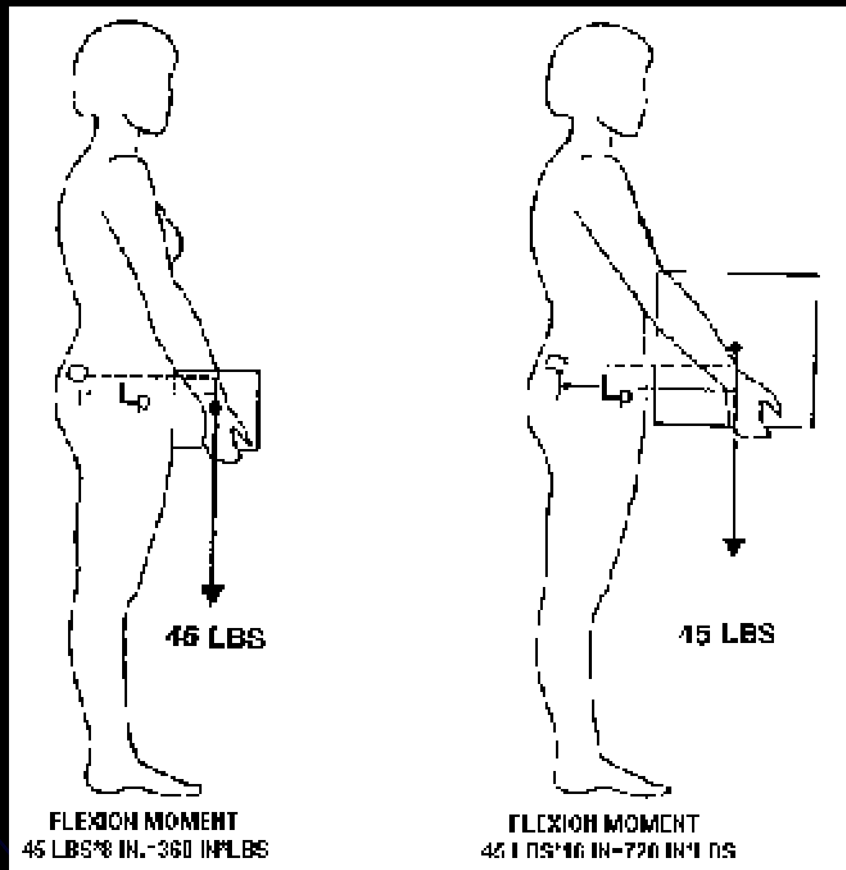


## Competition Lifts - the clean and jerk

Technique is designed to overcome relative weakness of our arms.

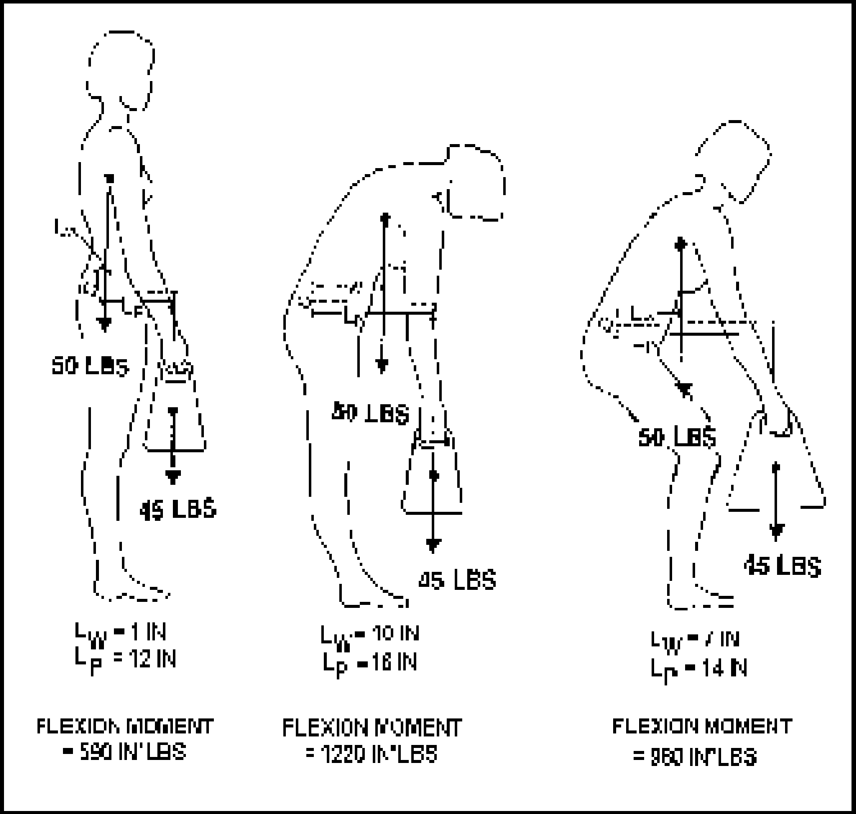
In all positions, elbows and shoulders are almost directly above or below the bar, thus creating small moments.


Lp
45 LBS
FLEXION MOMENT
45 LBS*8 IN.-360 IN*LBS
Lp
45 LBS
FLEXION MOMENT
45 LBS*16 IN-720 IN*LBS

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)

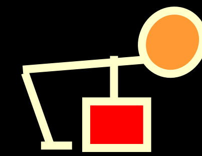
# Vertebral fractures

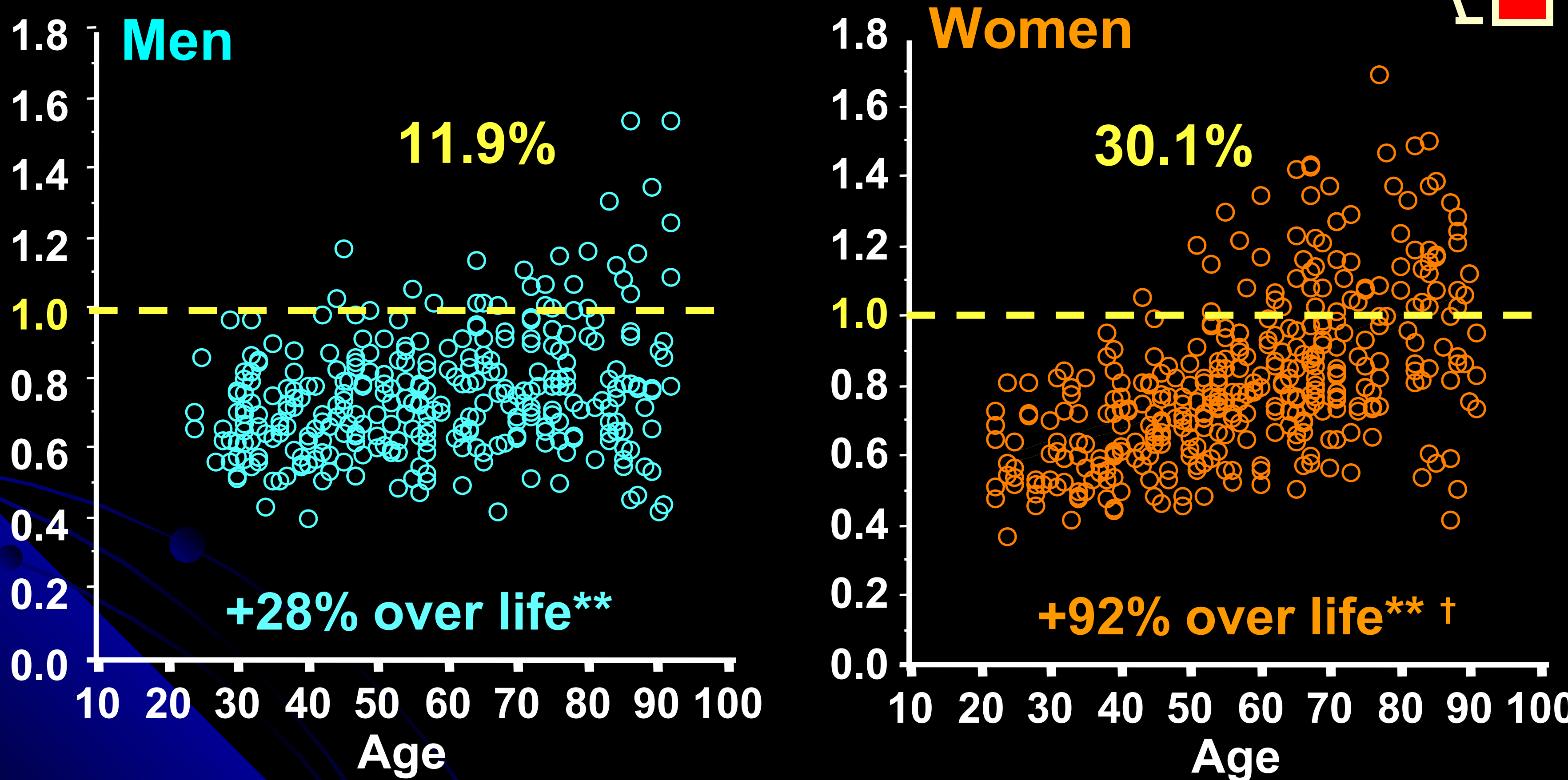
- Difficult to study
  - Definition is controversial
  - Many do not come to clinical attention
  - Slow vs. acute onset
  - The event that causes the fracture is often unknown

- 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

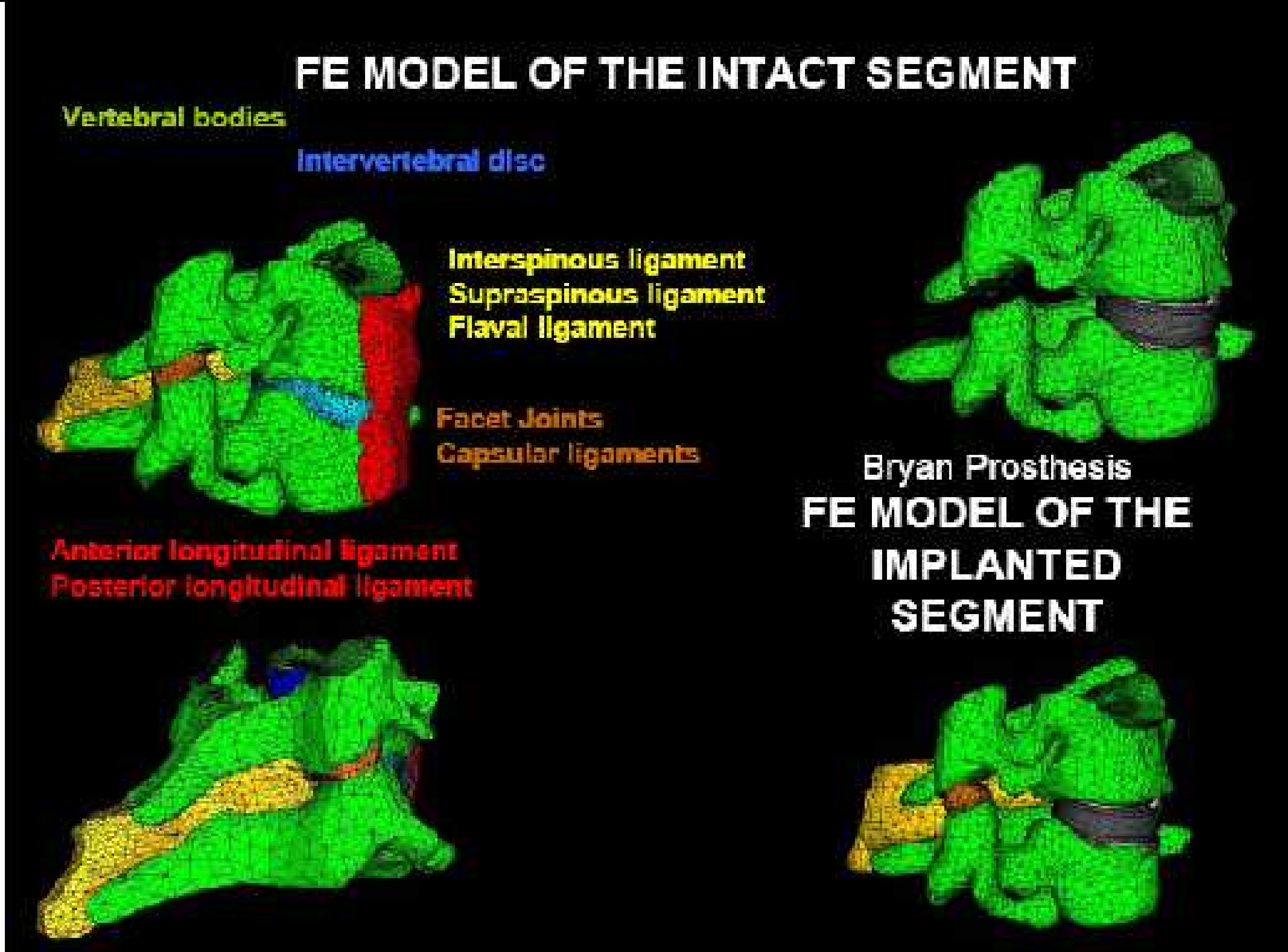


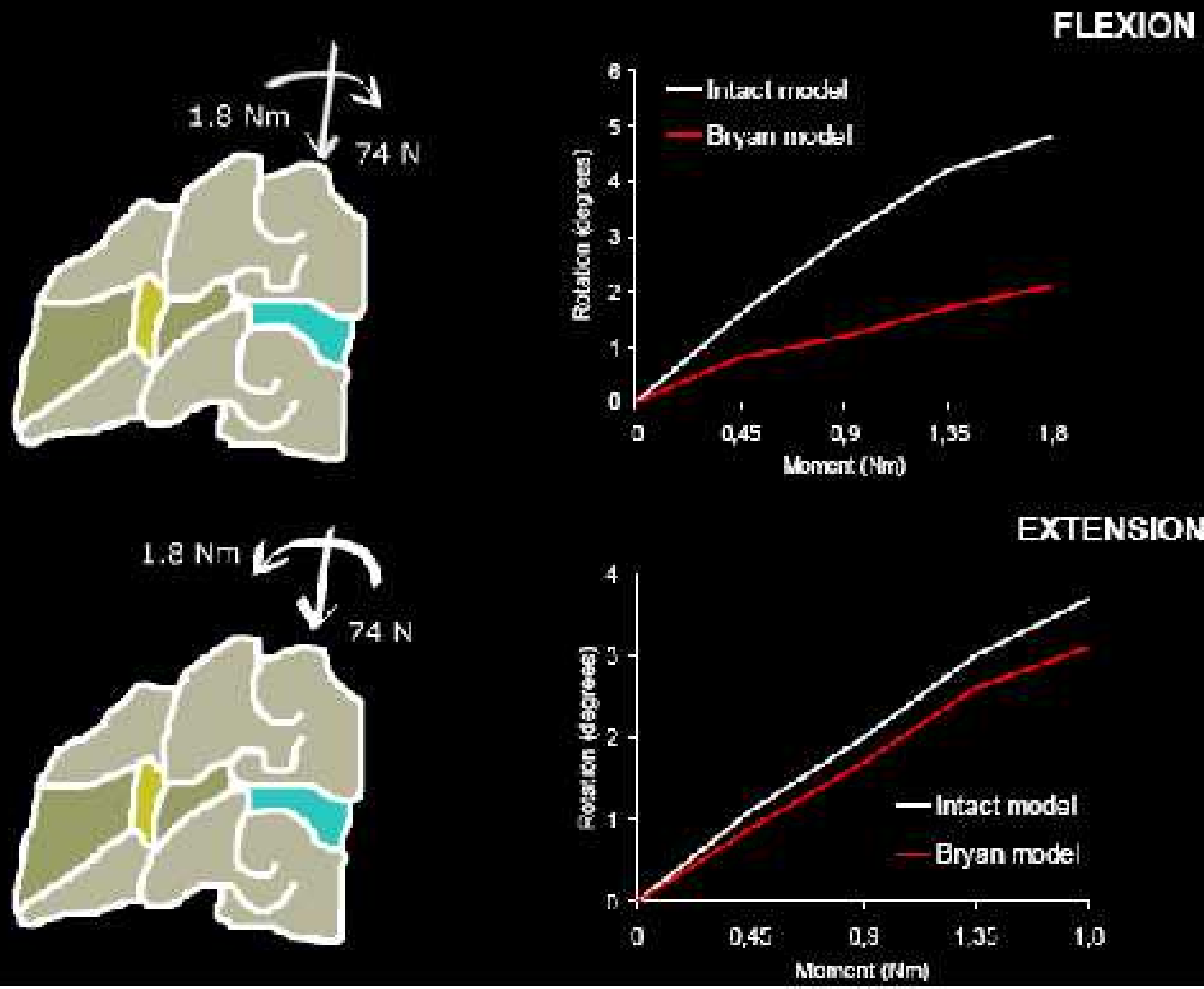



** P<0.005 for age-regressions

† p<0.01 for comparison of age-related change in M and W

Bouxsein et al. J Bone Miner Res. 2006; 21:1475-82

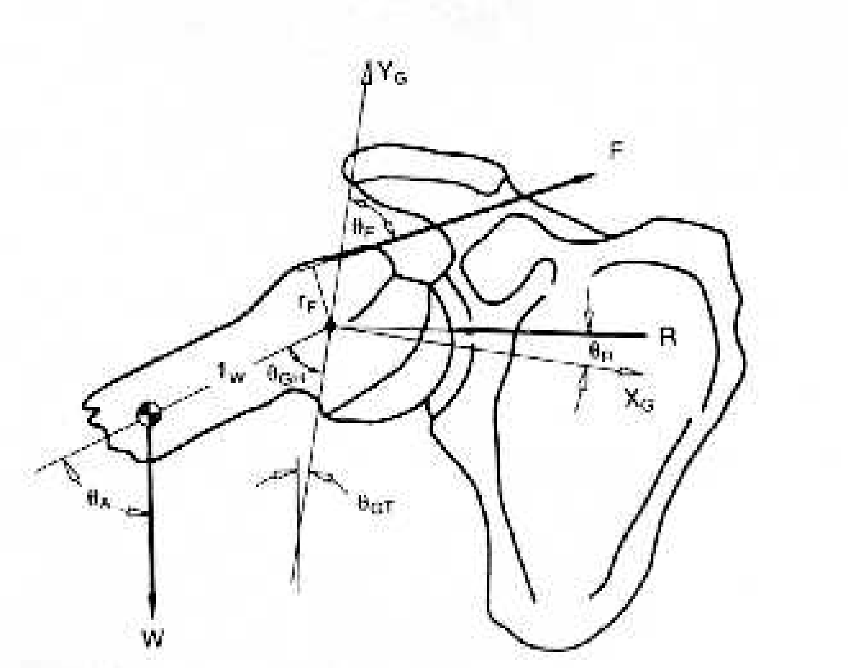

FE MODEL OF THE INTACT SEGMENT
Vertebral bodies
Intervertebral disc
Interspinous ligament
Supraspinous ligament
Flaval ligament
Facet Joints
Capsular ligaments
Anterior longitudinal ligament
Posterior longitudinal ligament
Bryan Prosthesis
FE MODEL OF THE IMPLANTED SEGMENT


FLEXION
1.8 Nm
74 N
Intact model
Bryan model
Rotation (degrees)
0
1
2
3
4
5
6
0
0,45
0,9
1,35
1,8
Moment (Nm)
EXTENSION
1.8 Nm
74 N
Intact model
Bryan model
Rotation (degrees)
1
2
3
4
0
0,45
Moment (Nm)

# Upper Extremity Biomechanics

# GLENOHUMERAL LOADING

- Method
  - Isometric arm abduction
  - Muscle force proportional to EMG
- Results
  - Max = 0.89 x BW
  - Max at $90^o$ abduction




Poppen, N.K. and Walker, P.S. (1978) *CORR* **135**:165-170.

# 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

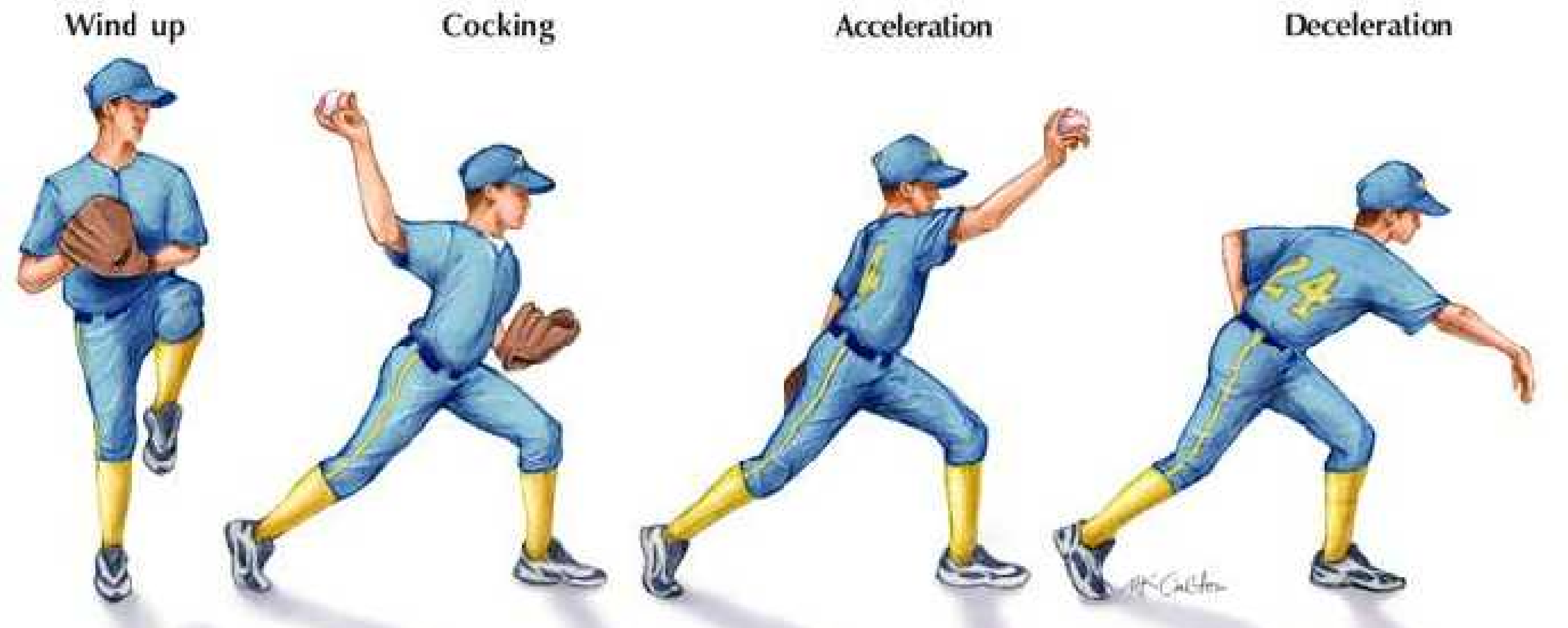



Fig. 1 The 4 phases of throwing

# 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