BIOMECHANICS

Fundamentals and Future

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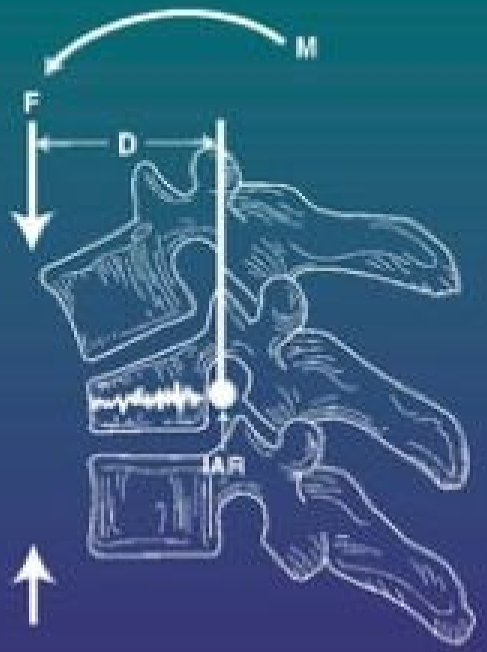
DECADE OF THE SPINE 2001 - 2010

DePuy Spine
Abbott Spine
OrthoMEMS
AxioMed
Computational BioDynamics
ProNeuron
SpineWave

BIOMECHANICS OF SPINE STABILIZATION



Electronic
Image
Collection

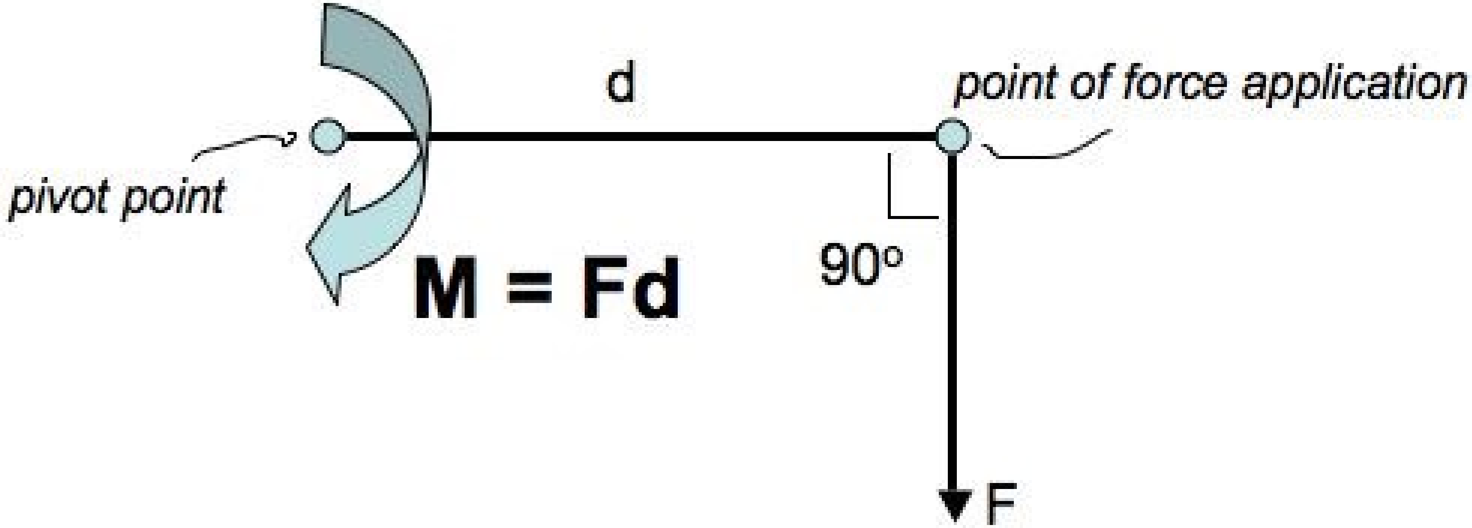
Edward C. Benzel, MD

Illustrations by Michael F. Norviel, CMI

BENDING MOMENT

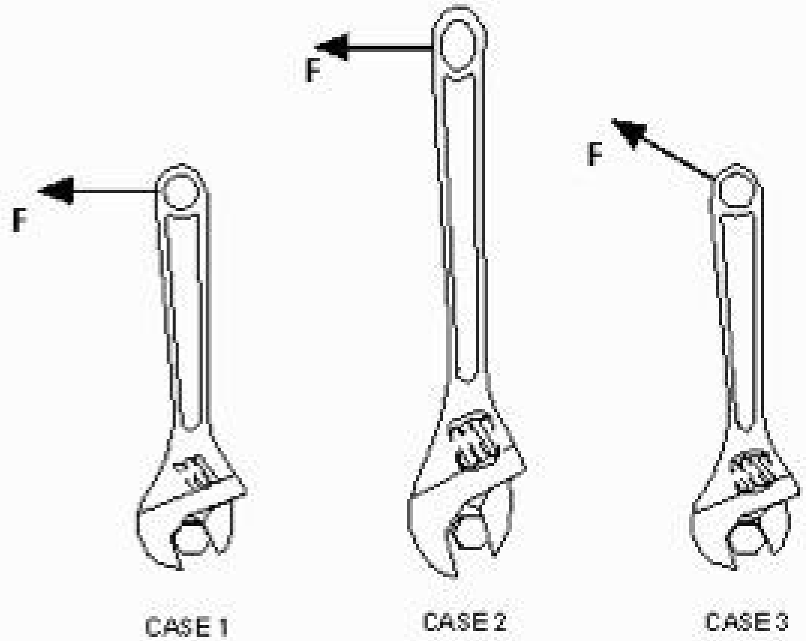
- **“Force X distance (moment arm)”**

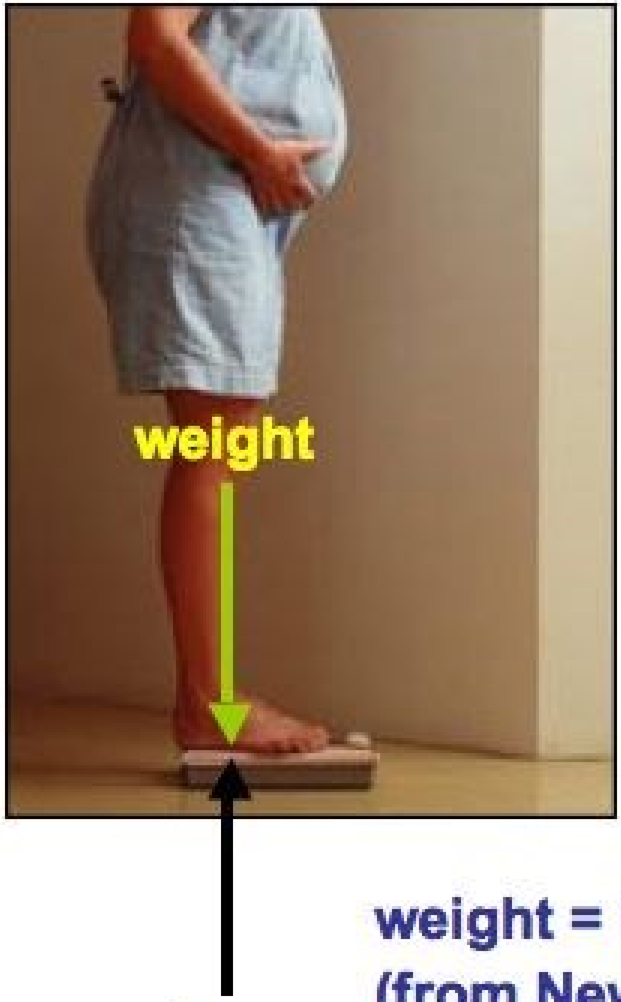
Units: Newton-meter = Nm



Quiz #1

Assuming magnitude of applied force F is same in each case, in which case is torque the greatest…the least?

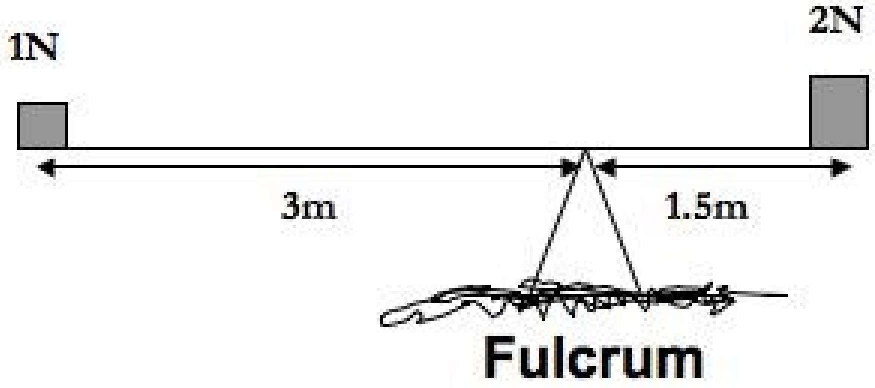


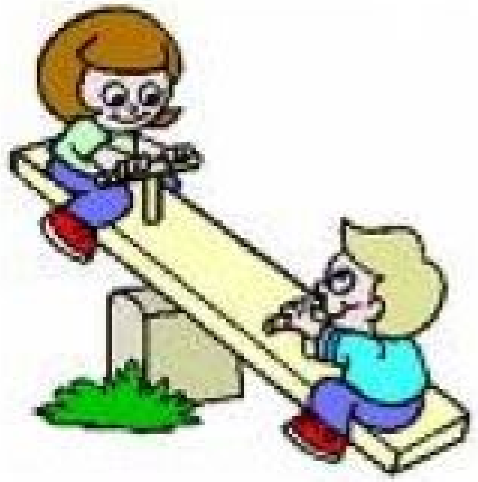


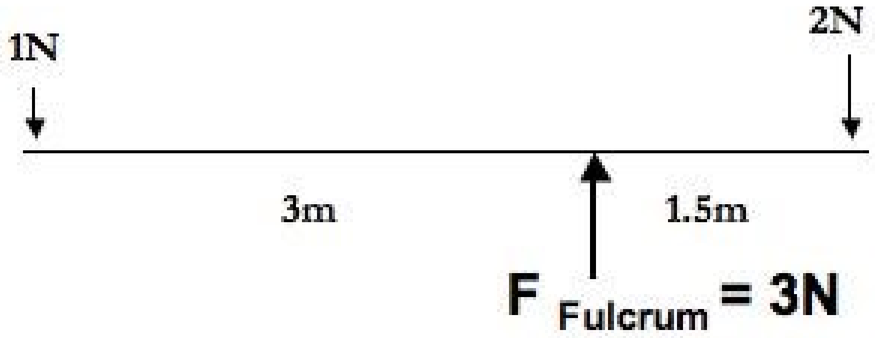
F_{scale}

weight = F_{scale}
(from Newton's 3rd law)

EXAMPLE
“Seesaw”

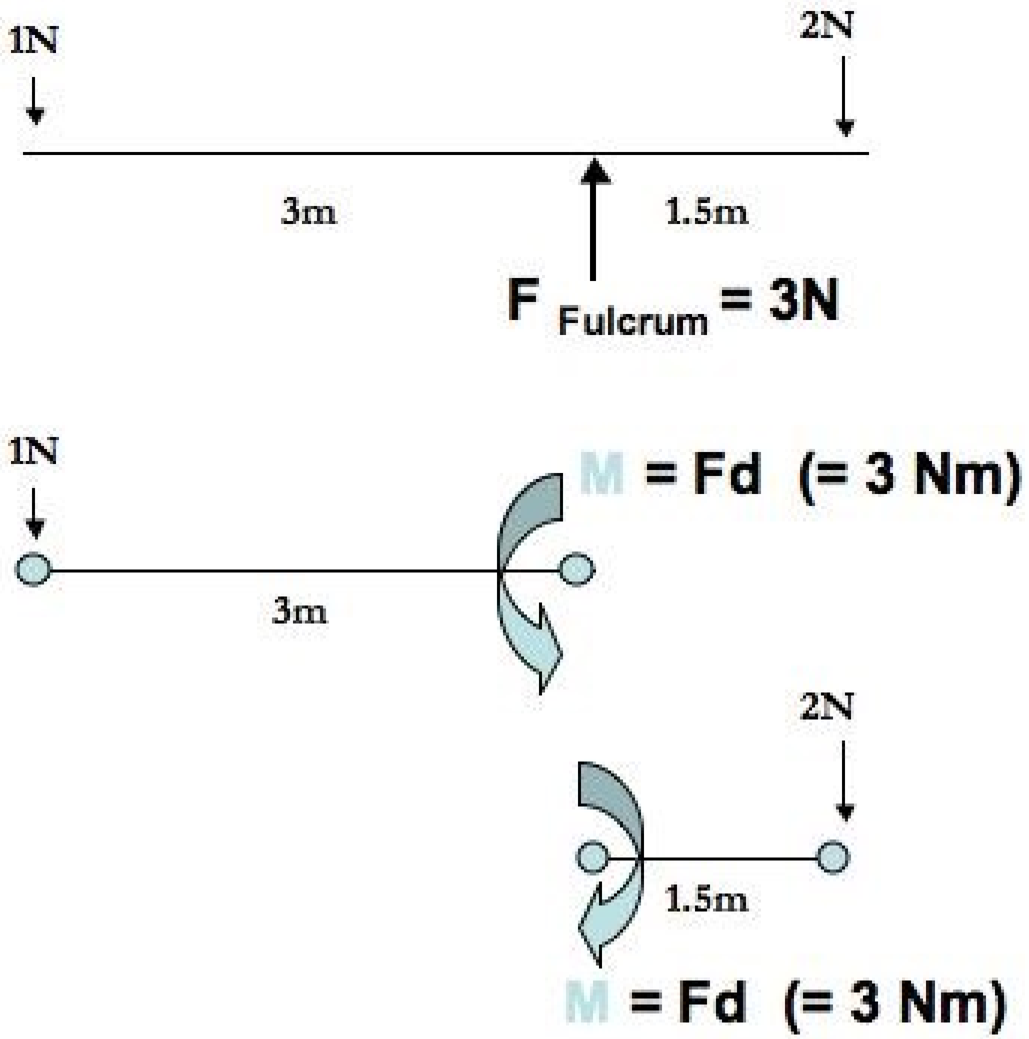






(Reaction force at fulcrum is equal & opposite to sum of applied forces—Newton’s 3rd)

Forces are Balanced!



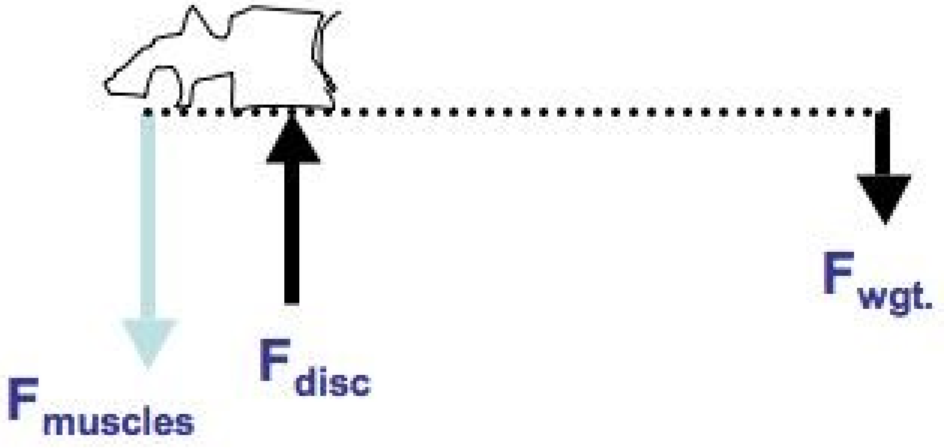
Moments are balanced, as well!

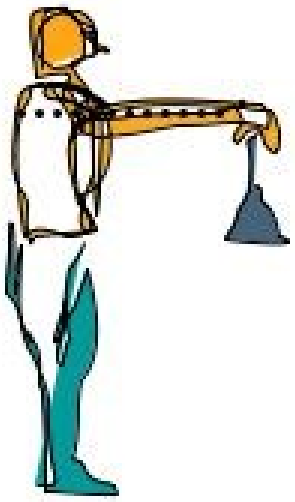
Practical Applications

Spinal Loads

SPINE BIOMECHANICS

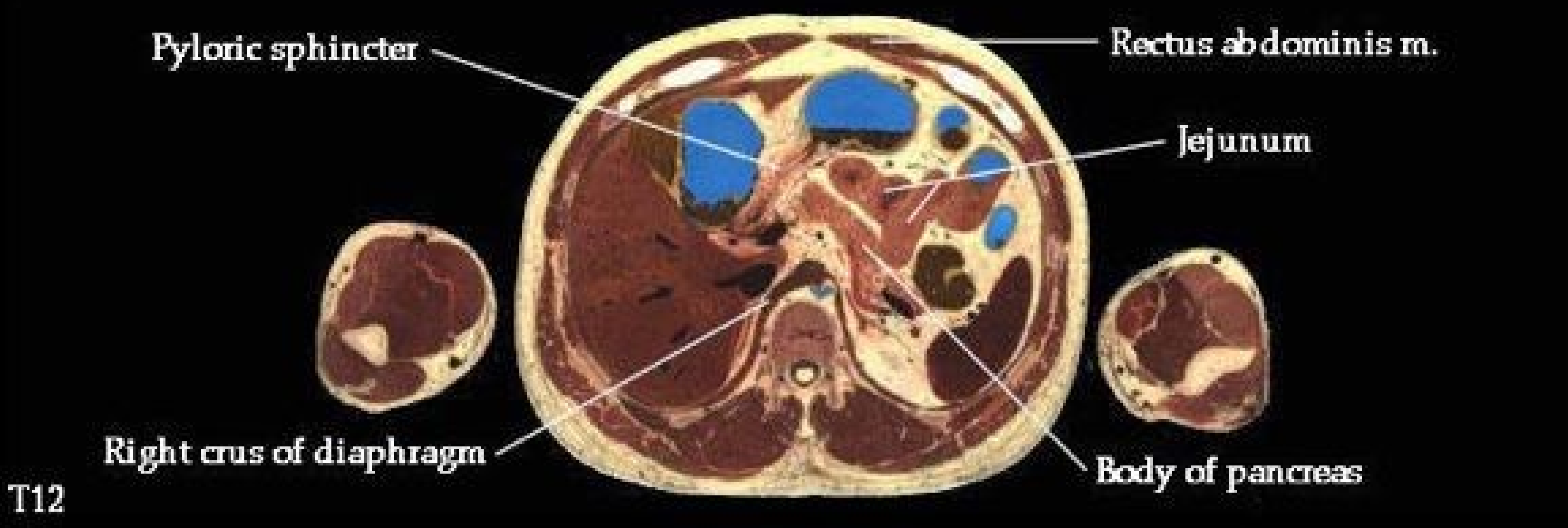
“Seesaw” model





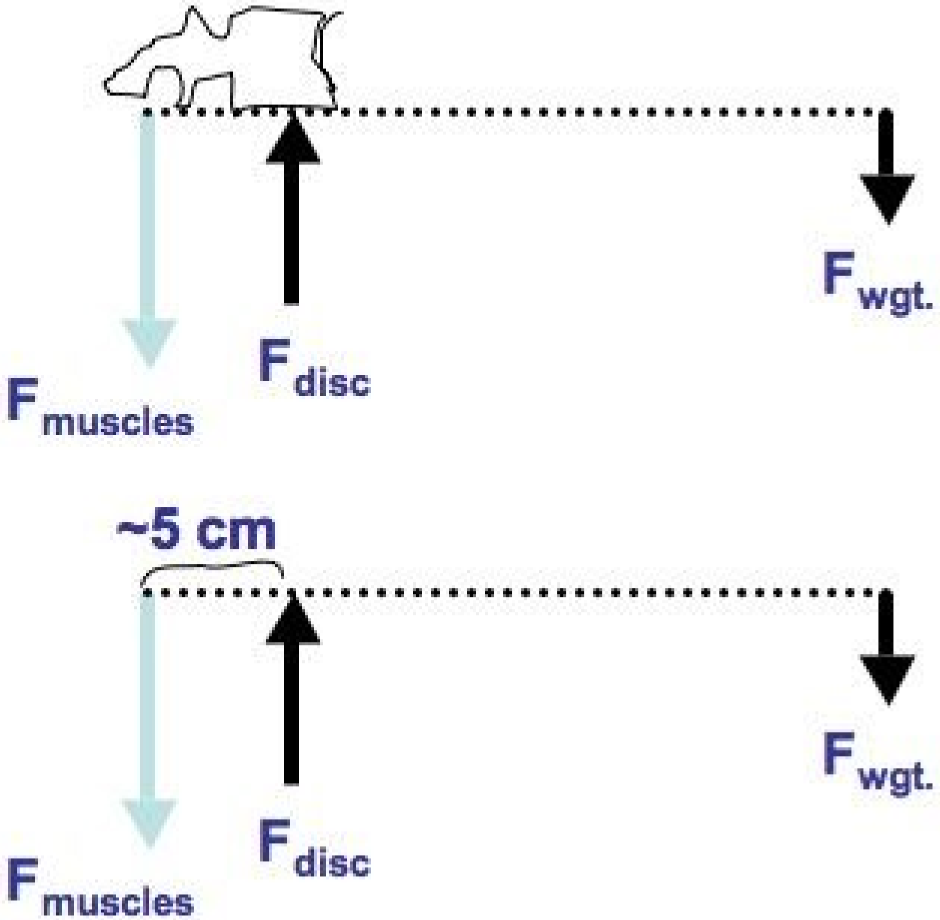
Back Muscles

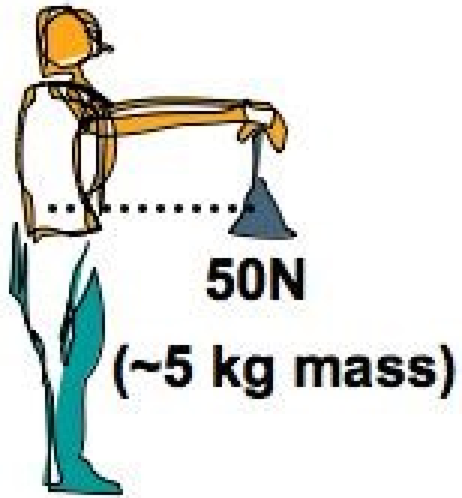
Suboptimal Leverage

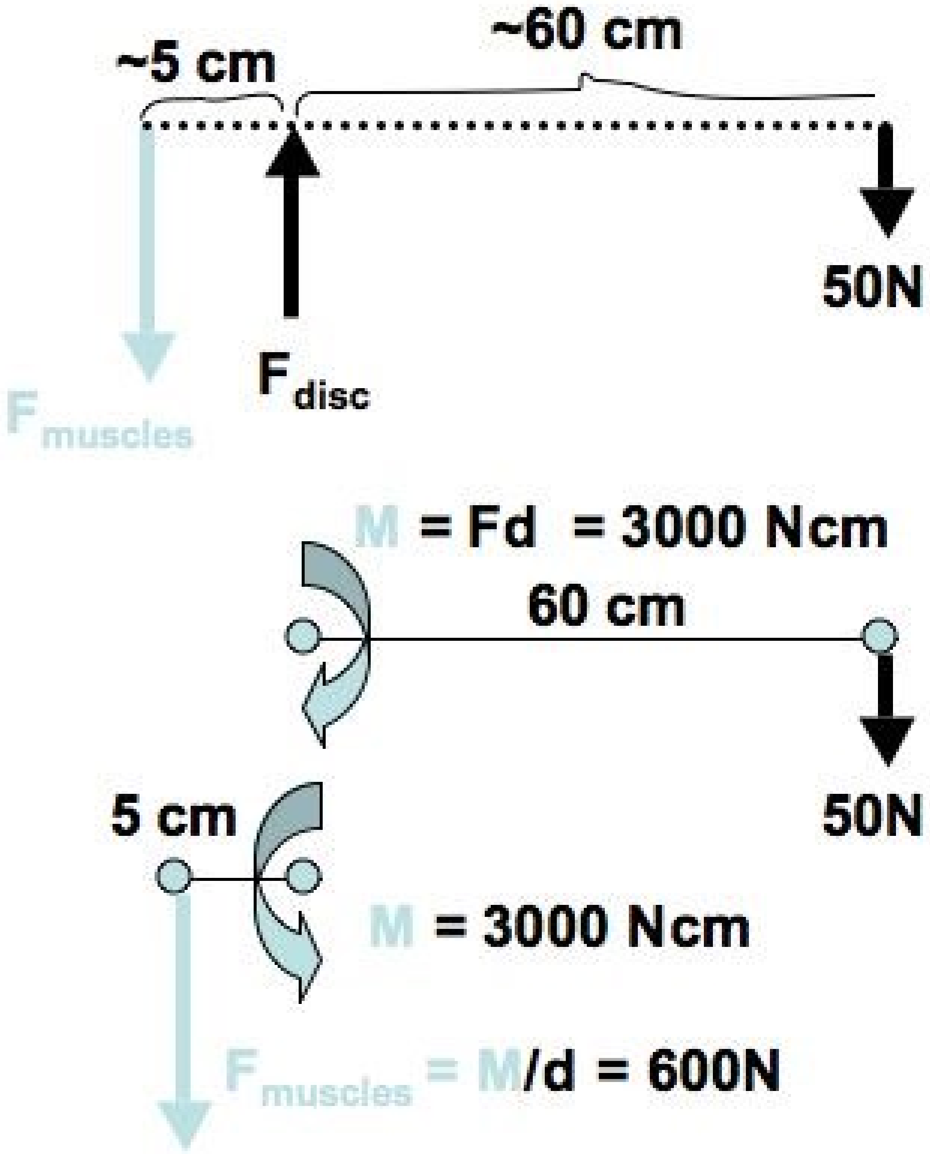


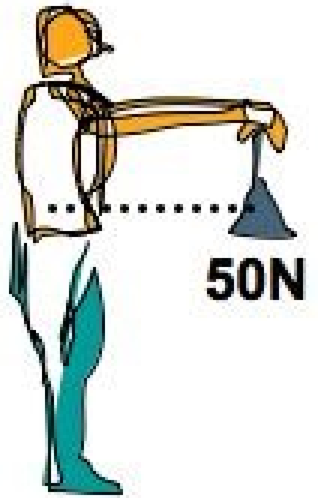
Back Muscles

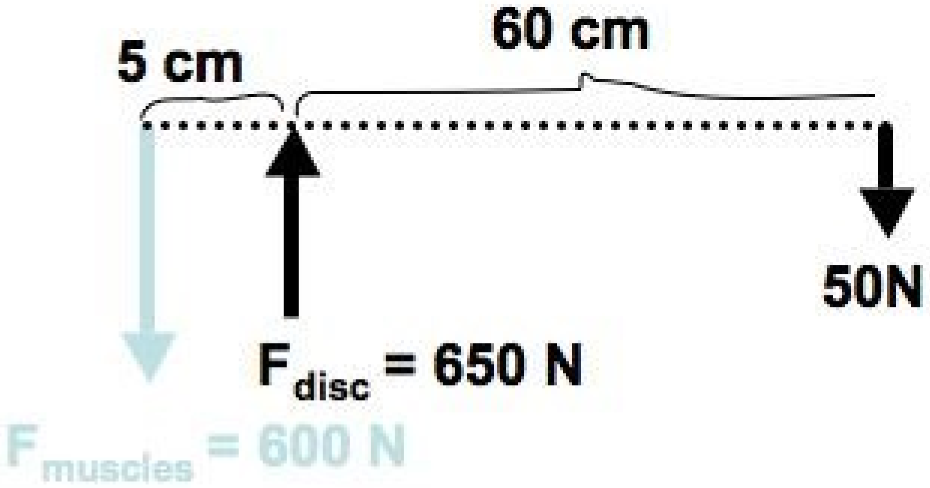
Short Moment Arm



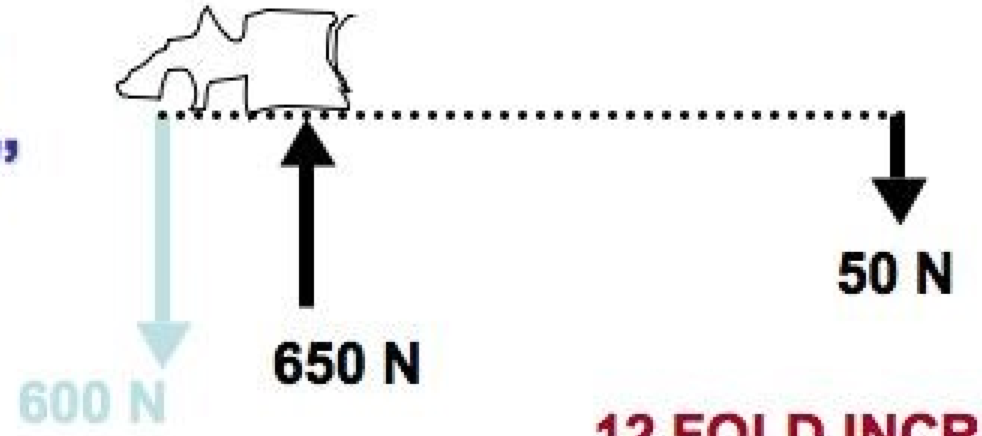

50N
(~5 kg mass)


~5 cm
~60 cm
50N
F disc
F muscles
M = Fd = 3000 Ncm
60 cm
50N
5 cm
M = 3000 Ncm
F muscles = M/d = 600N



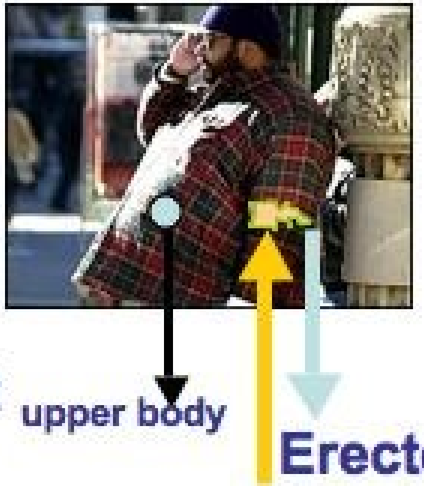


- **Poor leverage of back muscles → high muscle forces**
- **Disc, vertebra "pay the price"**



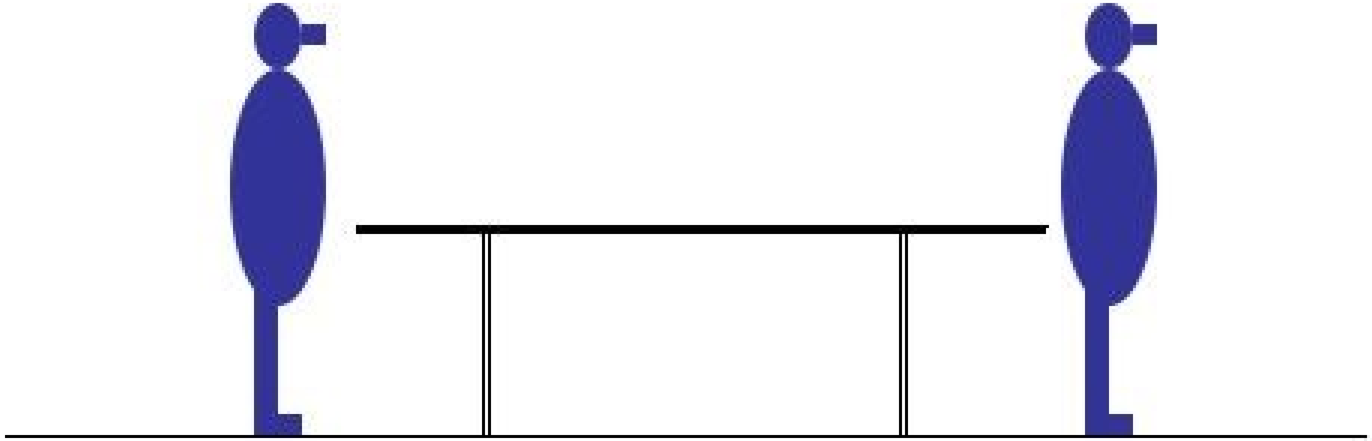
12 FOLD INCREASE

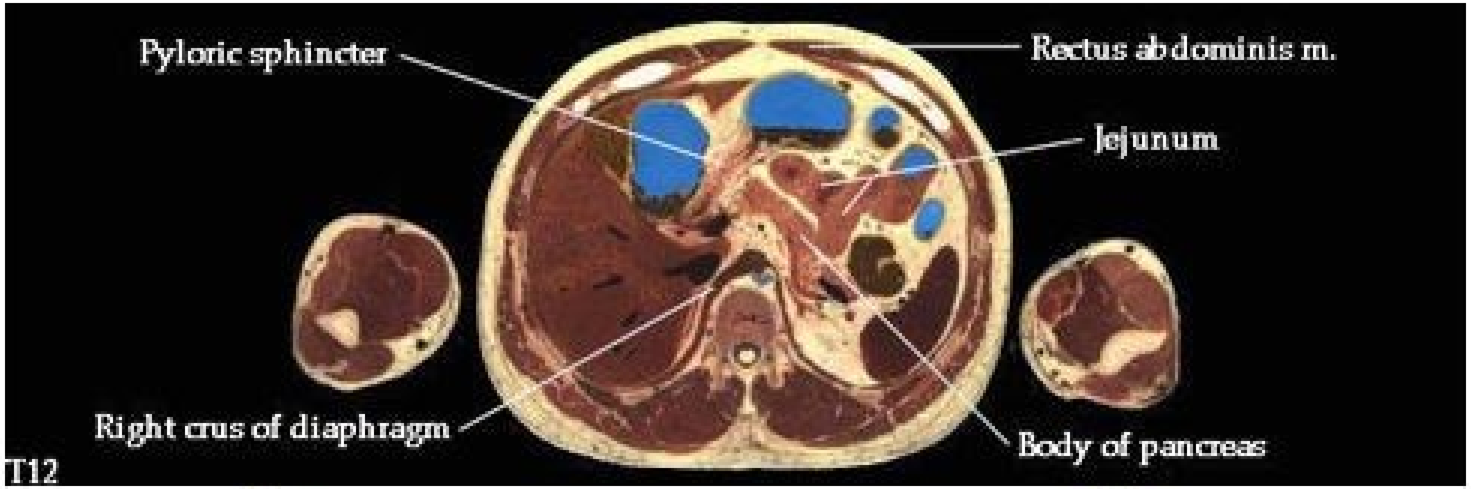
…but simple models effective for estimating spinal loads

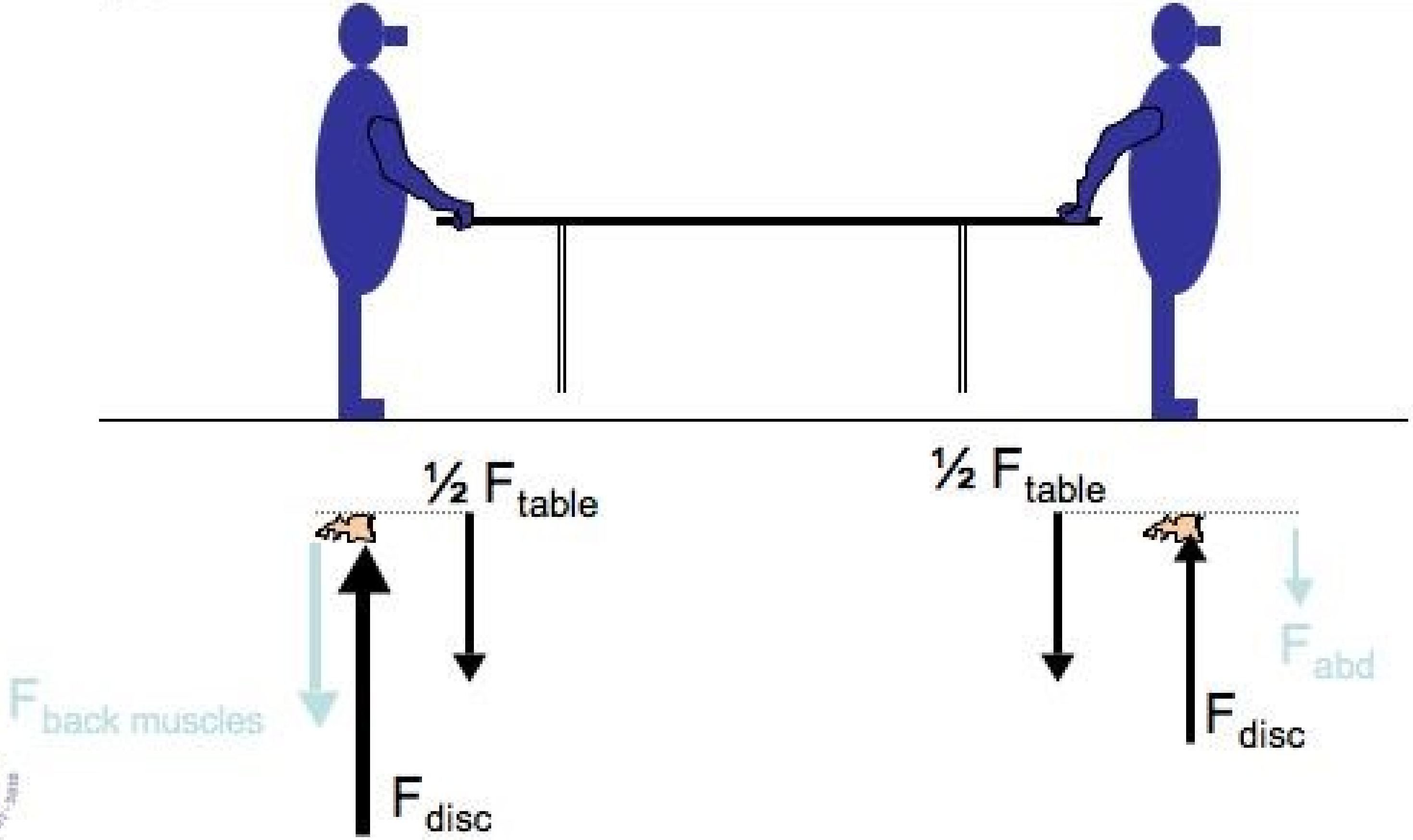


Quiz #2

…simple models effective for ergonomic analysis




Pyloric sphincter
Rectus abdominis m.
Jejunum
Right crus of diaphragm
Body of pancreas
T12


½ F_{table}
½ F_{table}
$F_{back\ muscles}$
F_{disc}
F_{abd}
F_{disc}

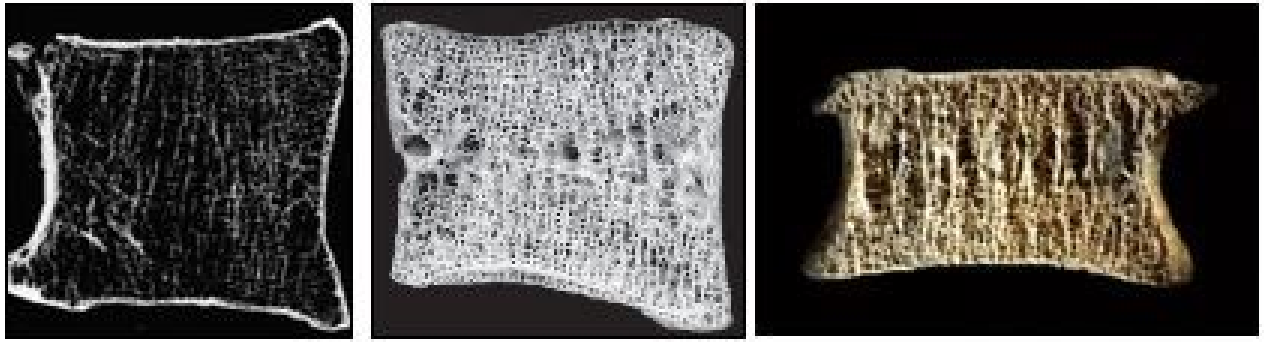
Adaptation

Change in the structure of bone to sustain changes in the external loading

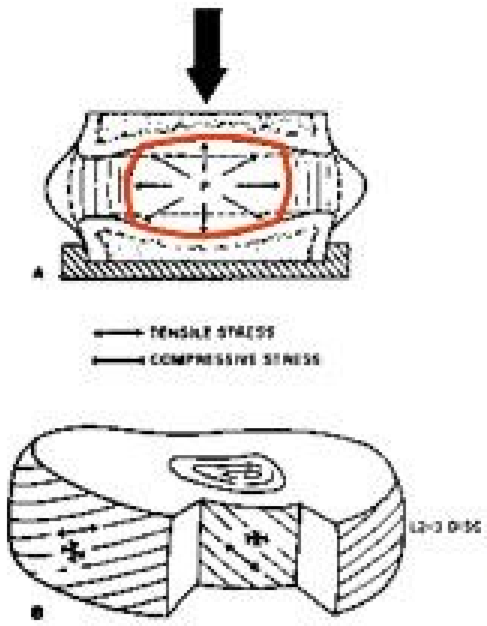
<u>Wolff's Law (1870):</u>

Bone structure forms to provide maximum strength with minimum mass.

Example: Trabecular bone in vertebral body is aligned in the vertical direction.

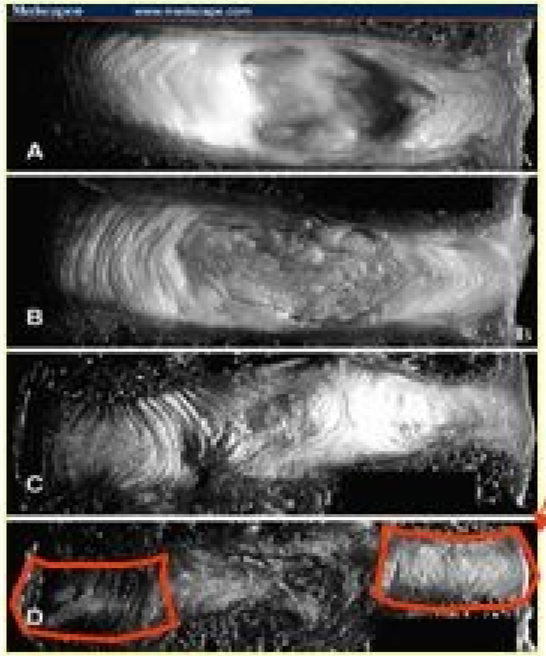


Load Transfer

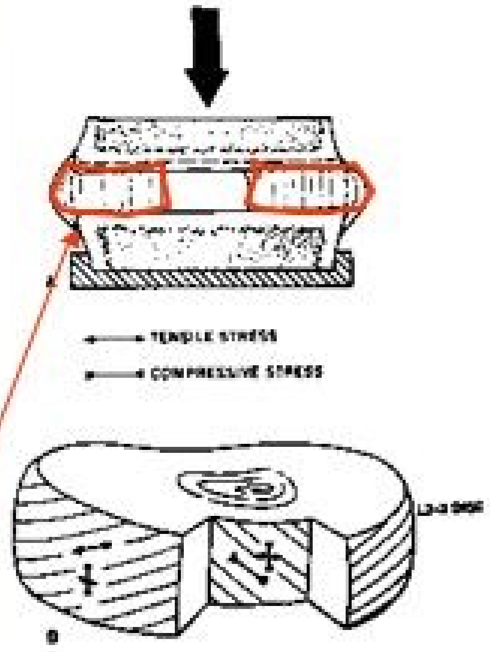


Normal*

Load transfer thru N+A



Degeneration'



Degenerated*

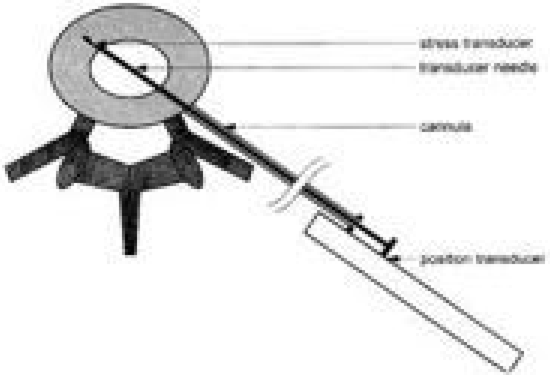
Load transfer thru A

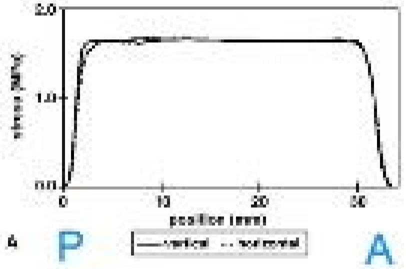
*: *White III and Panjabi, Clinical Biomechanics of the Spine, 1990*

' : *www.medscape.com*

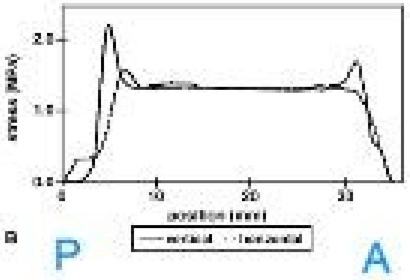
Load Transfer

Stress Profilometry

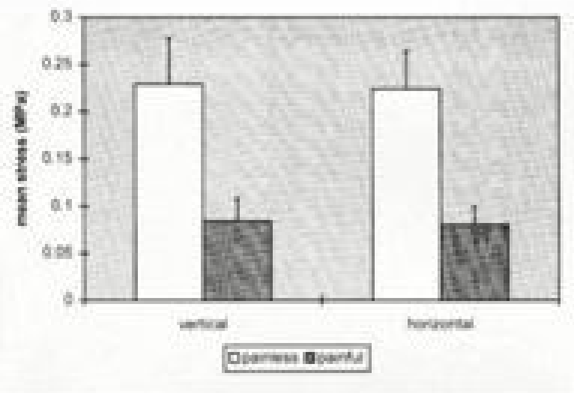


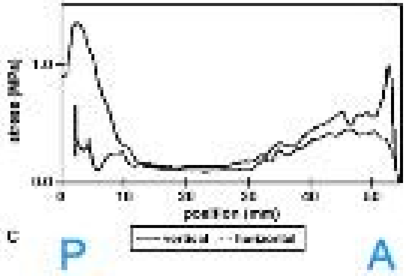


Normal

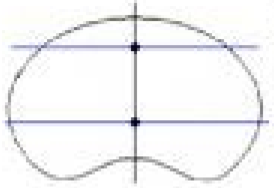


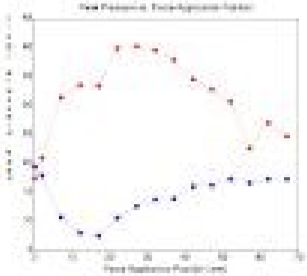
Moderately Degenerated





Significantly Degenerated





Range of Motion

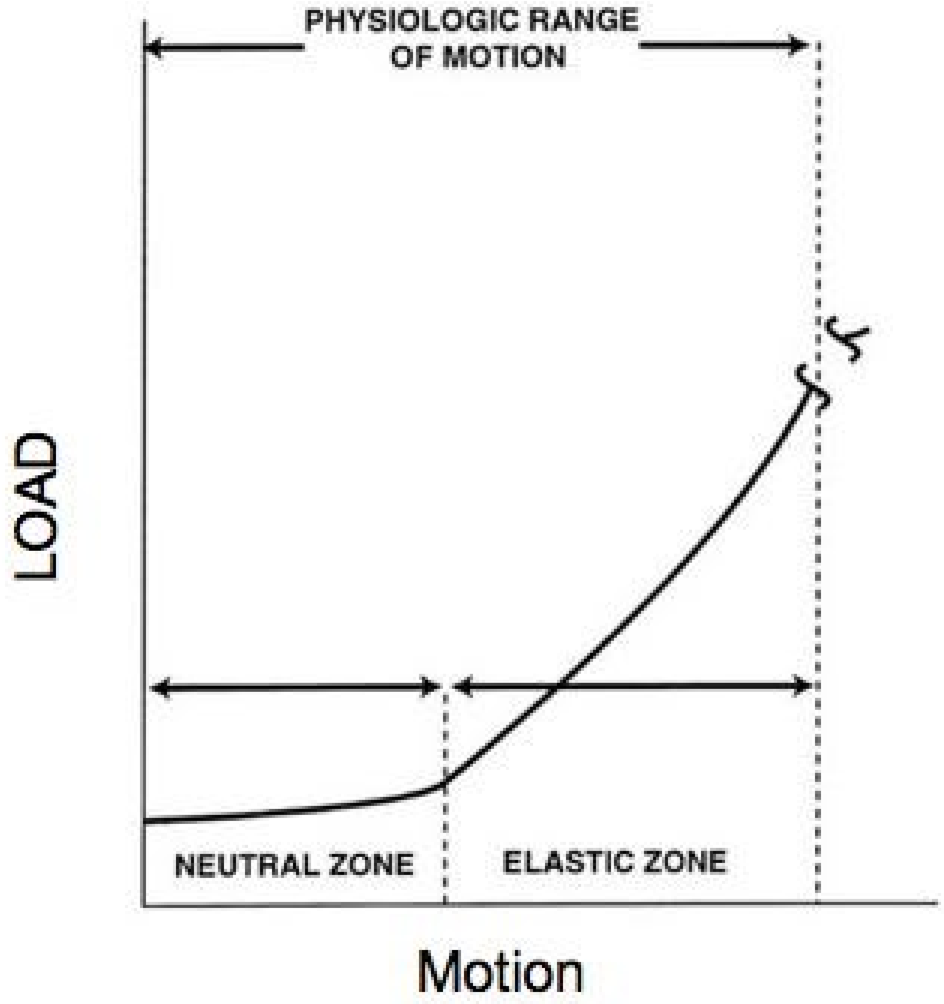
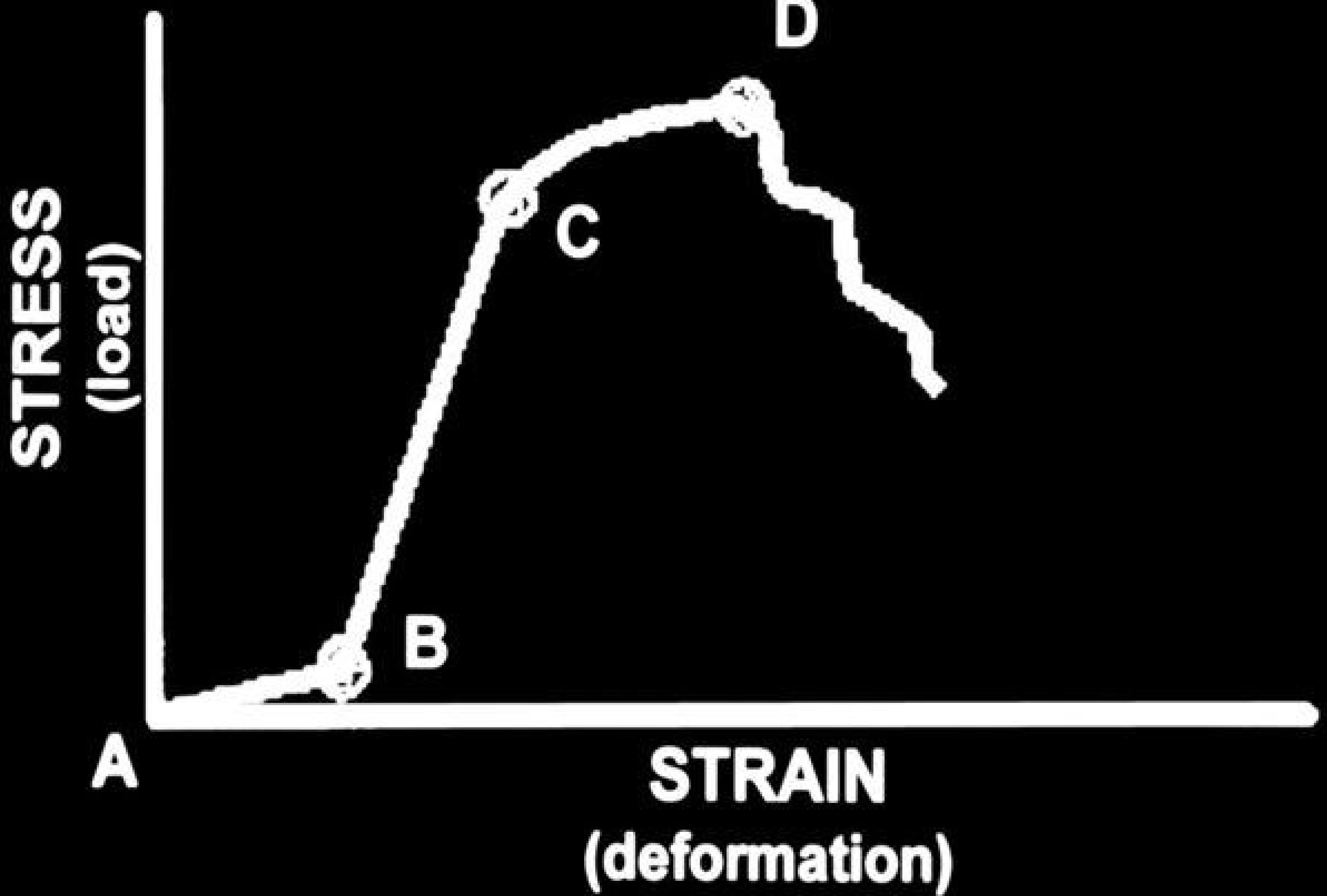
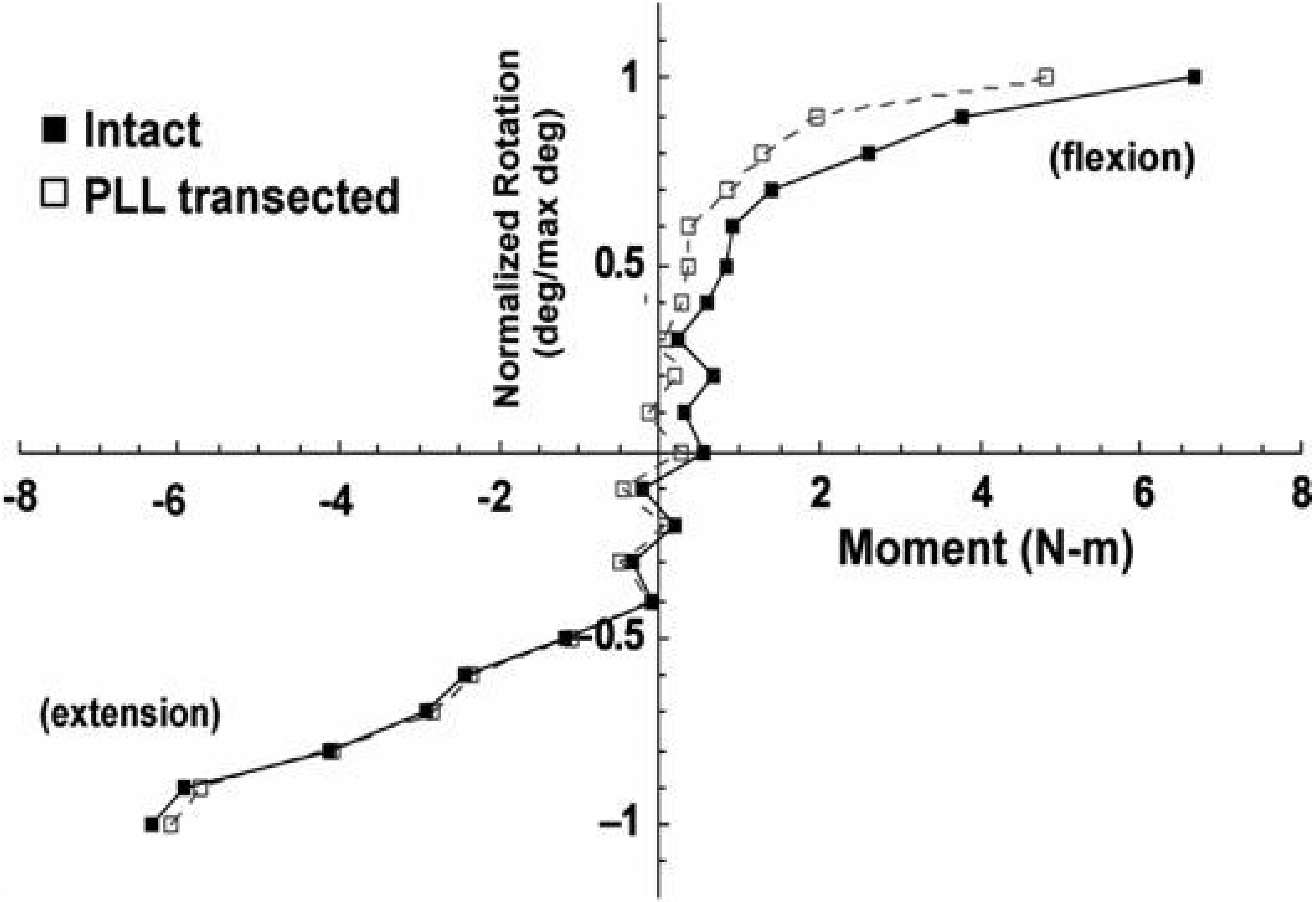
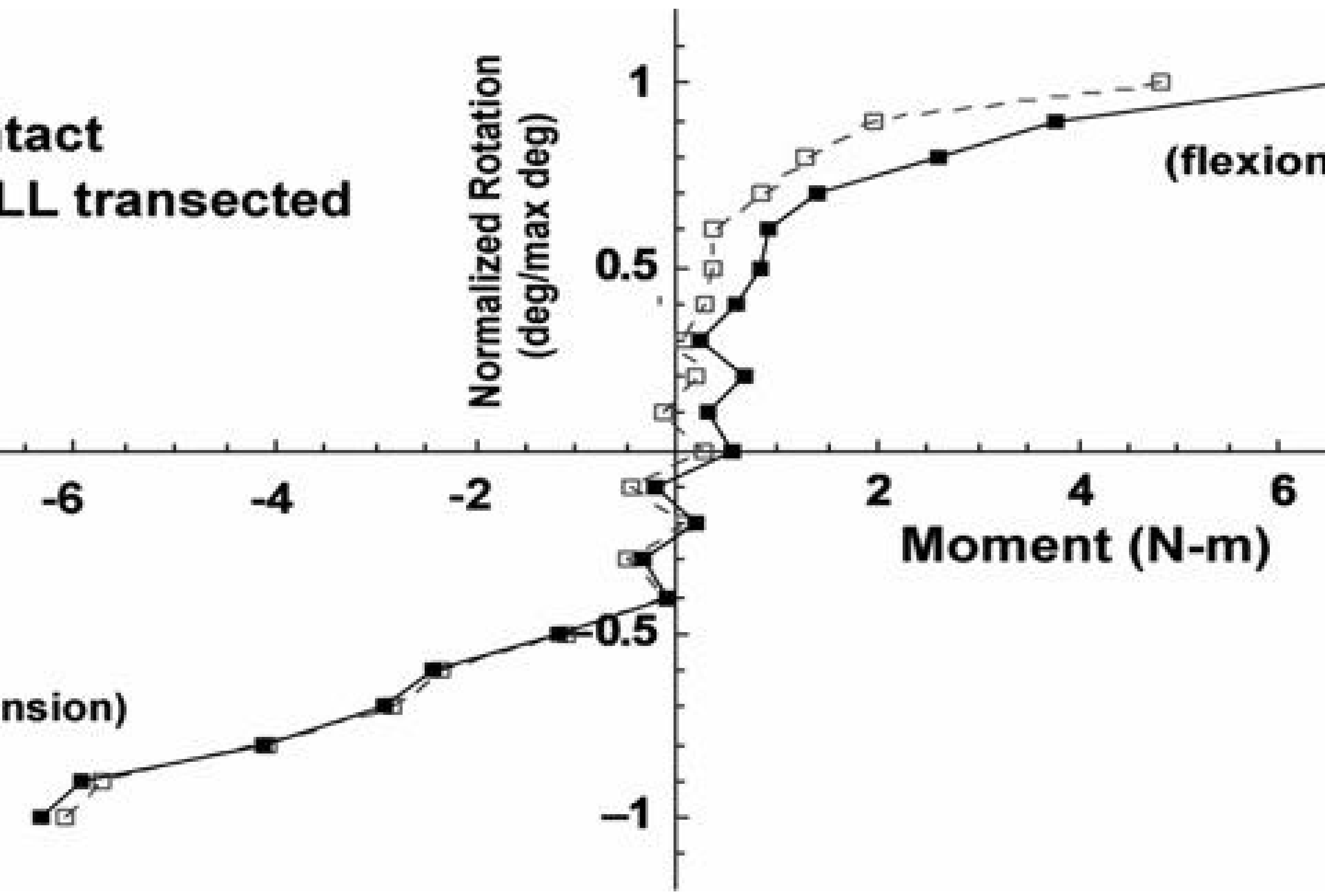


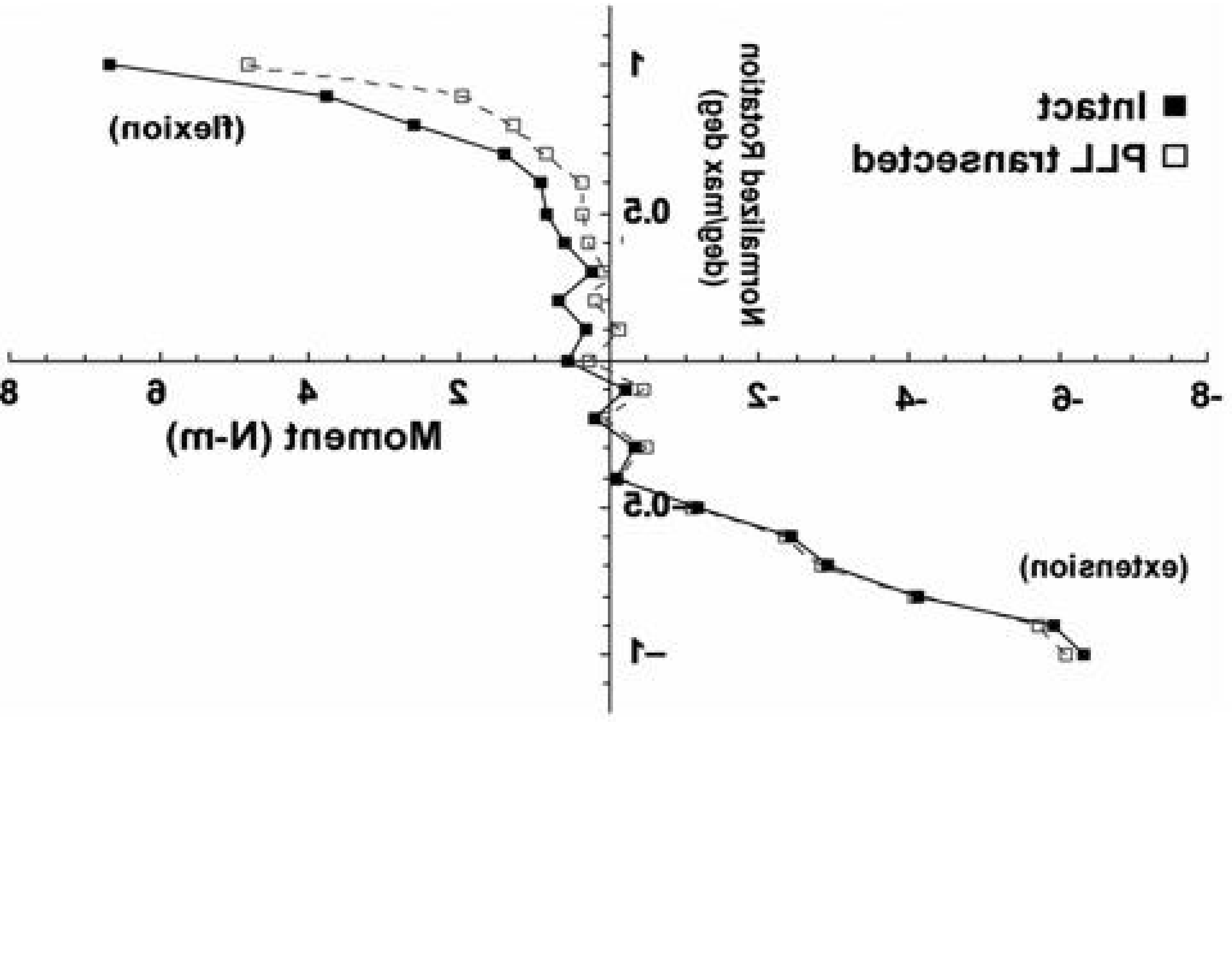
Figure 1-20 A typical load deformation curve depicting the neutral and elastic zones (deformation or strain versus load or stress).

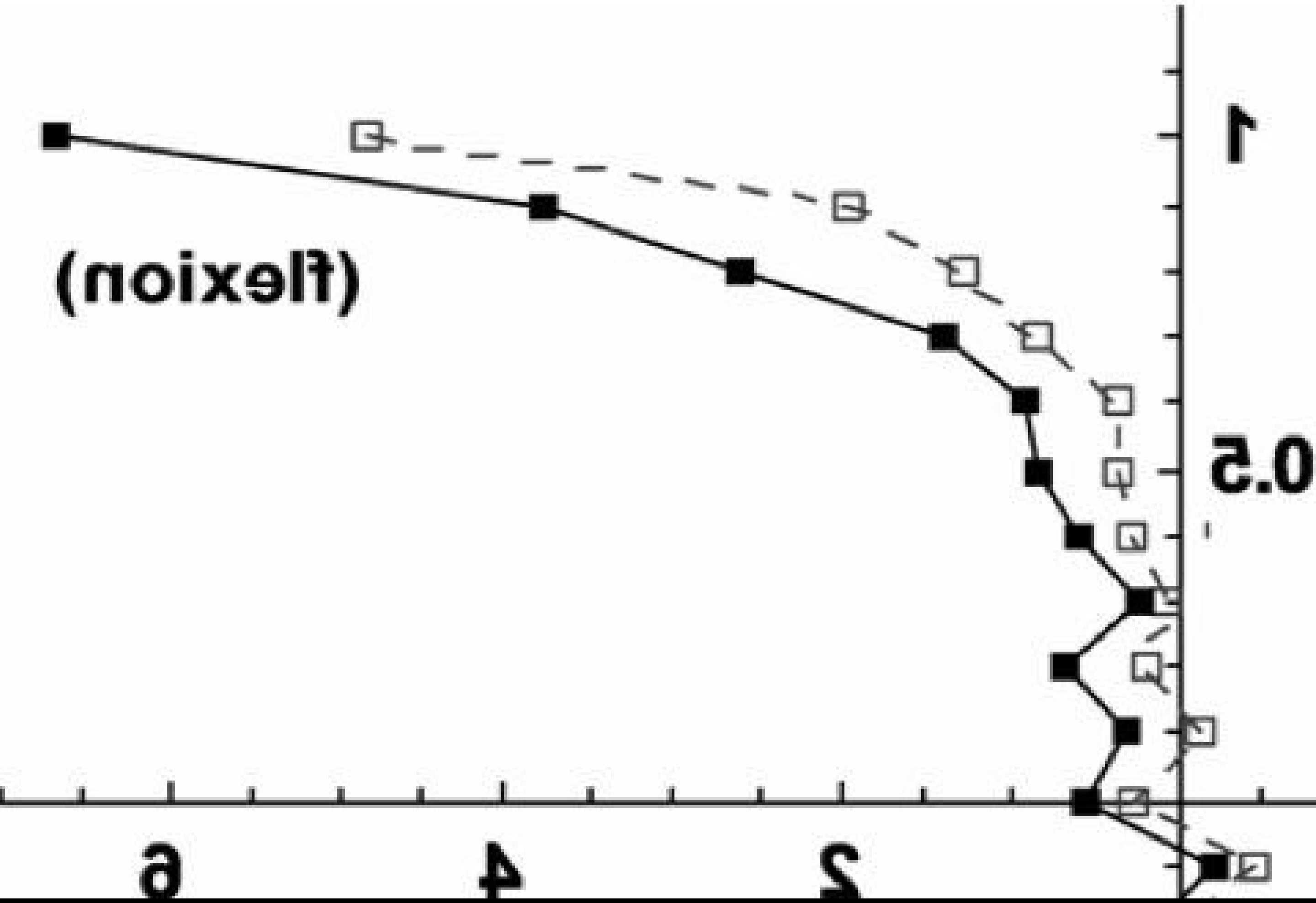


STRESS
(load)
D
C
B
A
STRAIN
(deformation)


Intact
PLL transected
Normalized Rotation
(deg/max deg)
1
0.5
-0.5
-1
(flexion)
(extension)
-8
-6
-4
-2
2
4
6
8
Moment (N-m)


tact
LL transected
Normalized Rotation
(deg/max deg)
1
0.5
-0.5
−1
-6
-4
-2
2
4
6
Moment (N-m)
(flexion
nsion)


Intact
PLL transected
Normalized Rotation
(deg/max deg)
Moment (N-m)
(flexion)
(extension)


(flexion)
1
0.5
6
4
2

Range of Motion

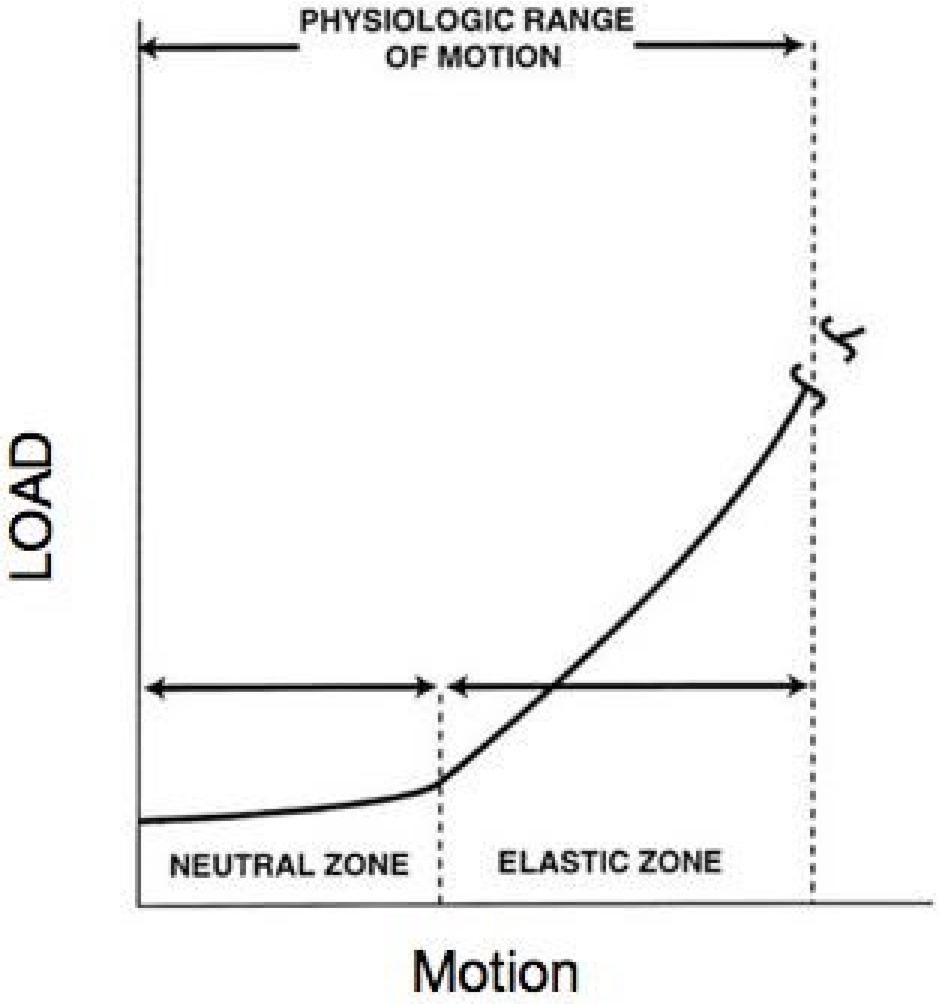
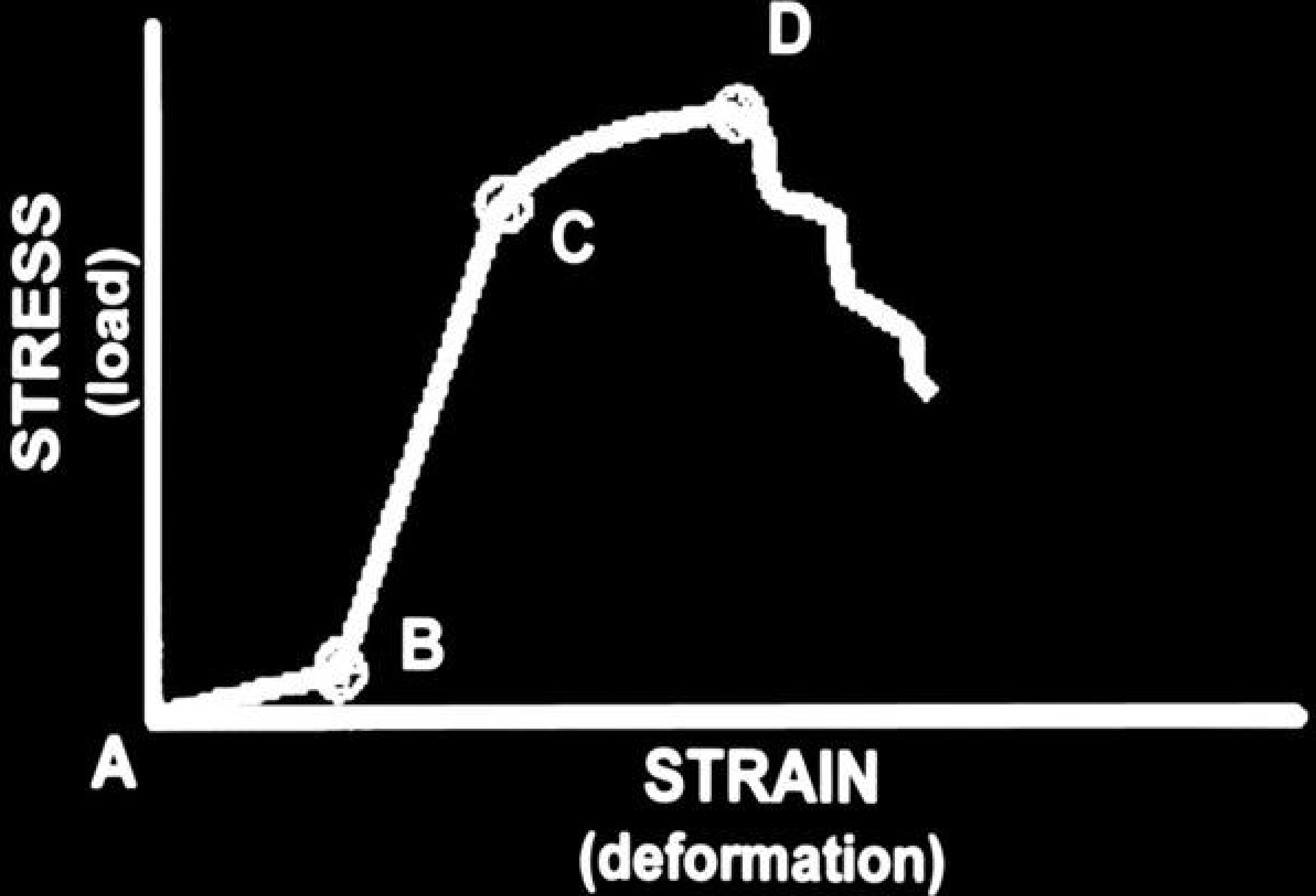
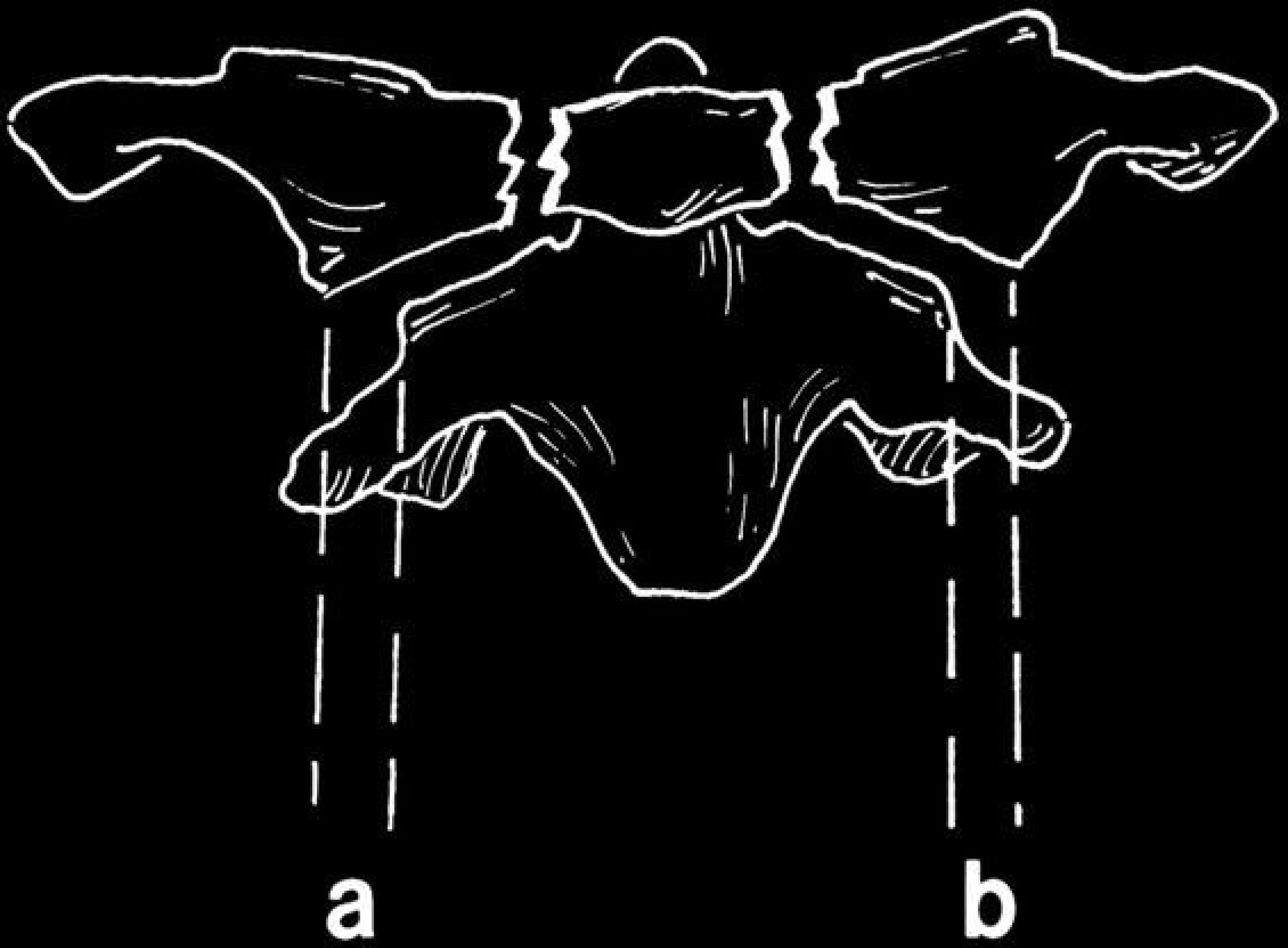
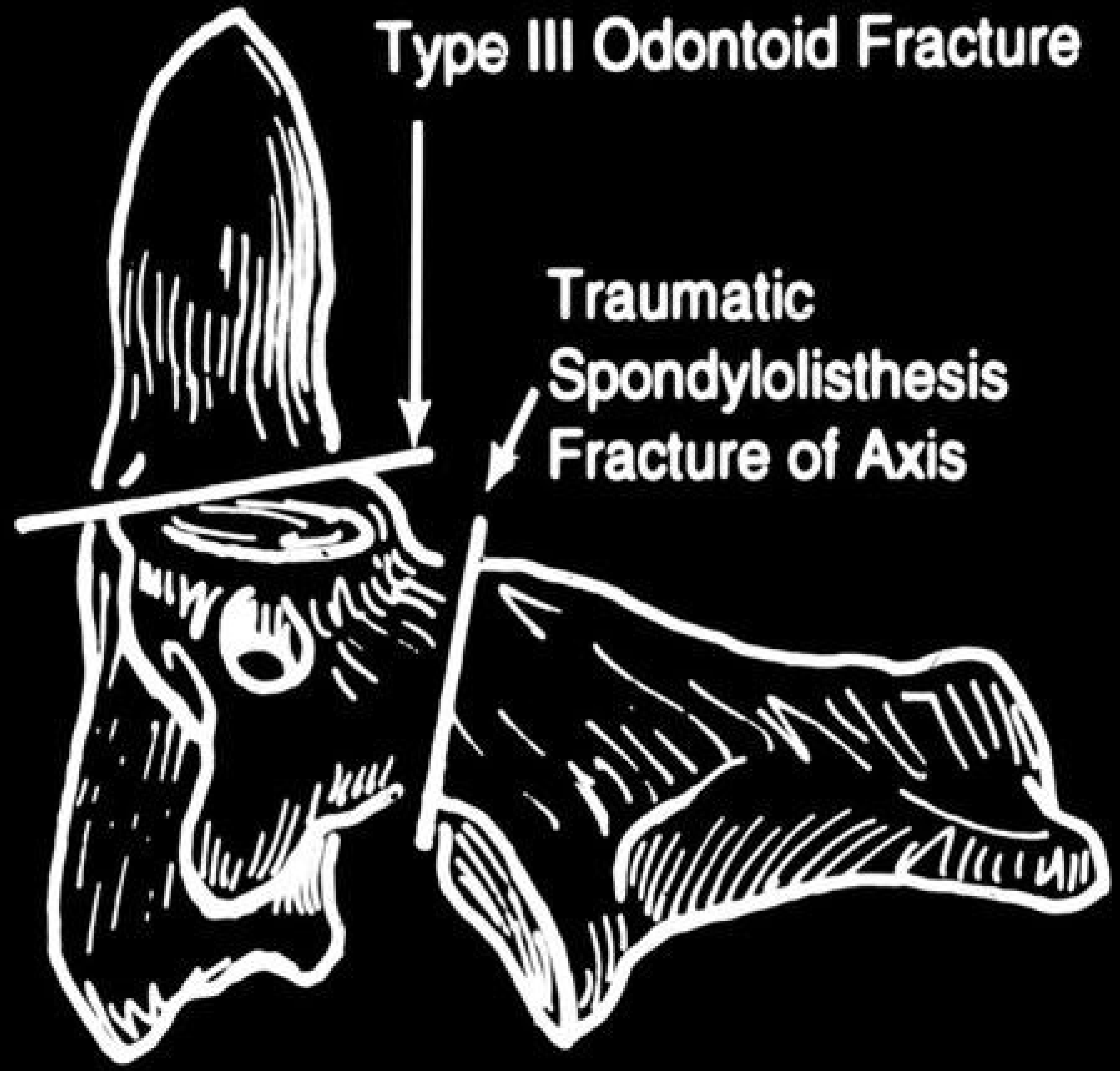


Figure 1-20 A typical load deformation curve depicting the neutral and elastic zones (deformation or strain versus load or stress).

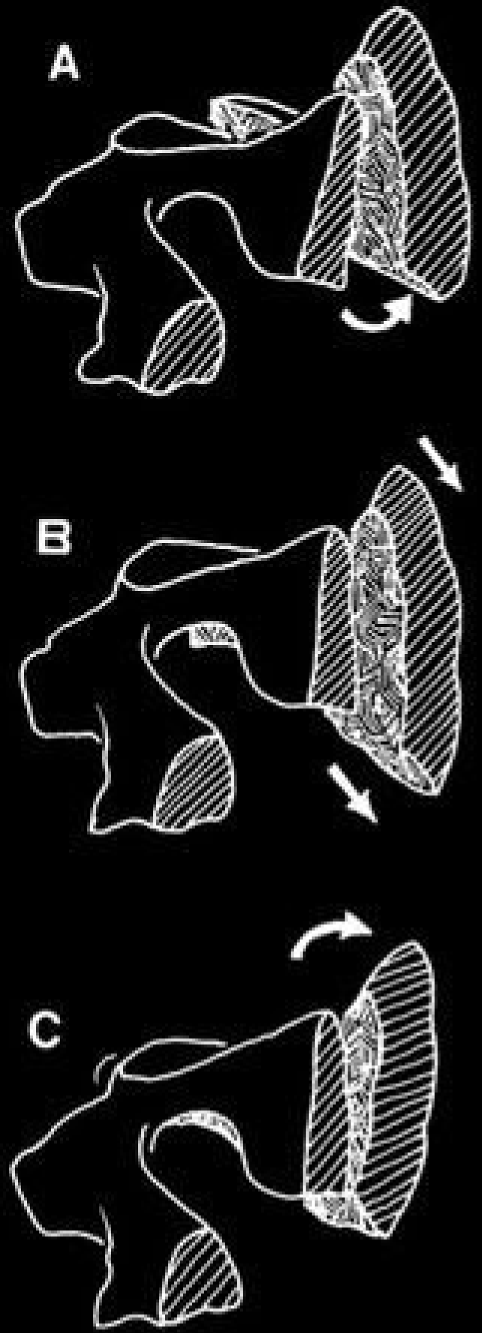

STRESS
(load)
D
C
B
A
STRAIN
(deformation)

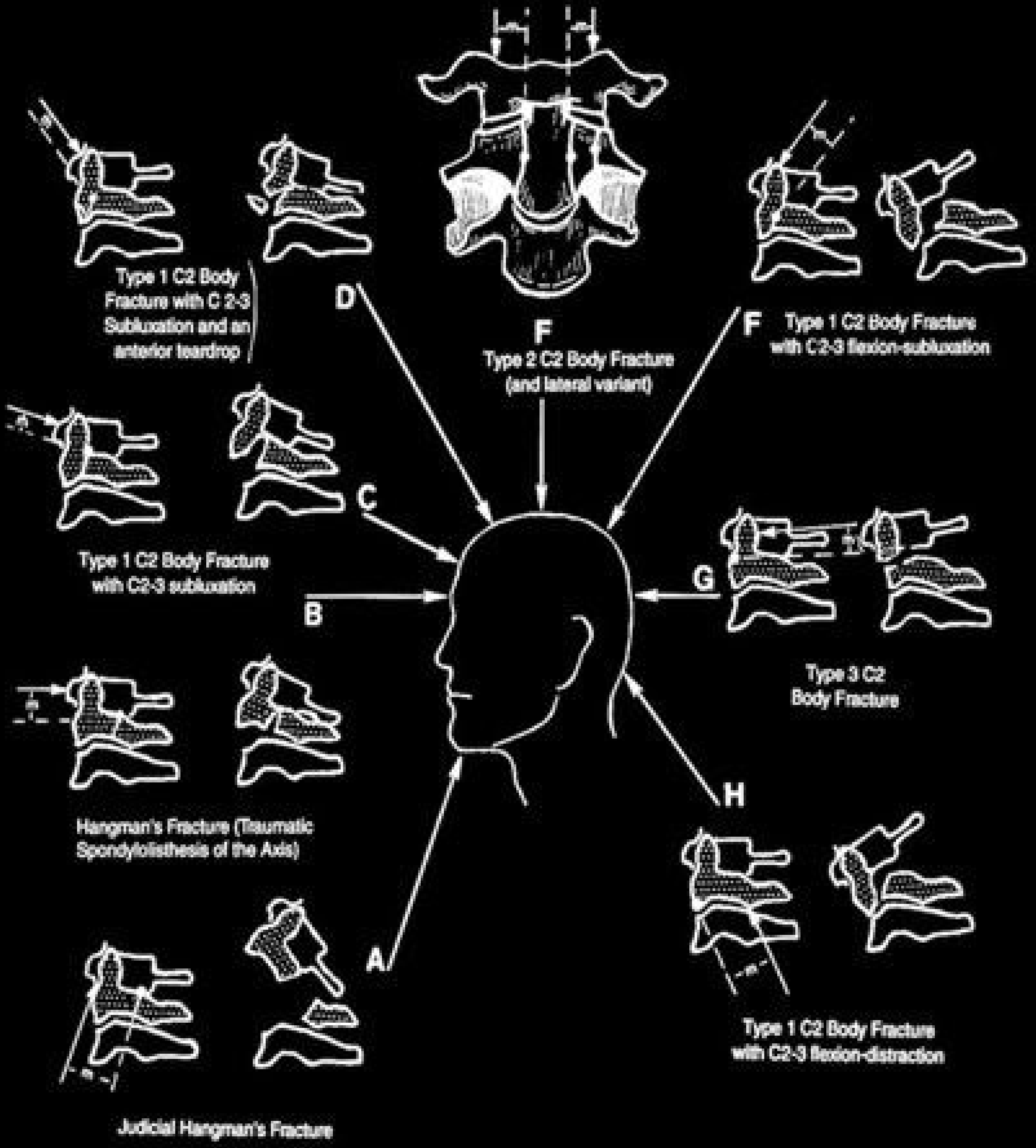
BIOMECHANICS
OF
SPINAL COLUMN
FAILURE


a
b


Type III Odontoid Fracture
Traumatic
Spondylolisthesis
Fracture of Axis

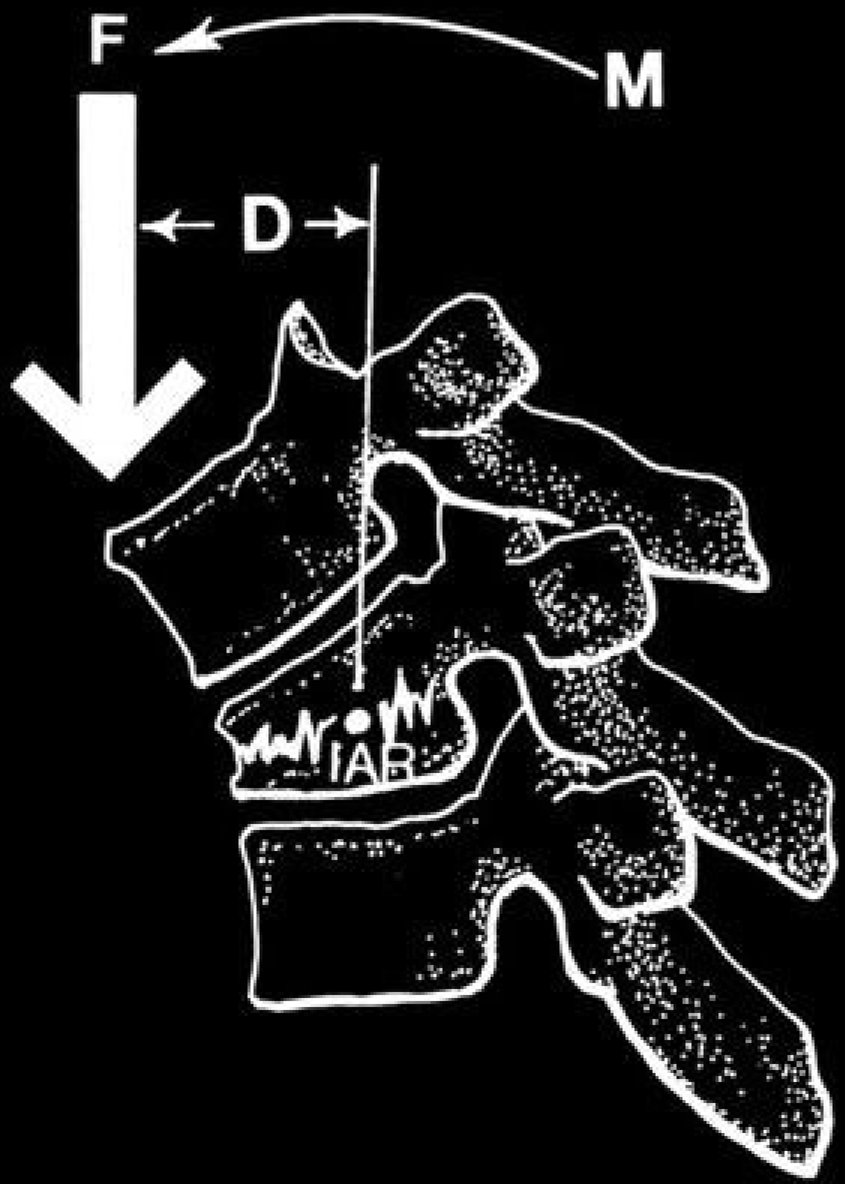

C-1
C-2
C-2
C-3
C-4

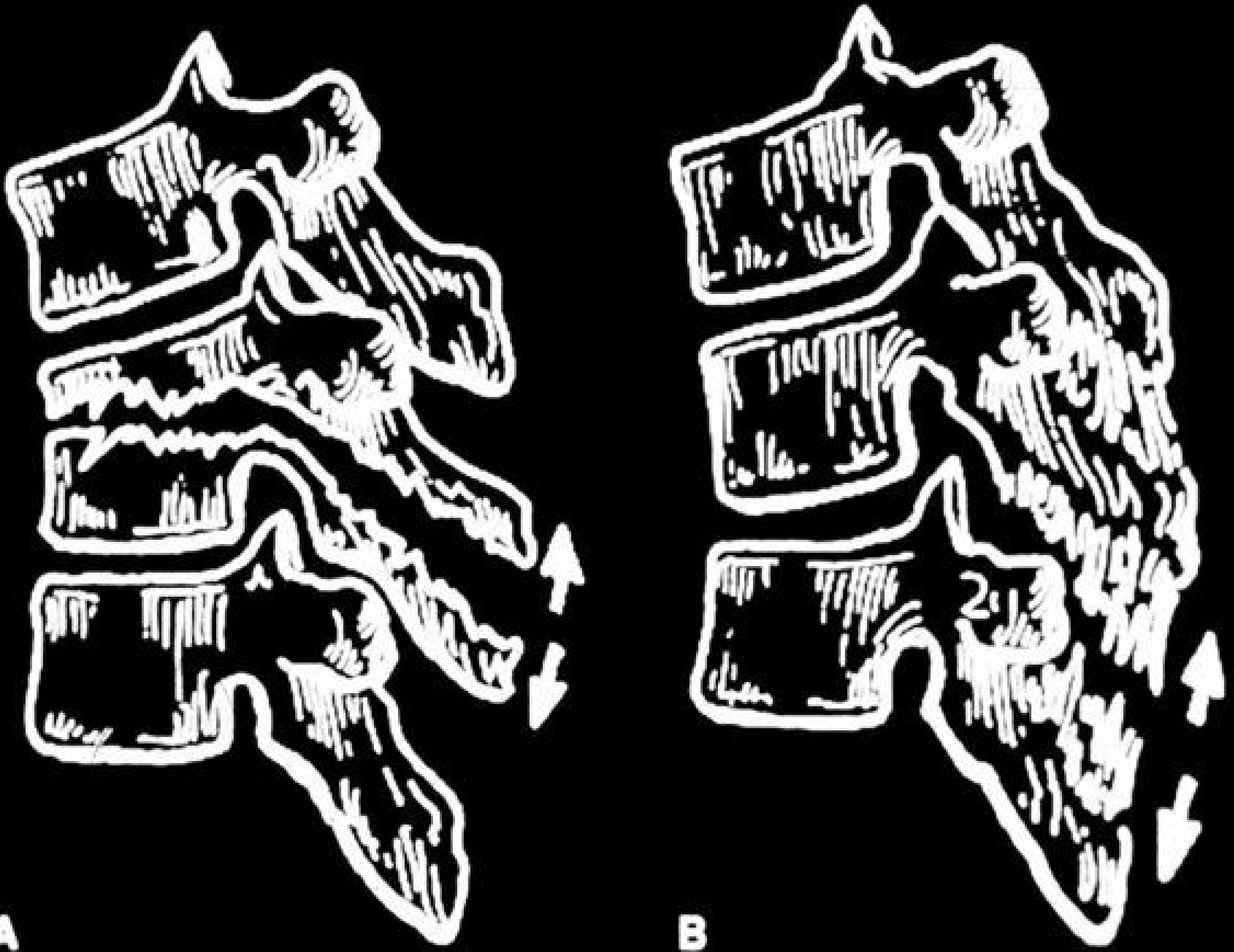

A
B
C


Type 1 C2 Body Fracture with C 2-3 Subluxation and an anterior teardrop
D
F
Type 2 C2 Body Fracture (and lateral variant)
F
Type 1 C2 Body Fracture with C2-3 flexion-subluxation
C
Type 1 C2 Body Fracture with C2-3 subluxation
B
G
Type 3 C2 Body Fracture
Hangman's Fracture (Traumatic Spondylolisthesis of the Axis)
H
A
Type 1 C2 Body Fracture with C2-3 flexion-distraction
Judicial Hangman's Fracture

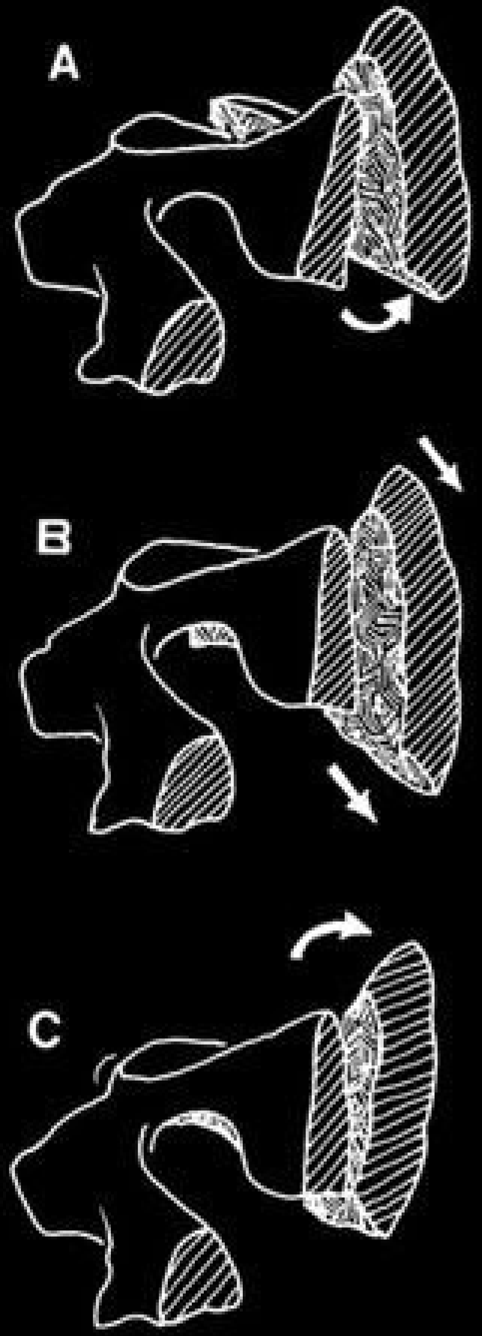
BIOMECHANICS OF SUBAXIAL SPINE FAILURE

$$M = F \times D$$

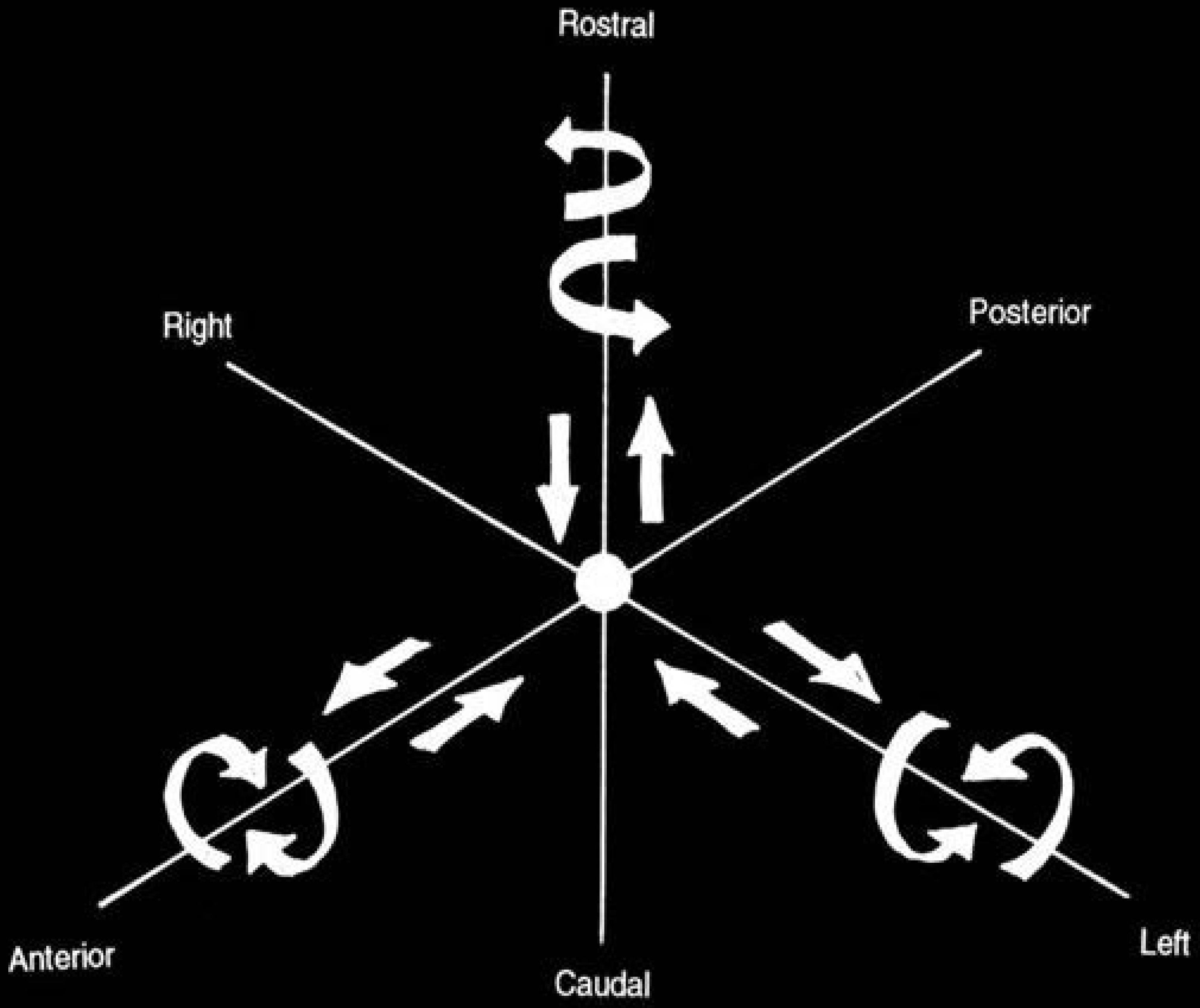

F
M
D
IAR



A B


A
B
C

BIOMECHANICS
OF
SPINE
INSTRUMENTATION


Rostral
Right
Posterior
Anterior
Caudal
Left

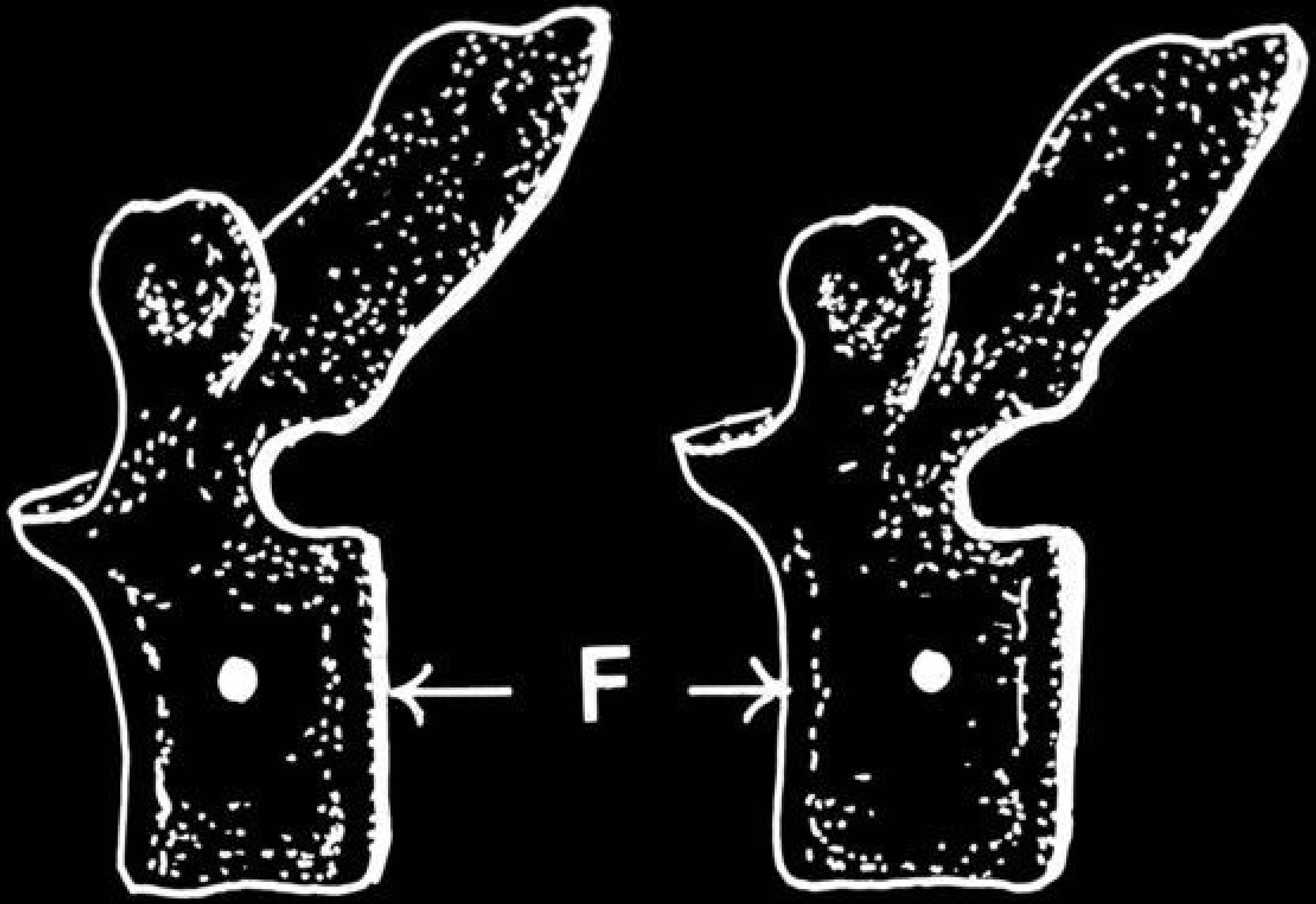

M
F
D
IAR

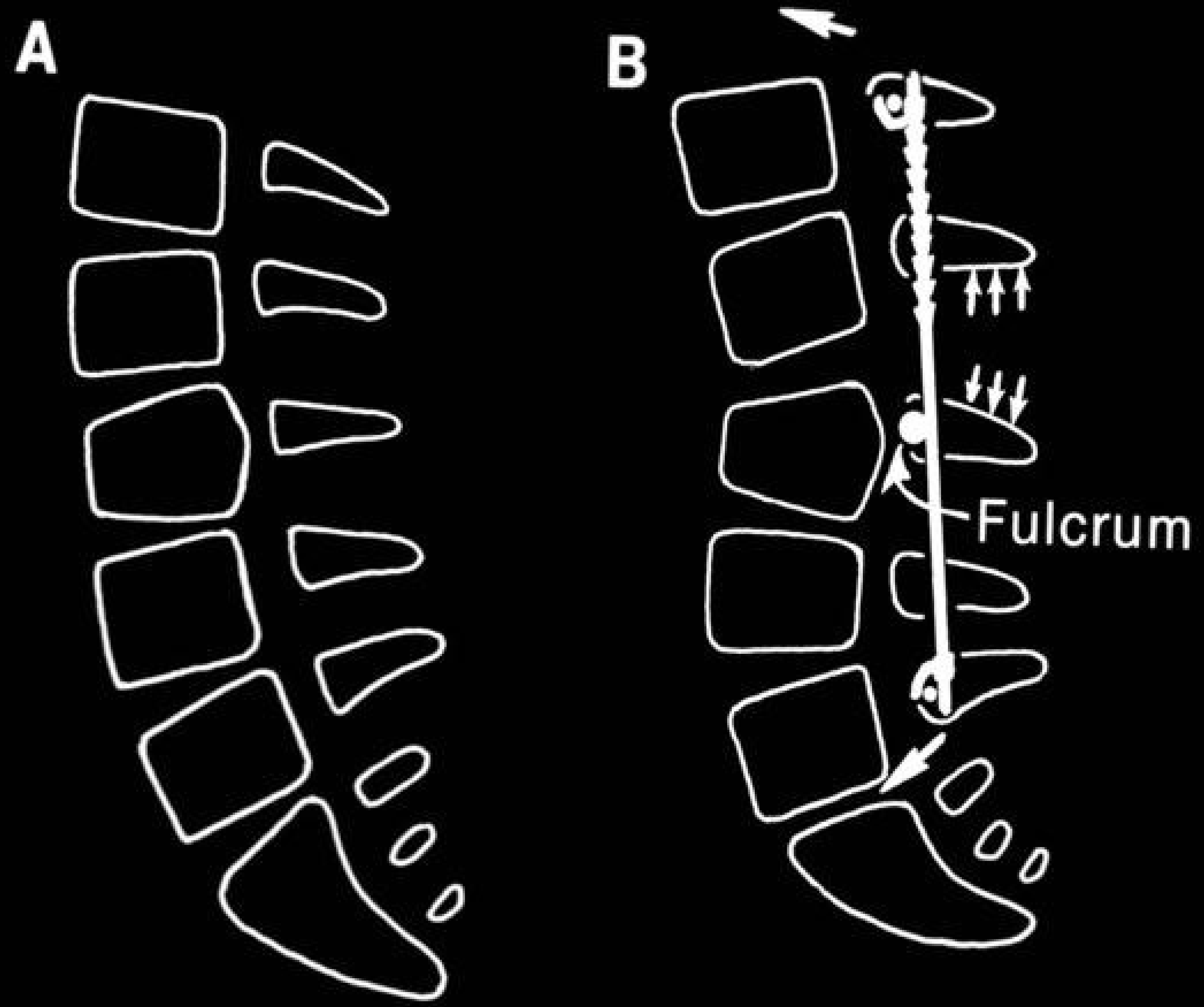
M = F X D

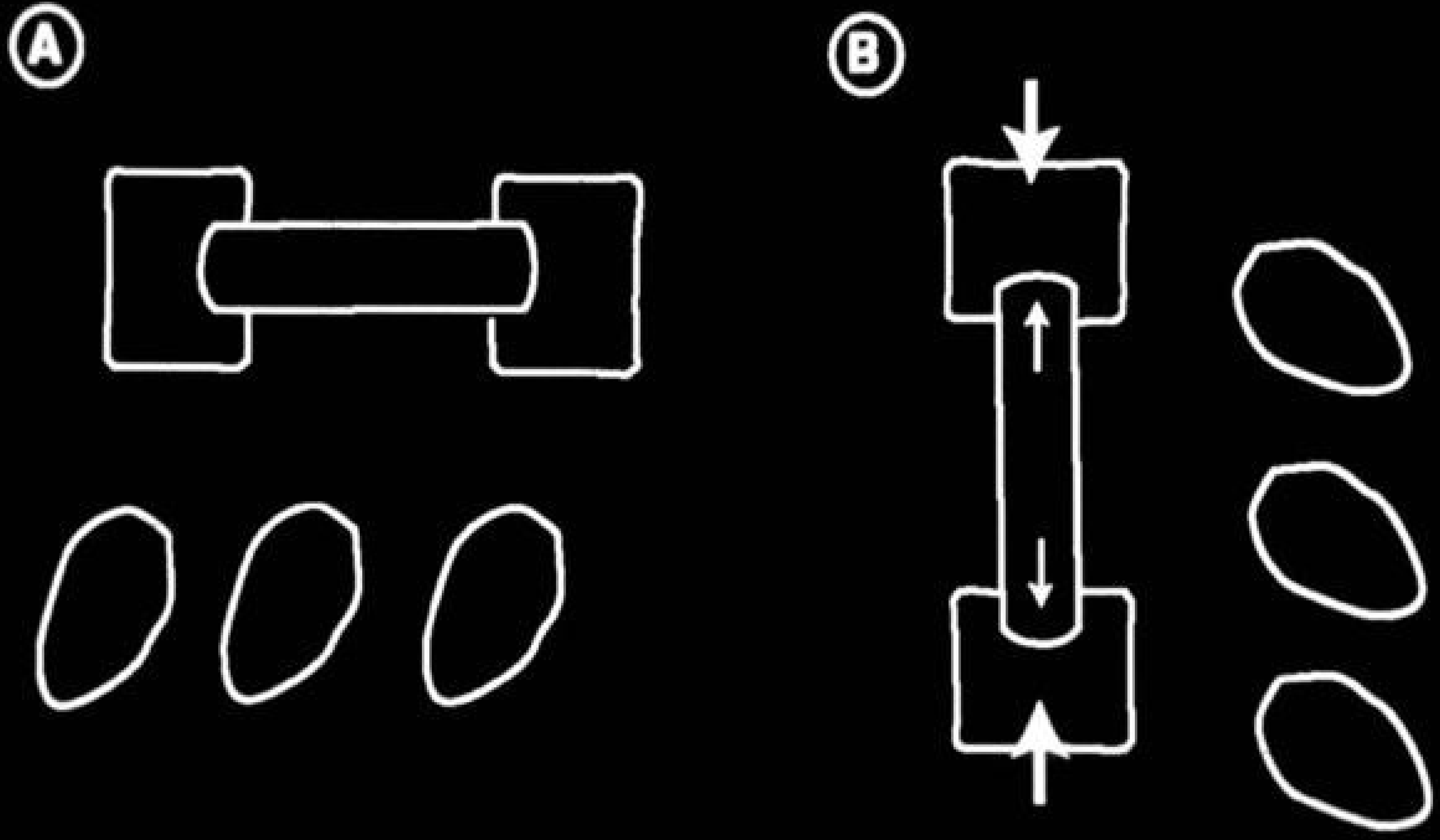
Load Bearing
Load Sharing

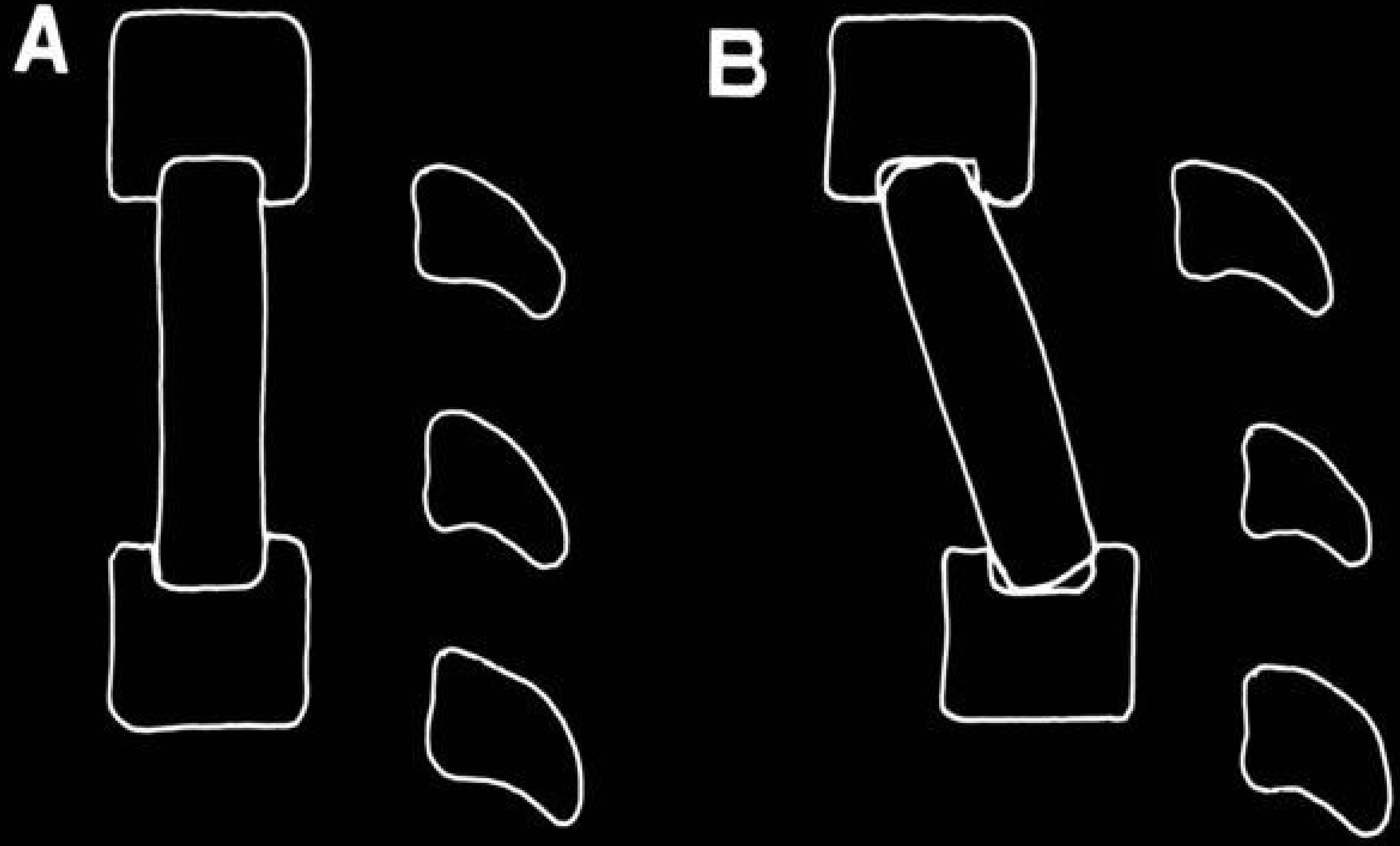
SIX MECHANISMS

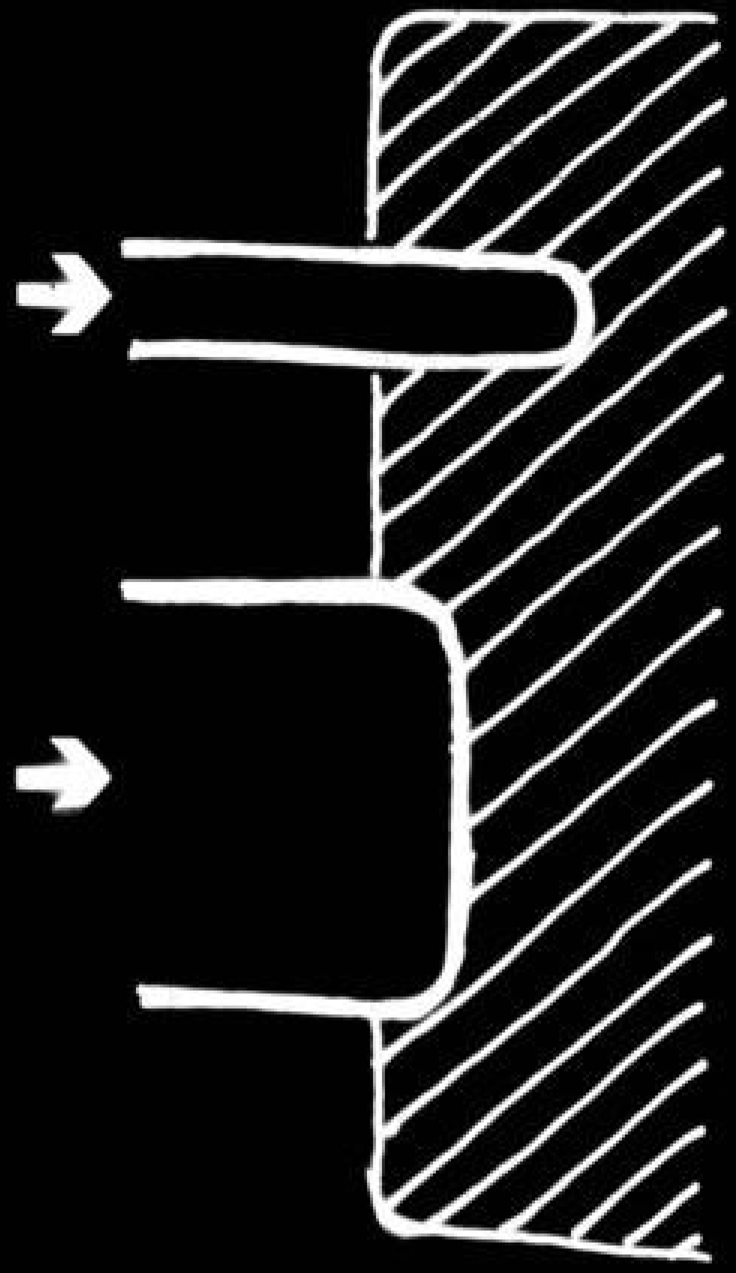
Distraction
Three-Point Bending
Tension-Band Fixation
Fixed Moment Arm Cantilever Beam Fixation
Non-Fixed Moment Arm Cantilever Beam Fixation
Applied Moment Arm Cantilever Beam Fixation

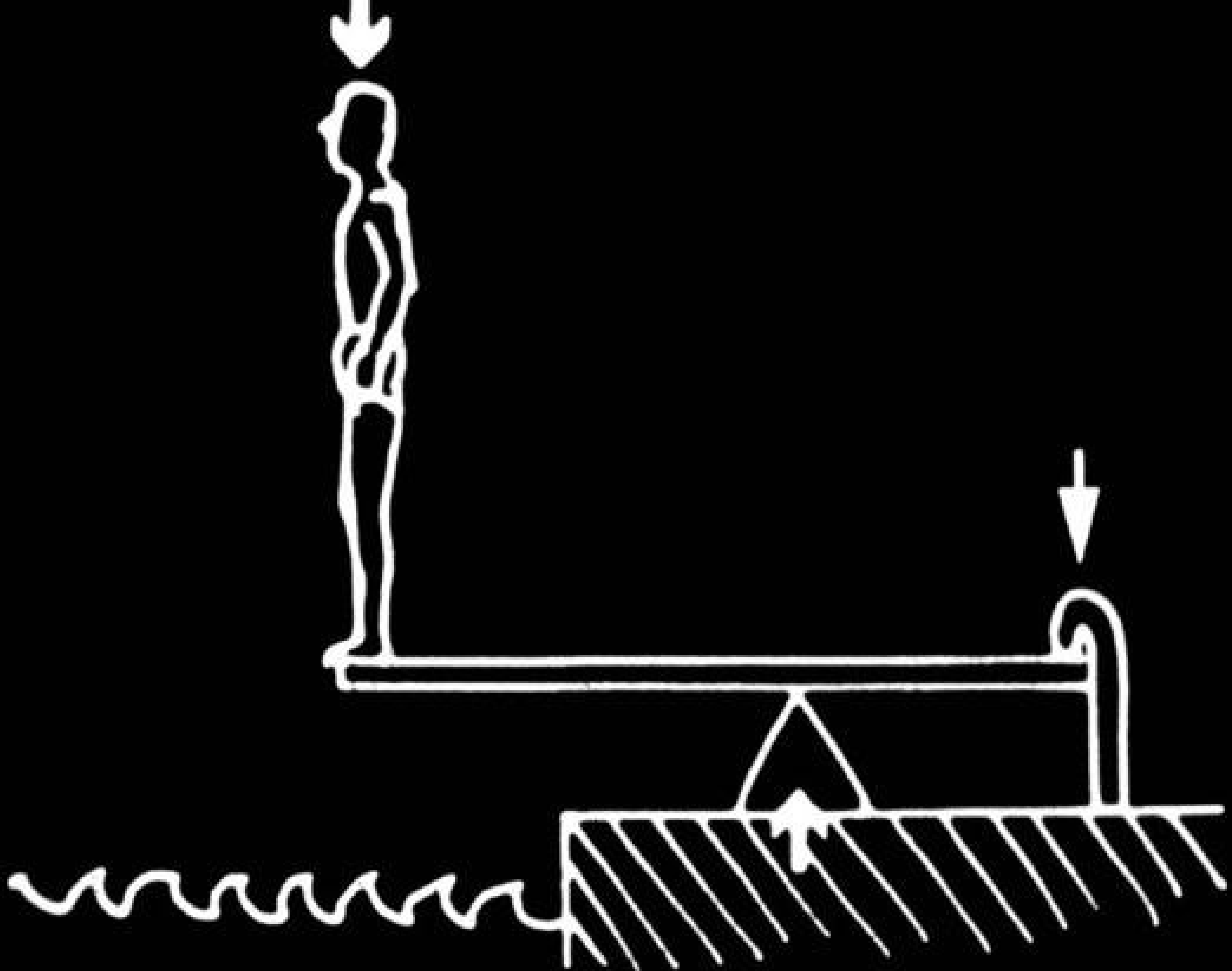

F

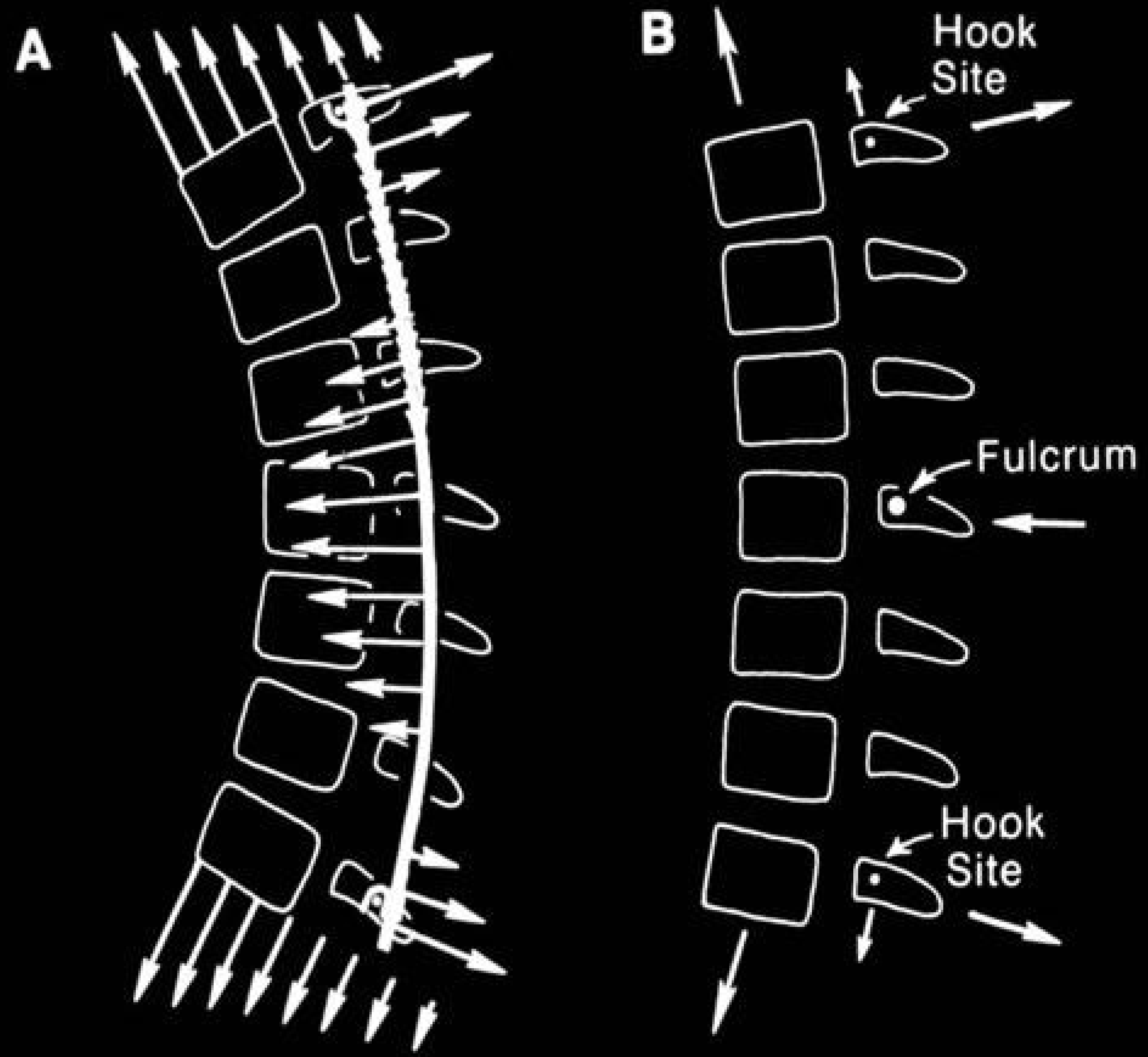

A
B
Fulcrum

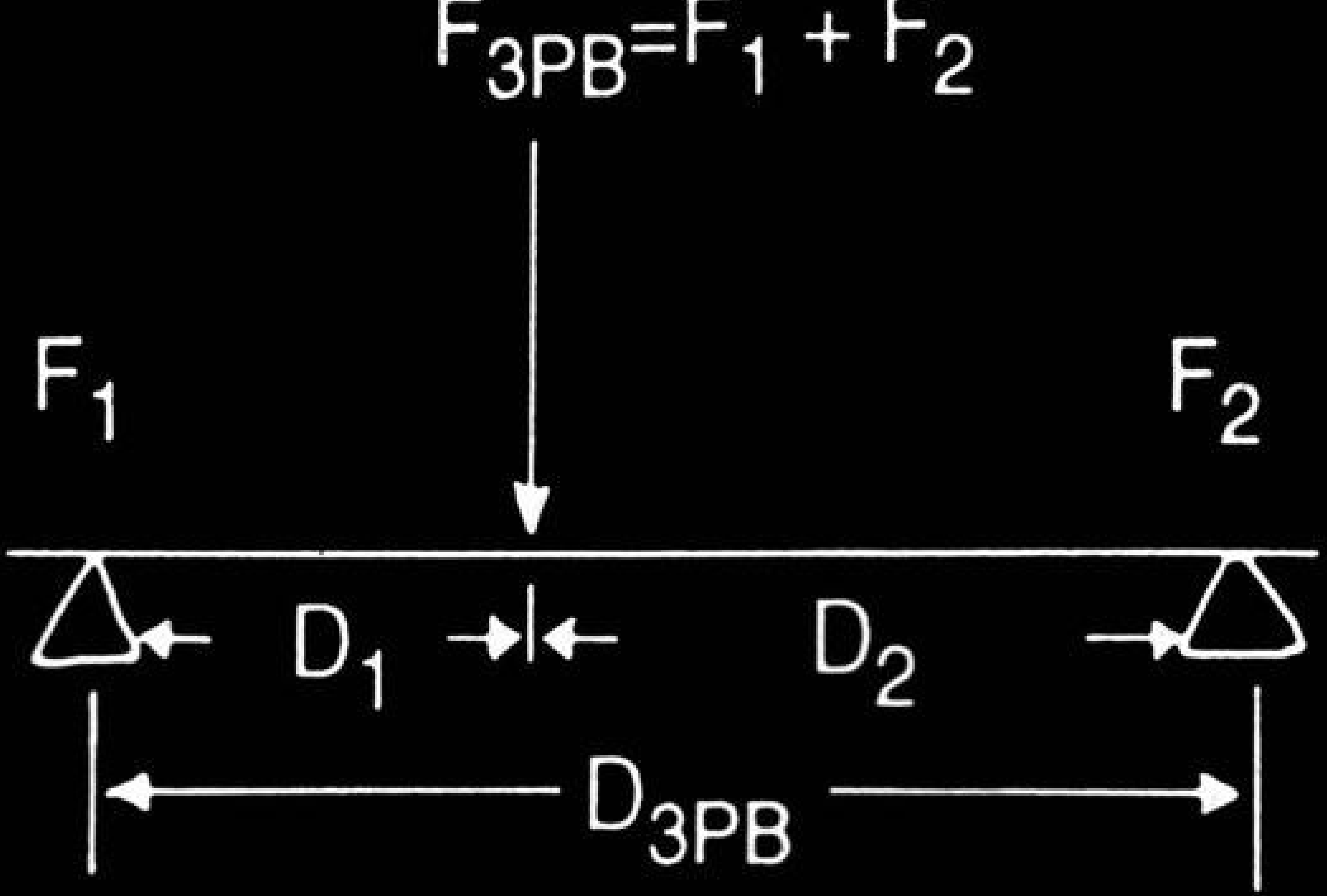

A
B


A
B



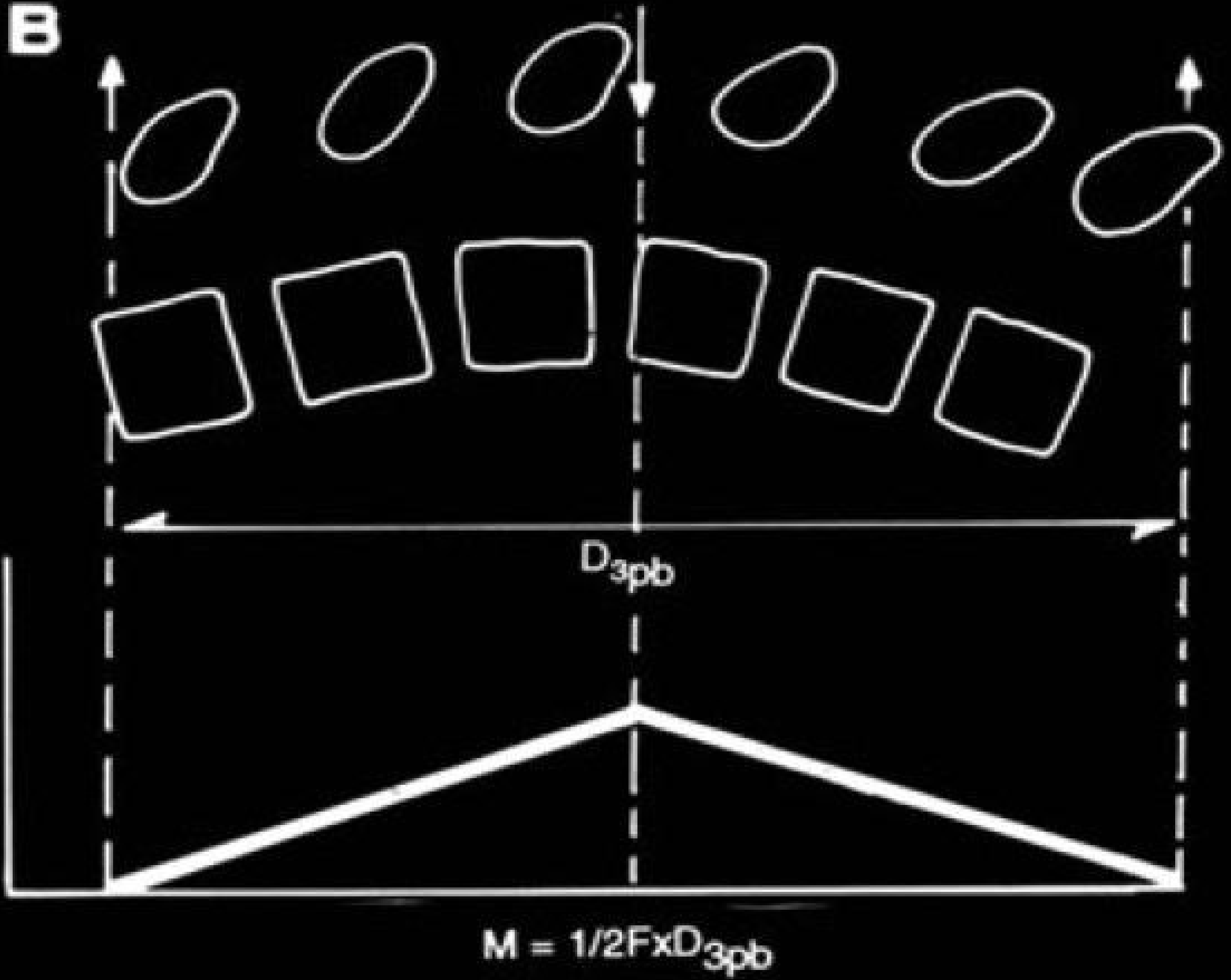


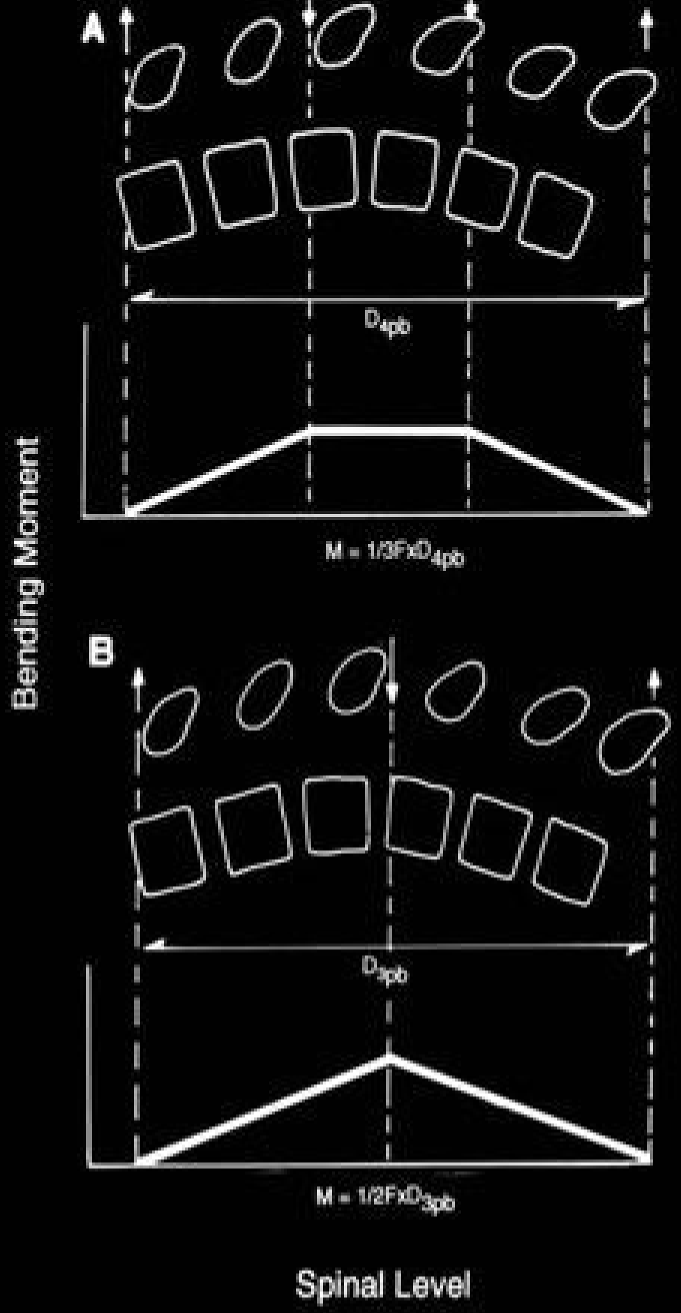

A
B
Hook
Site
Fulcrum
Hook
Site

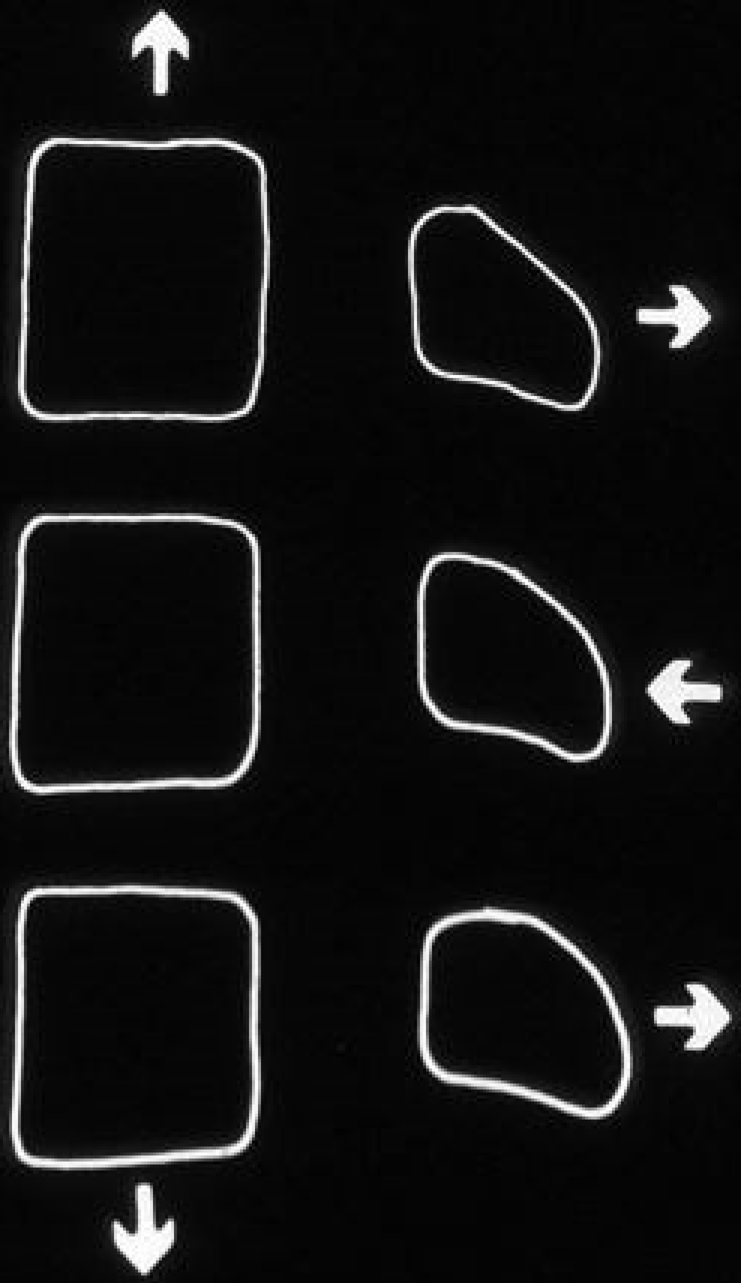


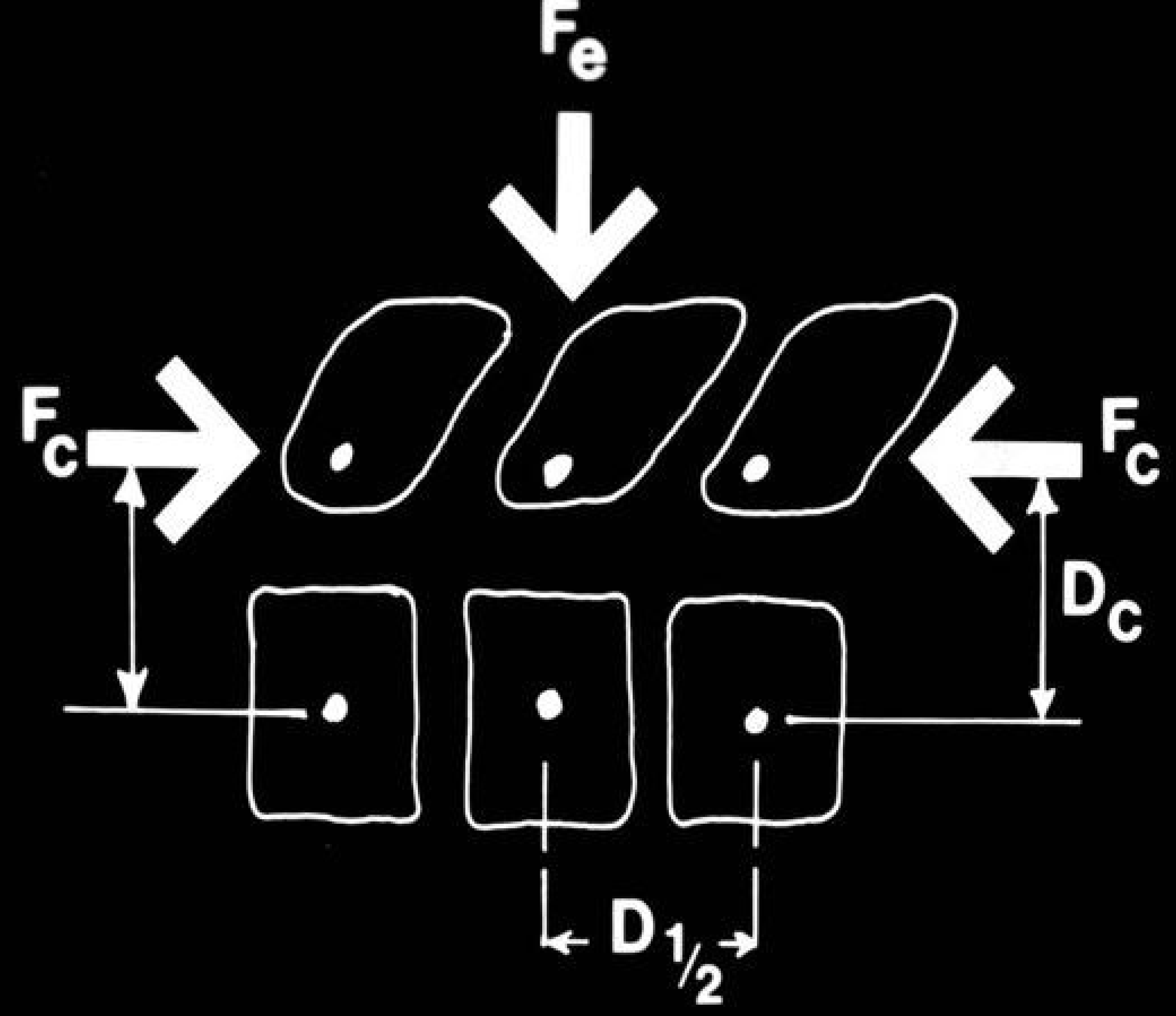
B

$$M = \frac{D_1 \times D_2 \times F_{3pb}}{D_{3pb}}$$

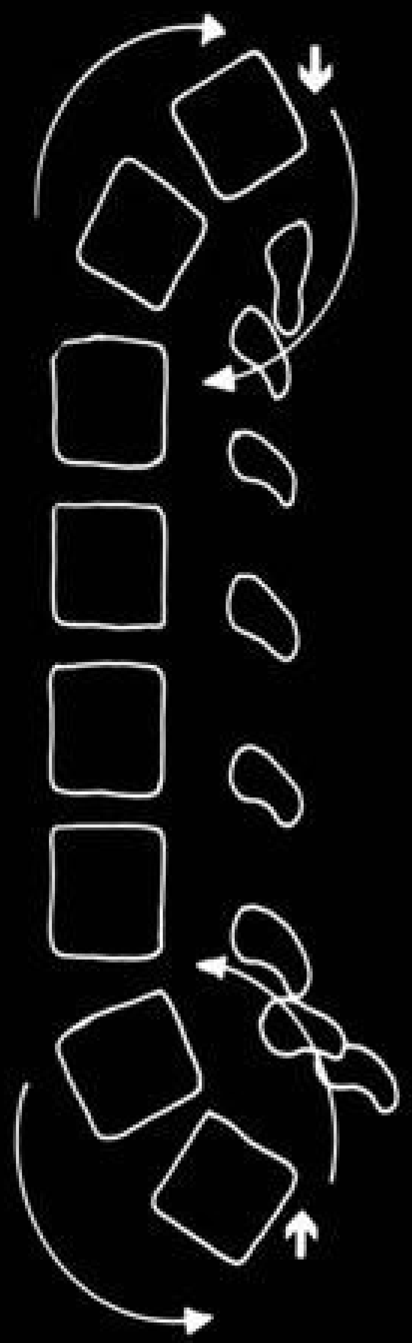

B
D_{3pb}
$M = 1/2F \times D_{3pb}$

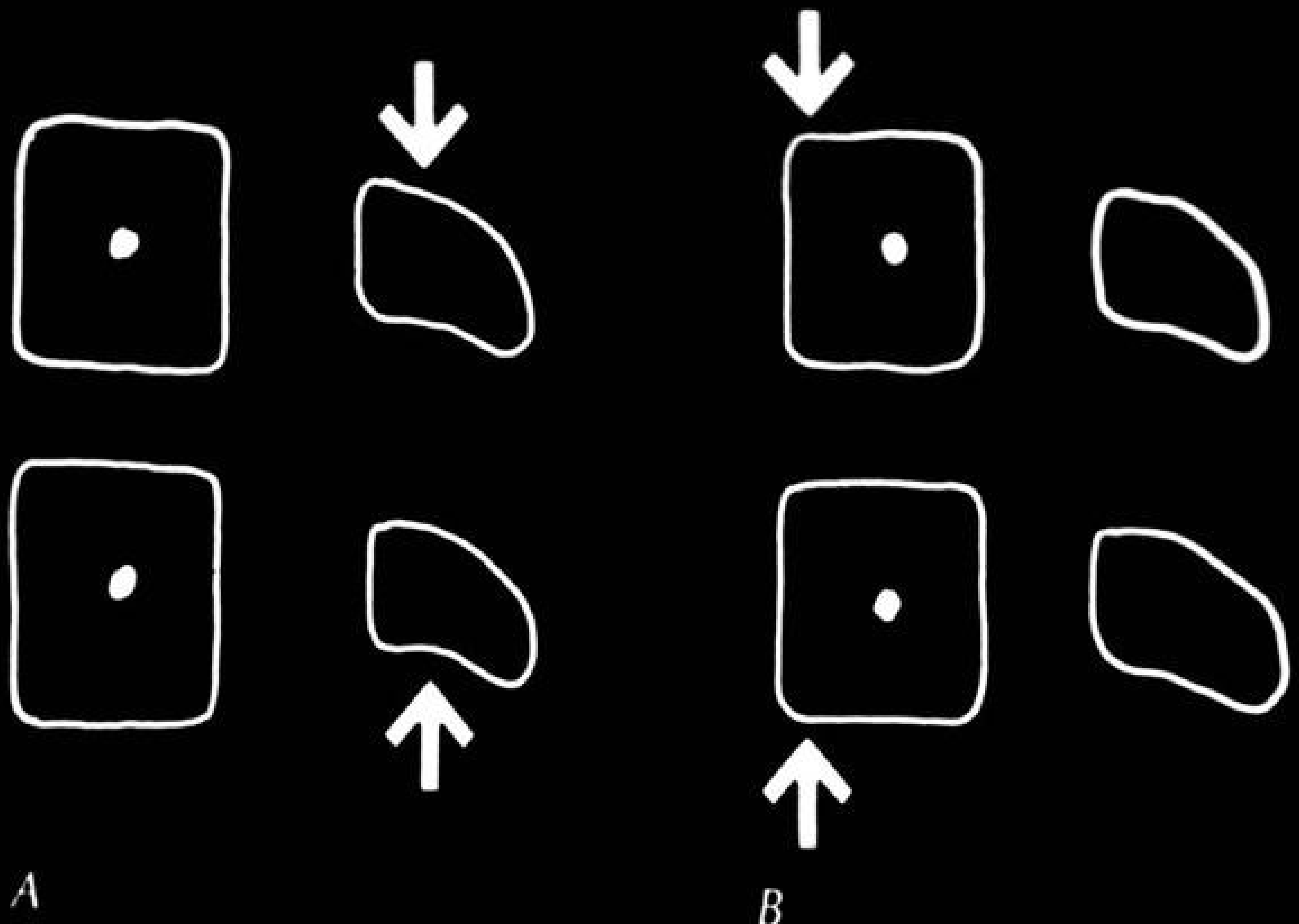

A
D_{4pb}
M = 1/3FxD$_{4pb}$
B
D_{3pb}
M = 1/2FxD$_{3pb}$
Bending Moment
Spinal Level

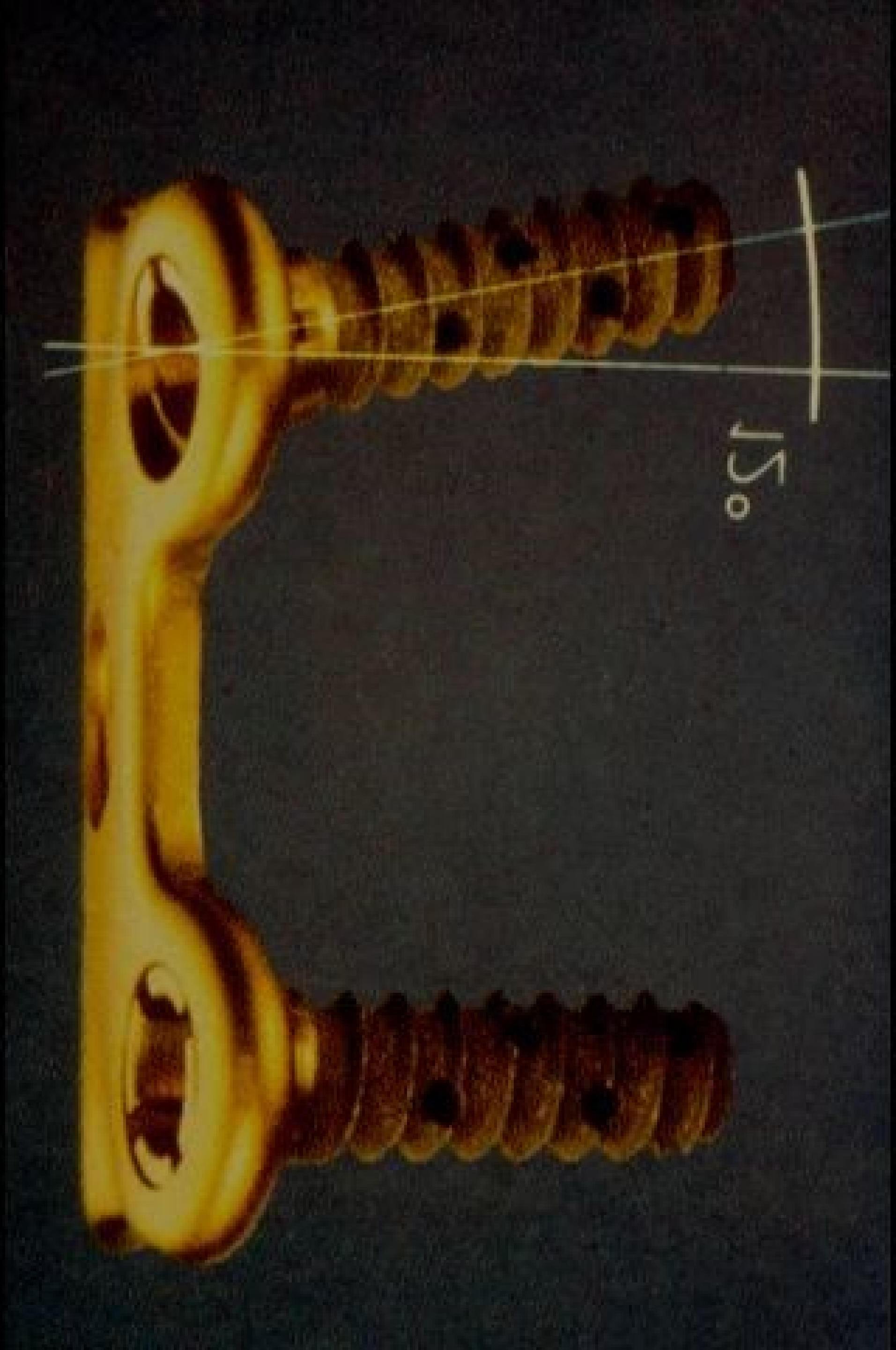




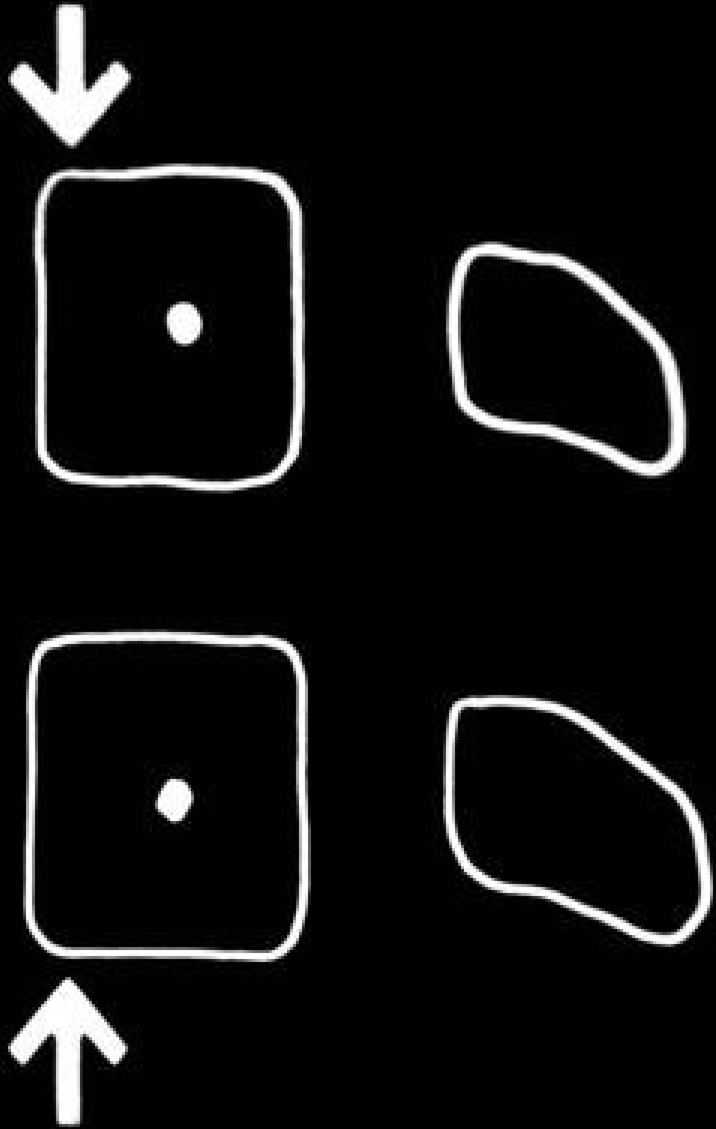
F_e
F_c
F_c
D_c
$D_{1/2}$

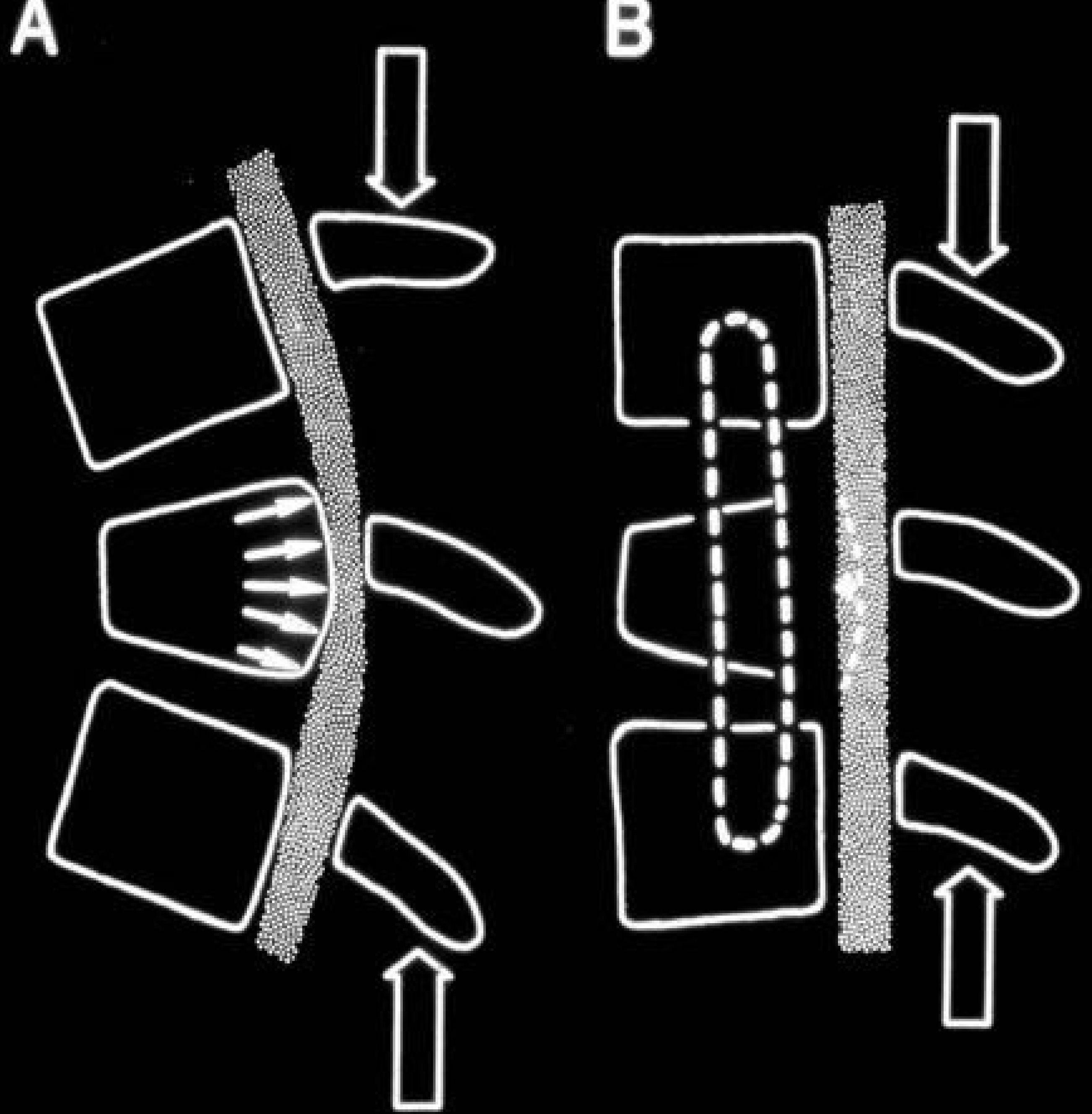


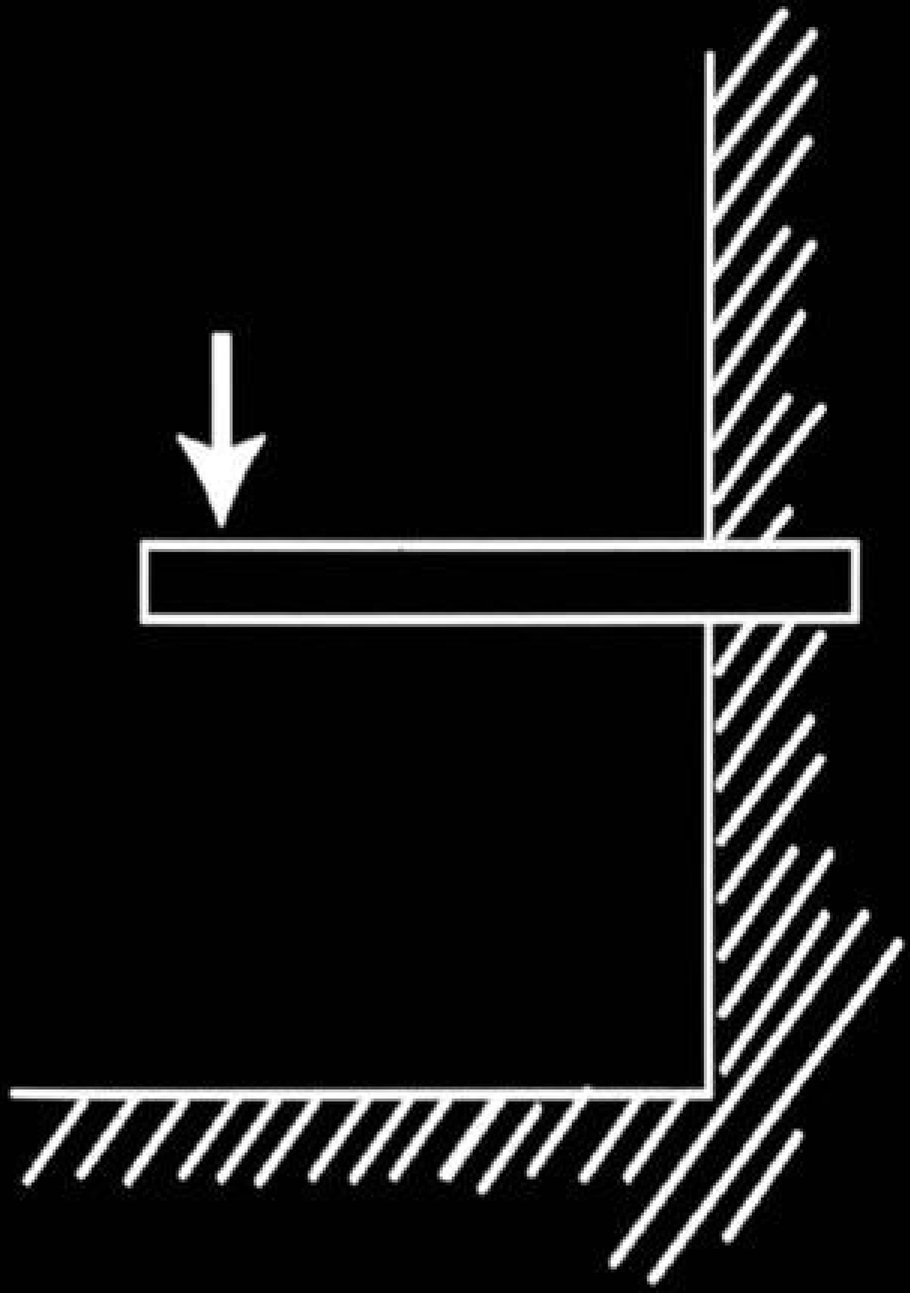

A
B

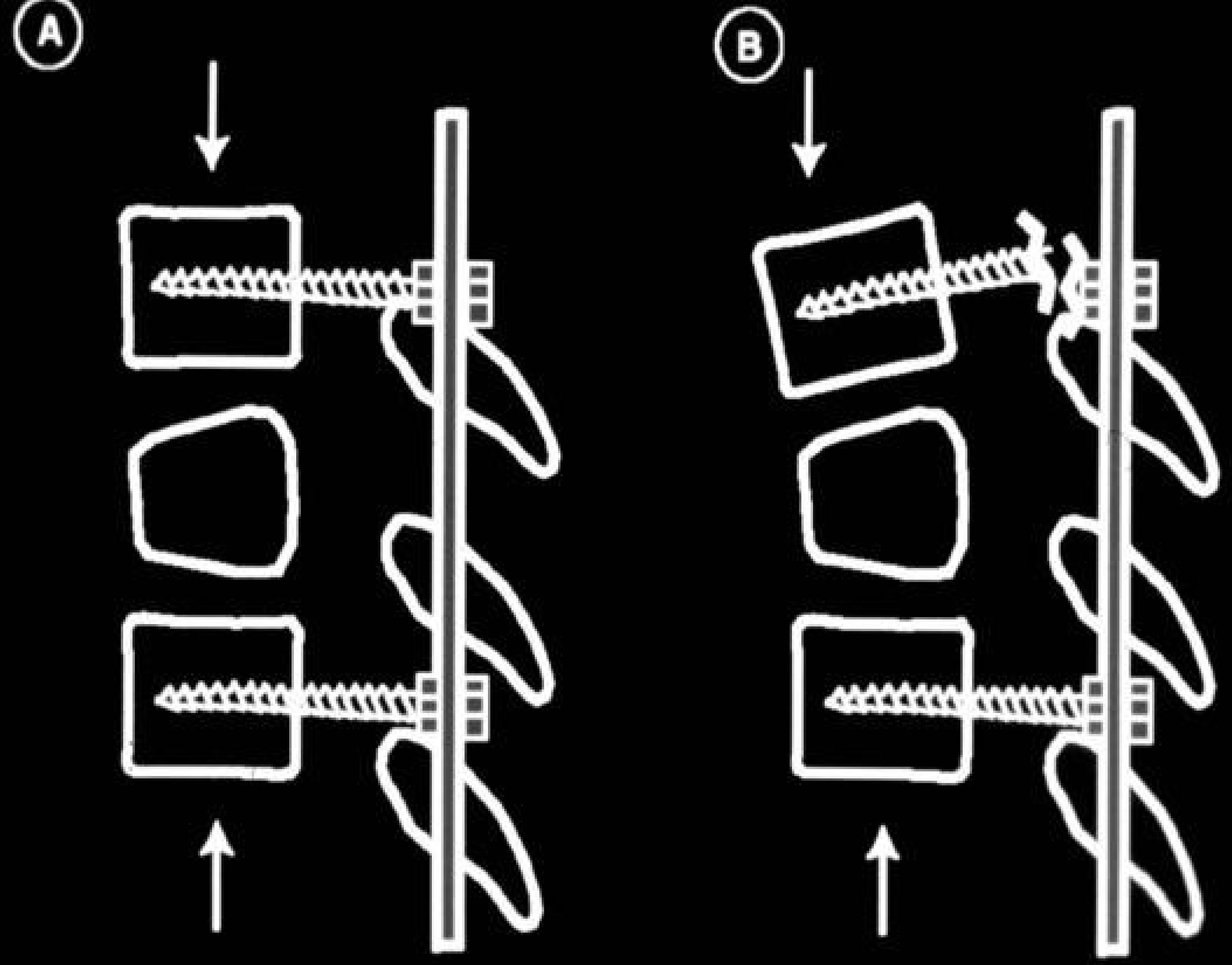

15°

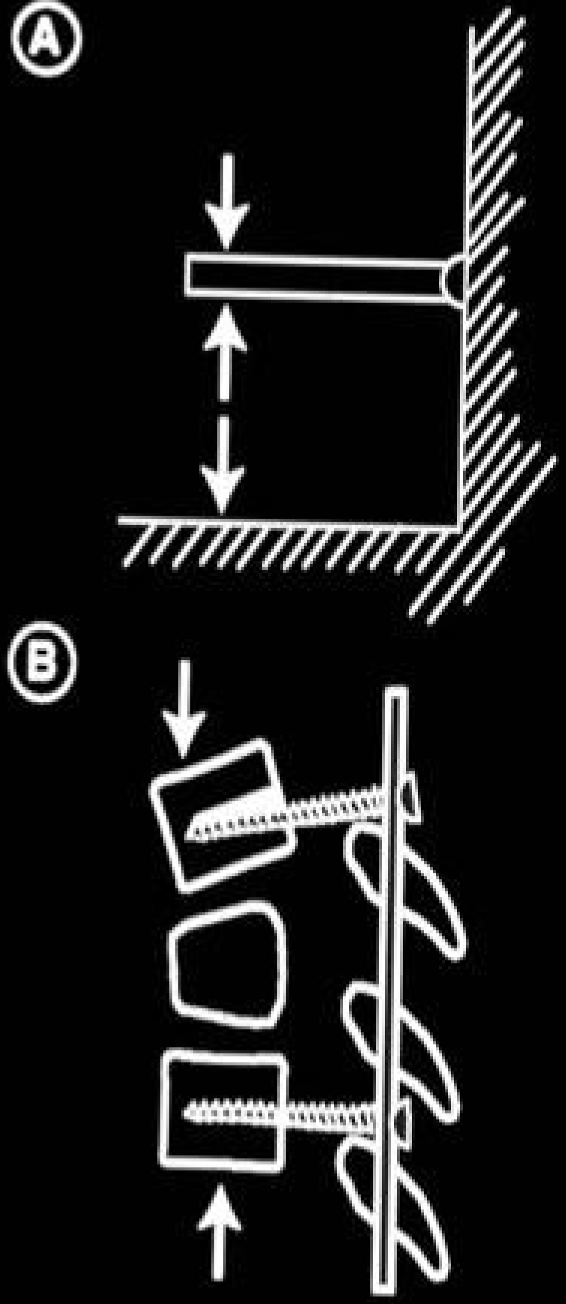

15°

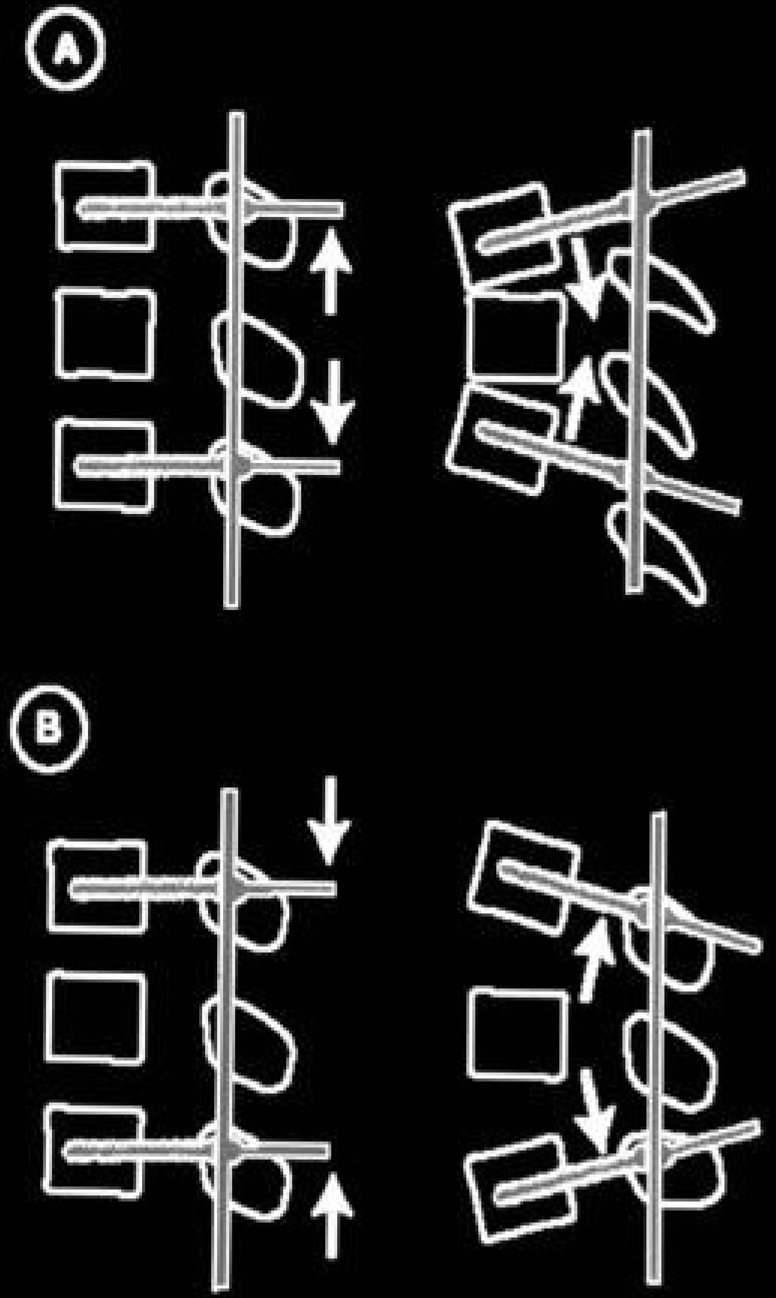


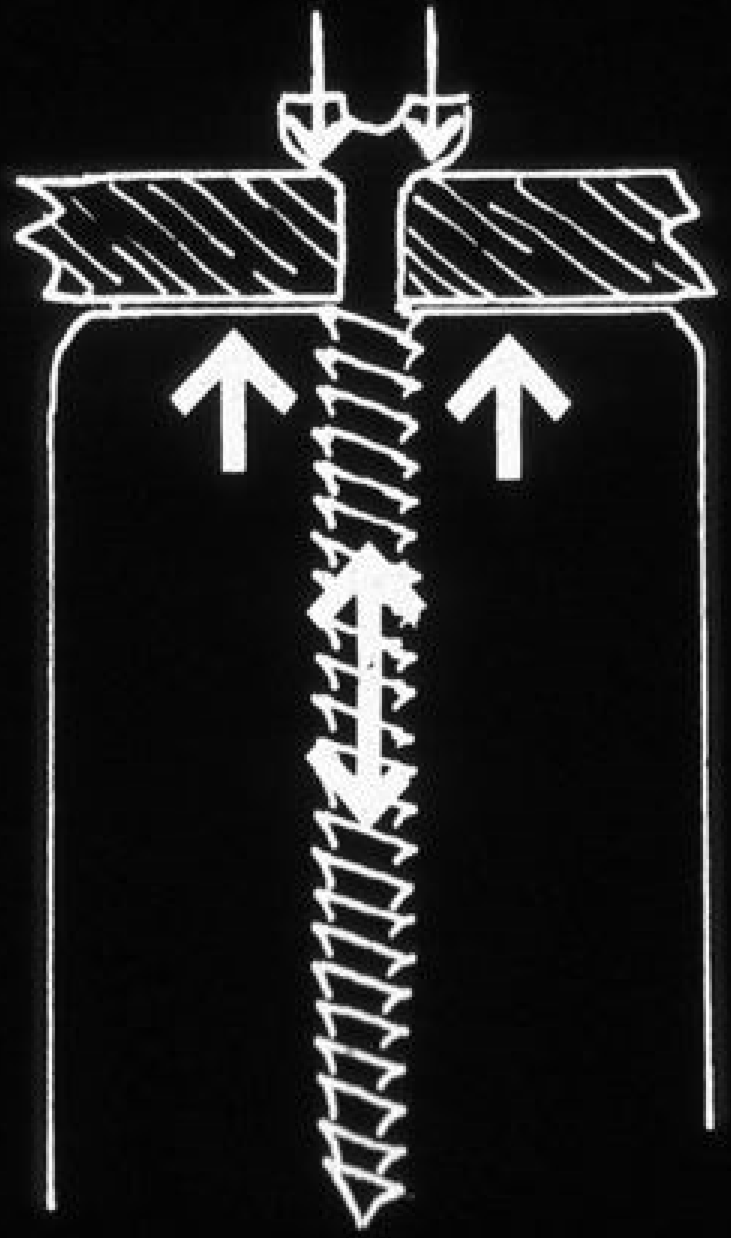

A
B

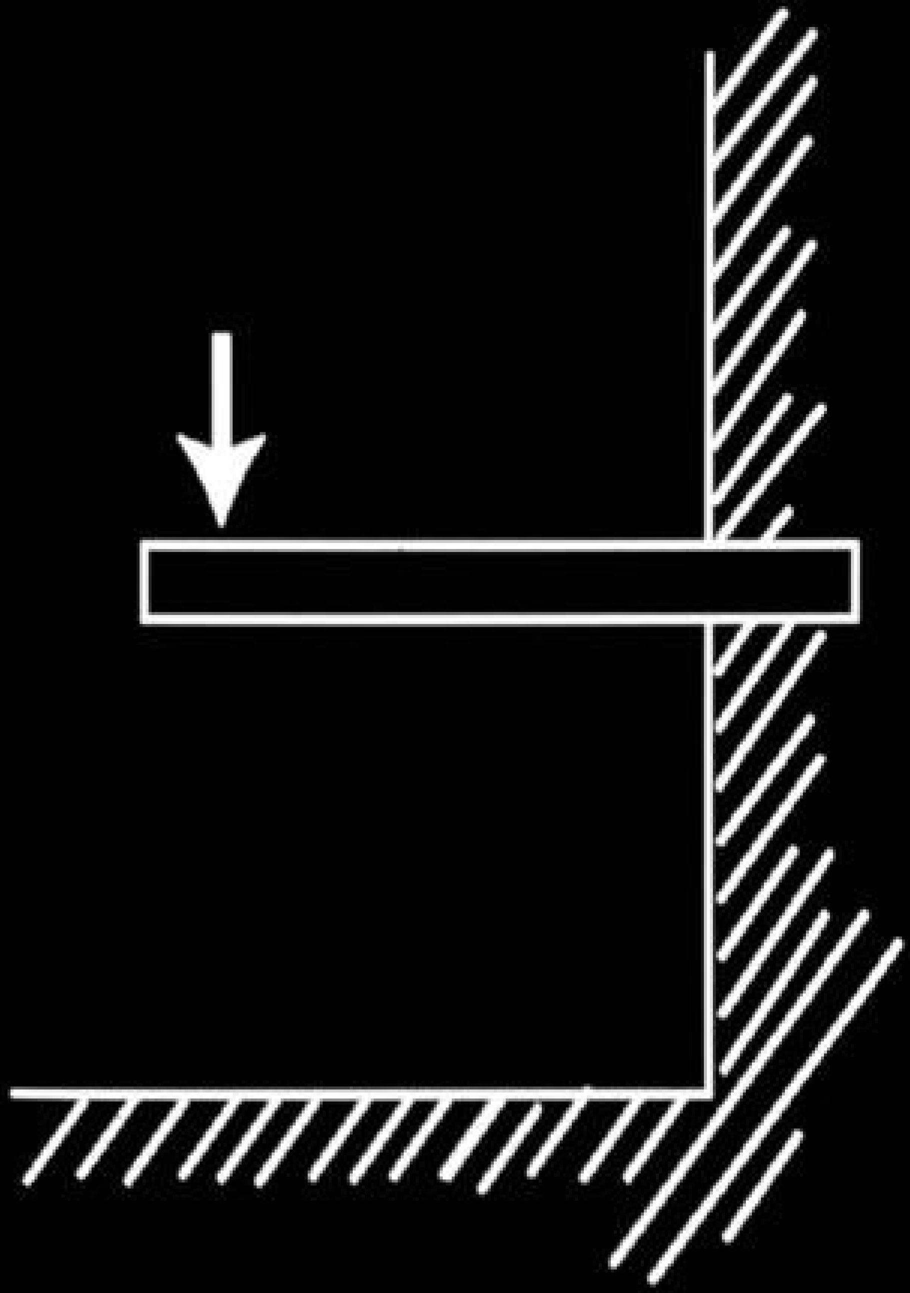



A
B


A
B


A
B



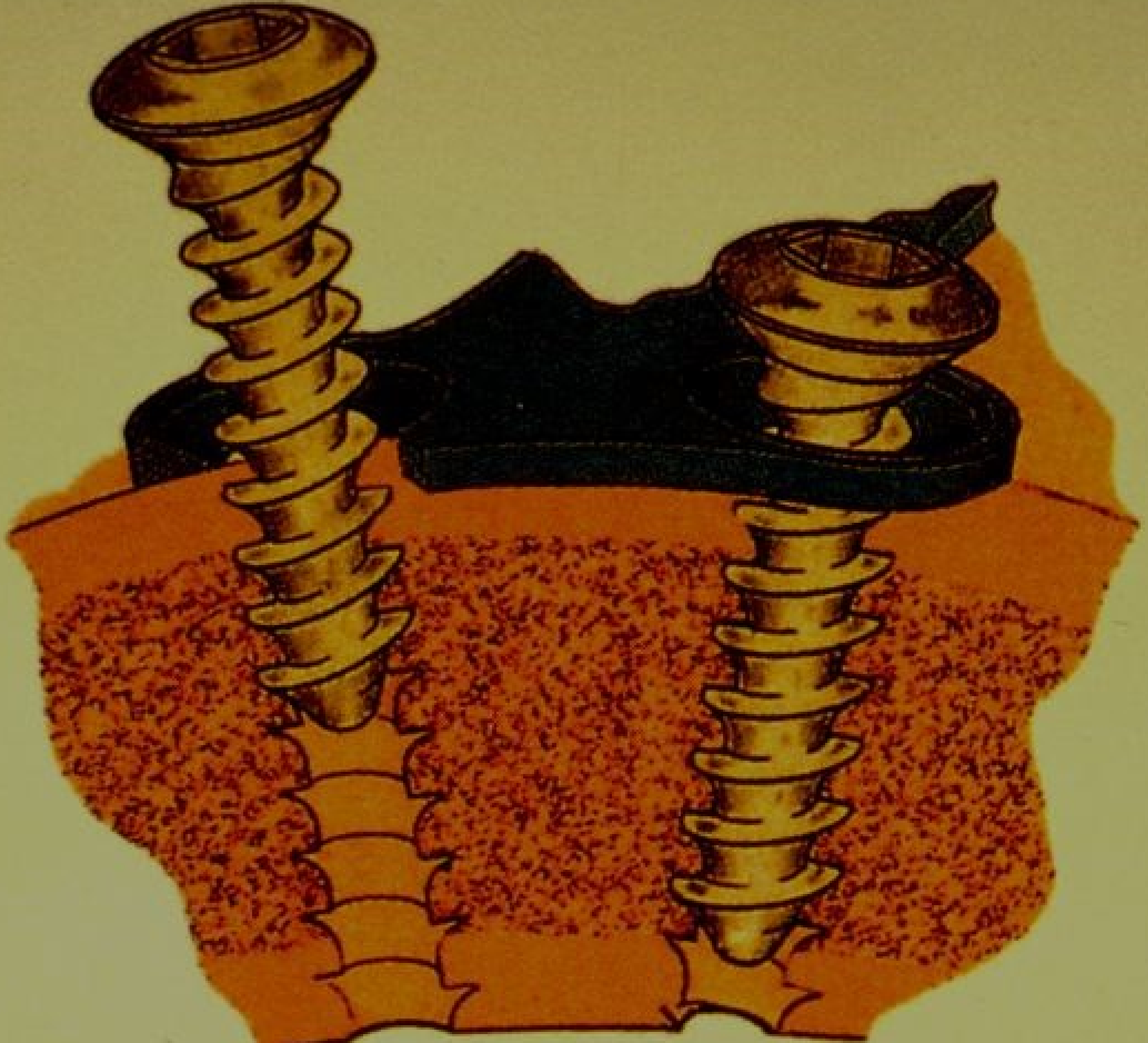


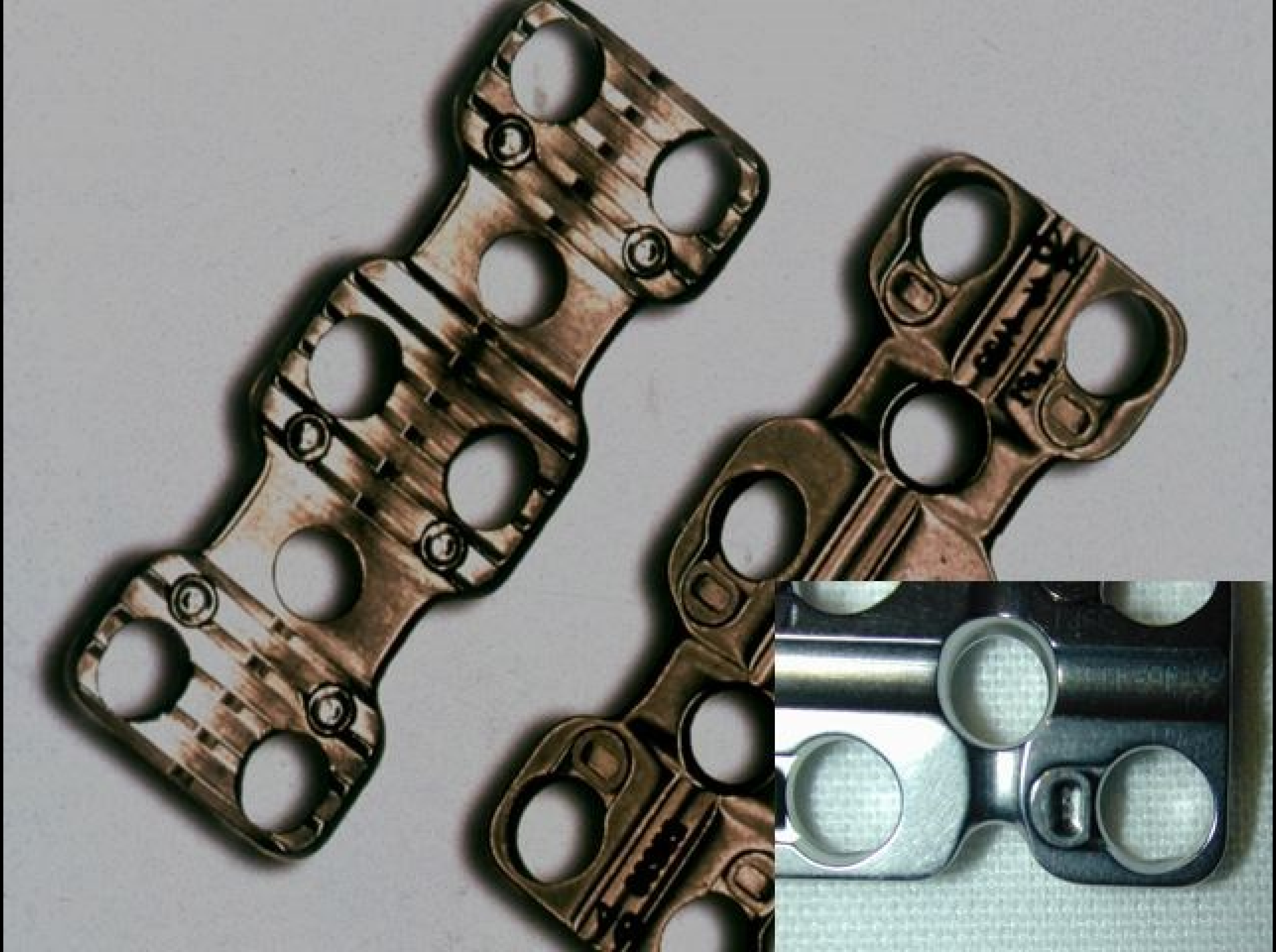
Dynamic Fixation

Wolff's Law

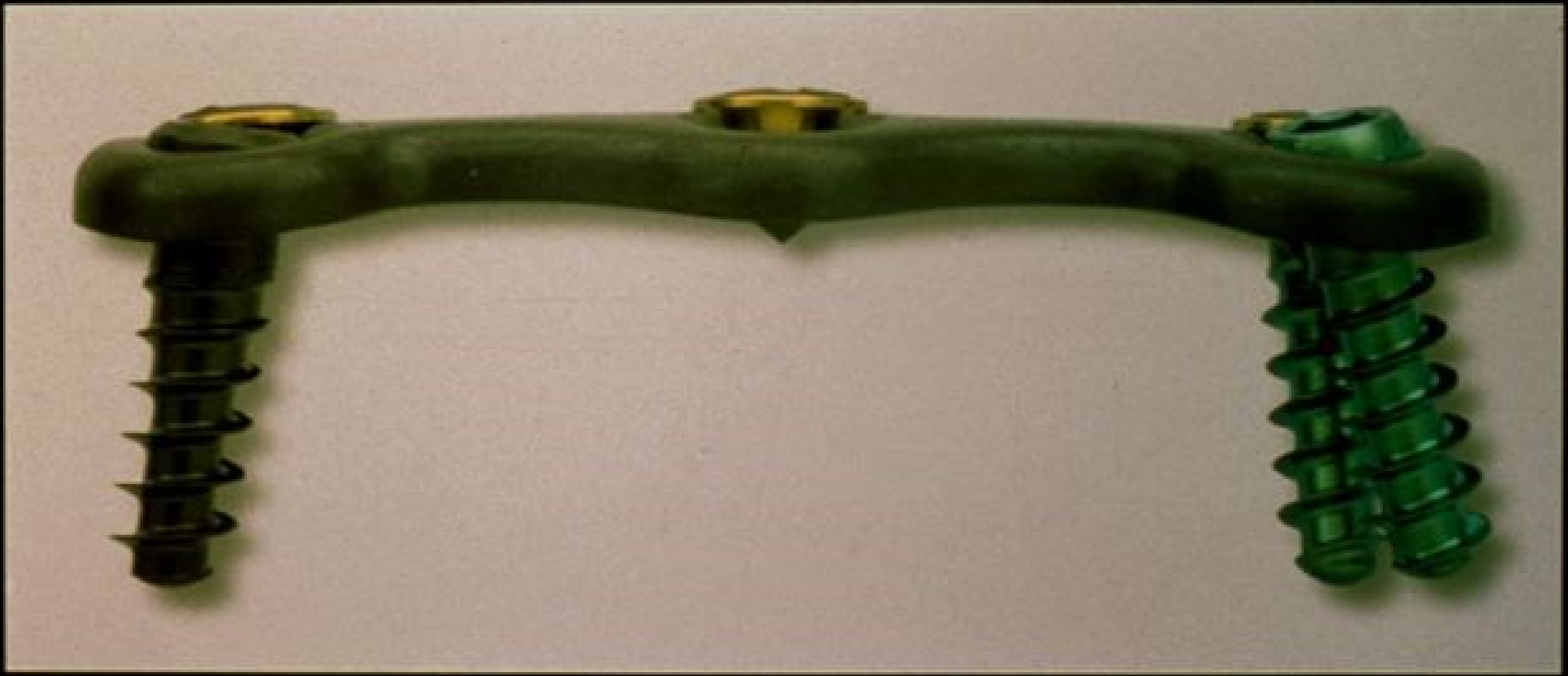
Every change in the form and function of a bone, or of function alone, is followed by specific definitive change in its internal architecture and equally definitive secondary changes in its external configuration, in accordance with mathematical laws.

"Structure is nothing else than the physical expression of function… under pathologic conditions the structure and form of the parts change according to the abnormal conditions of force transmission"



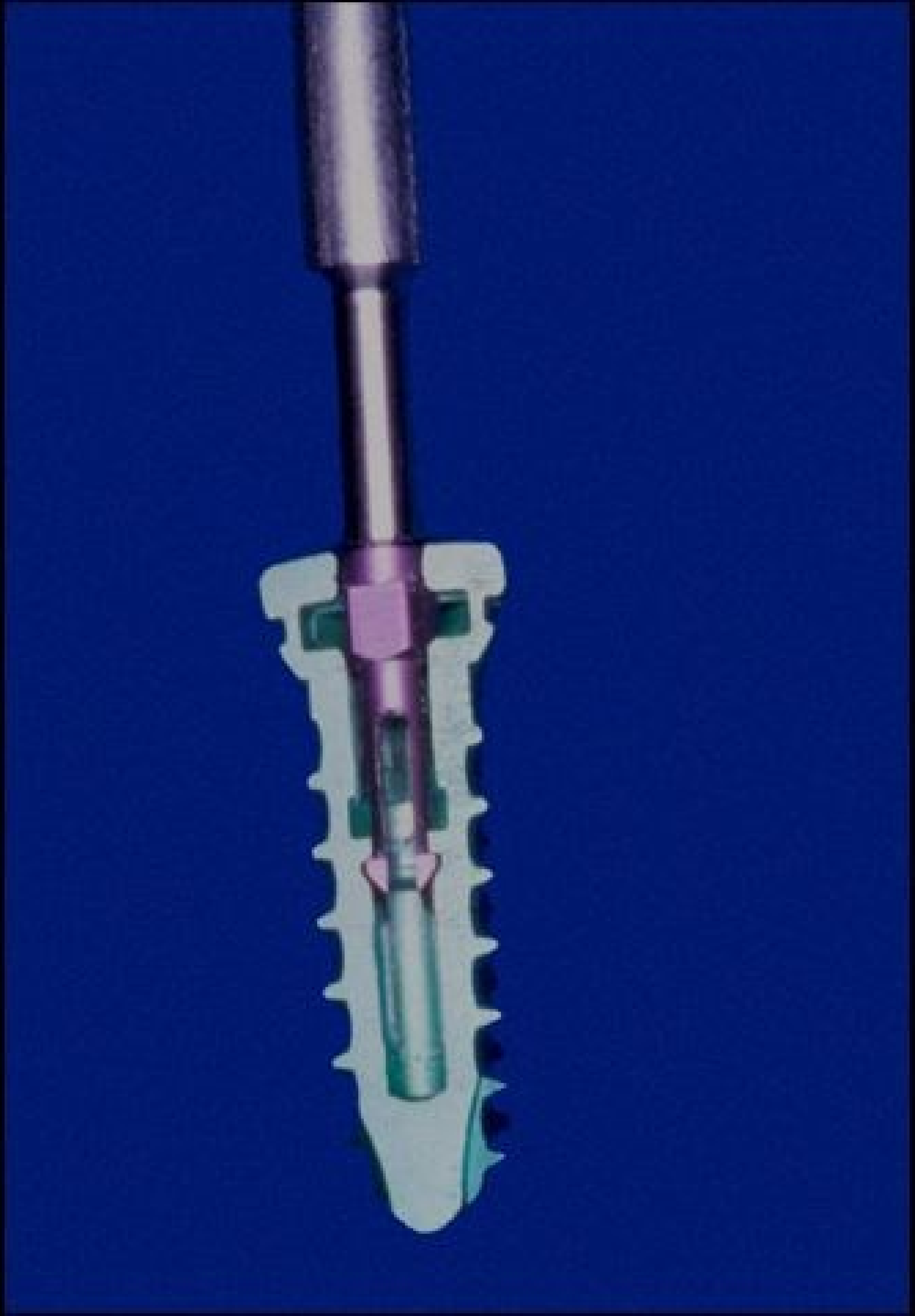


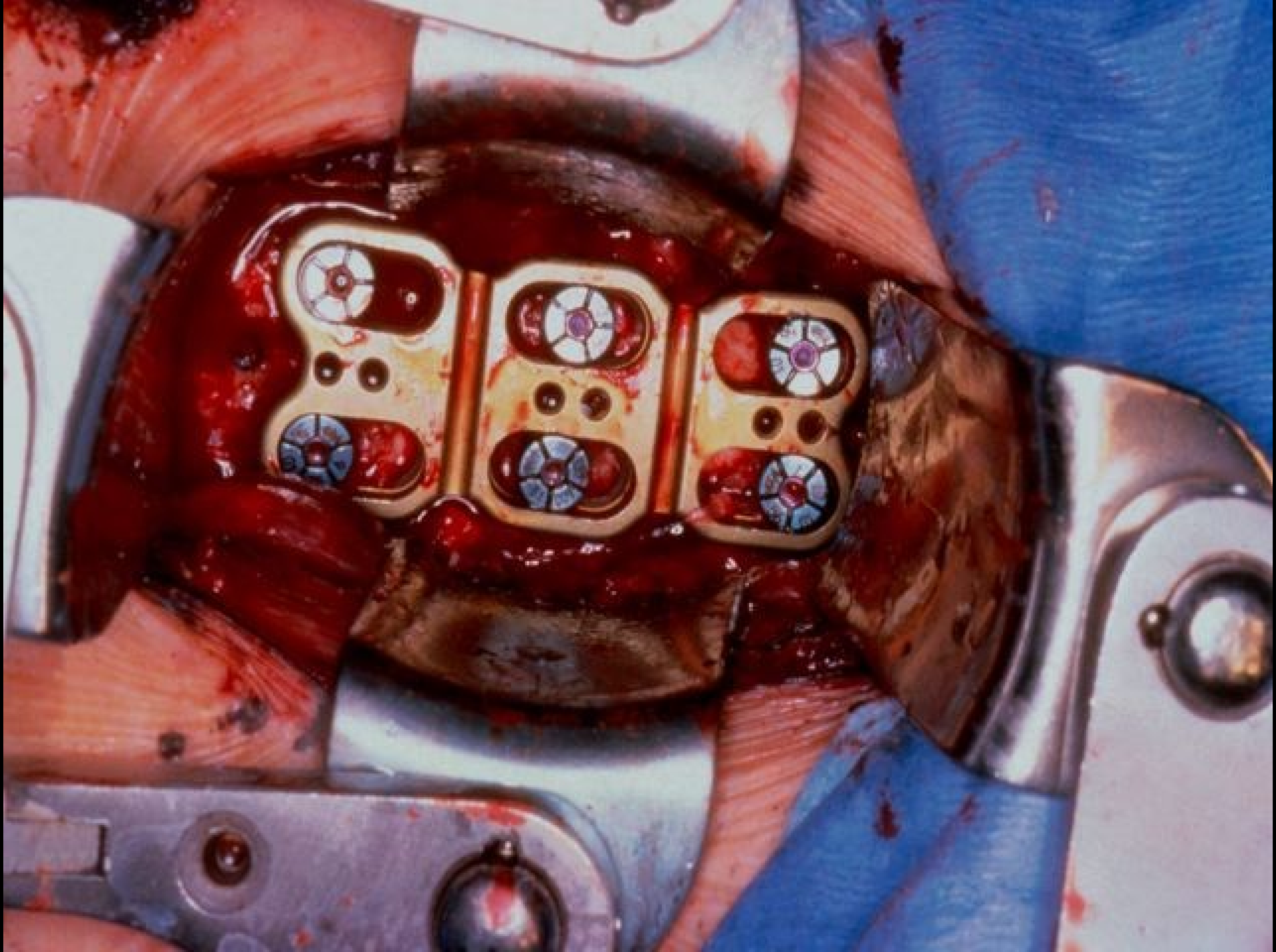
Hybrid

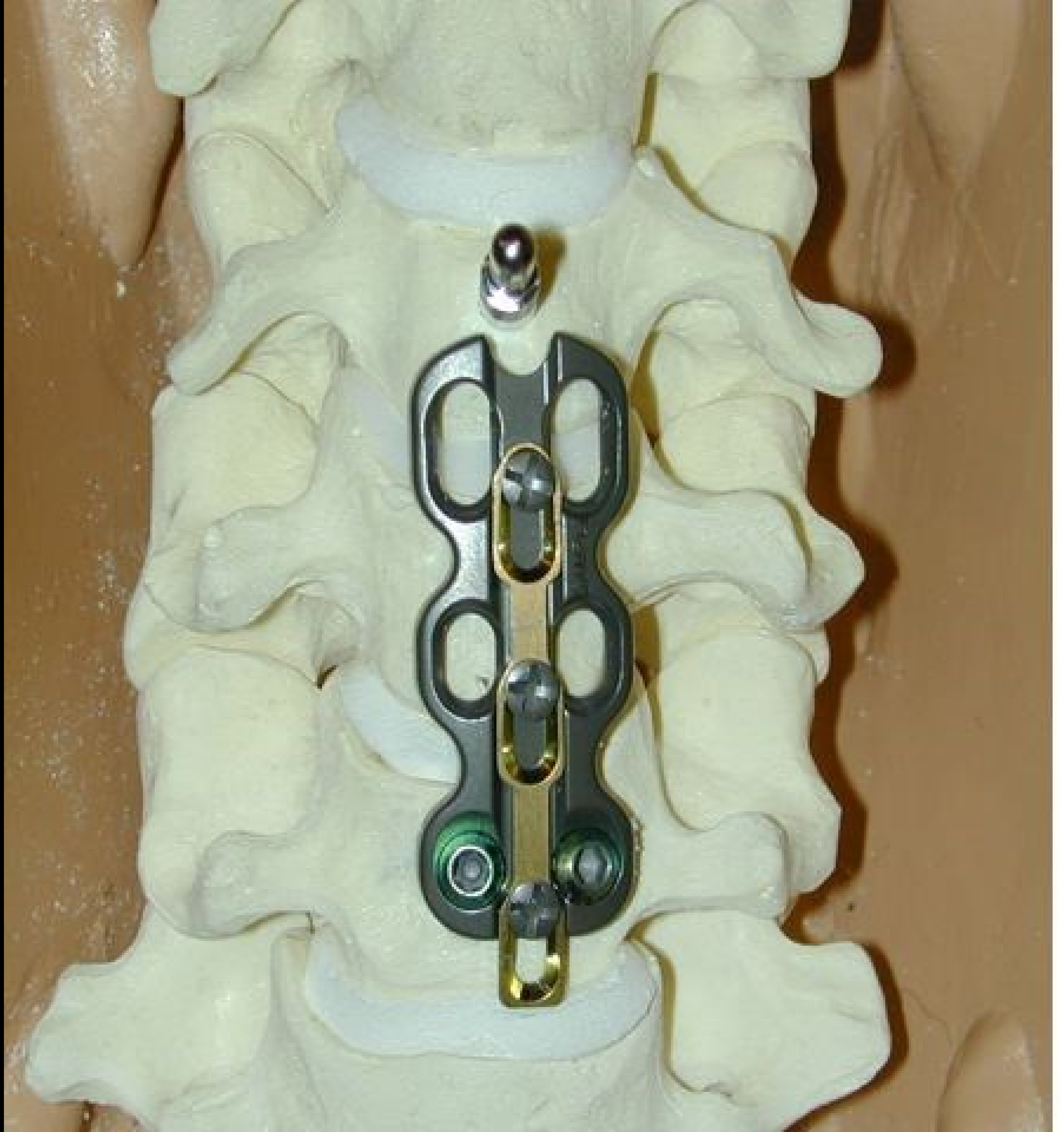



-0130


T 20
0130



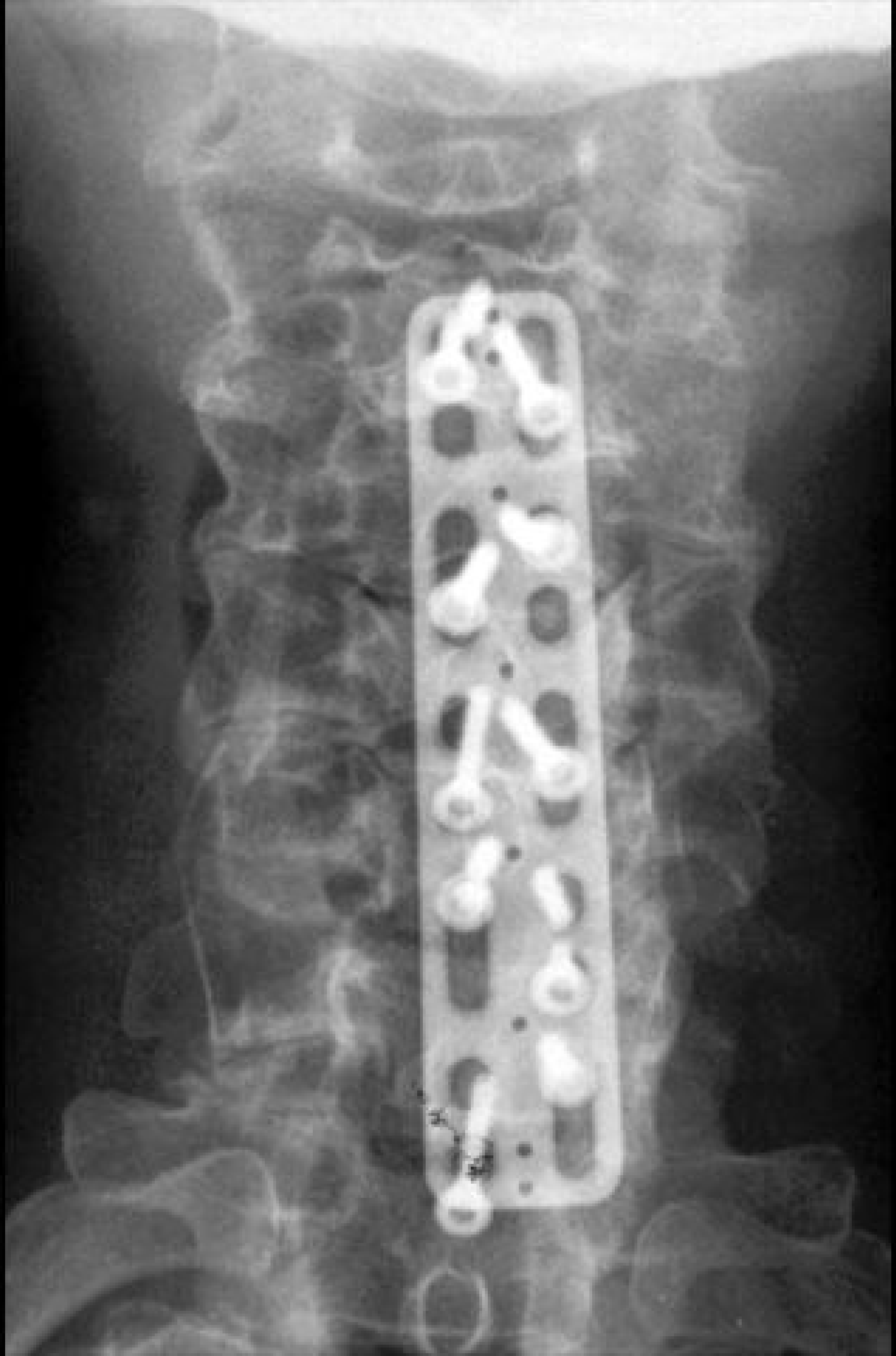




CONSTRUCT FAILURE

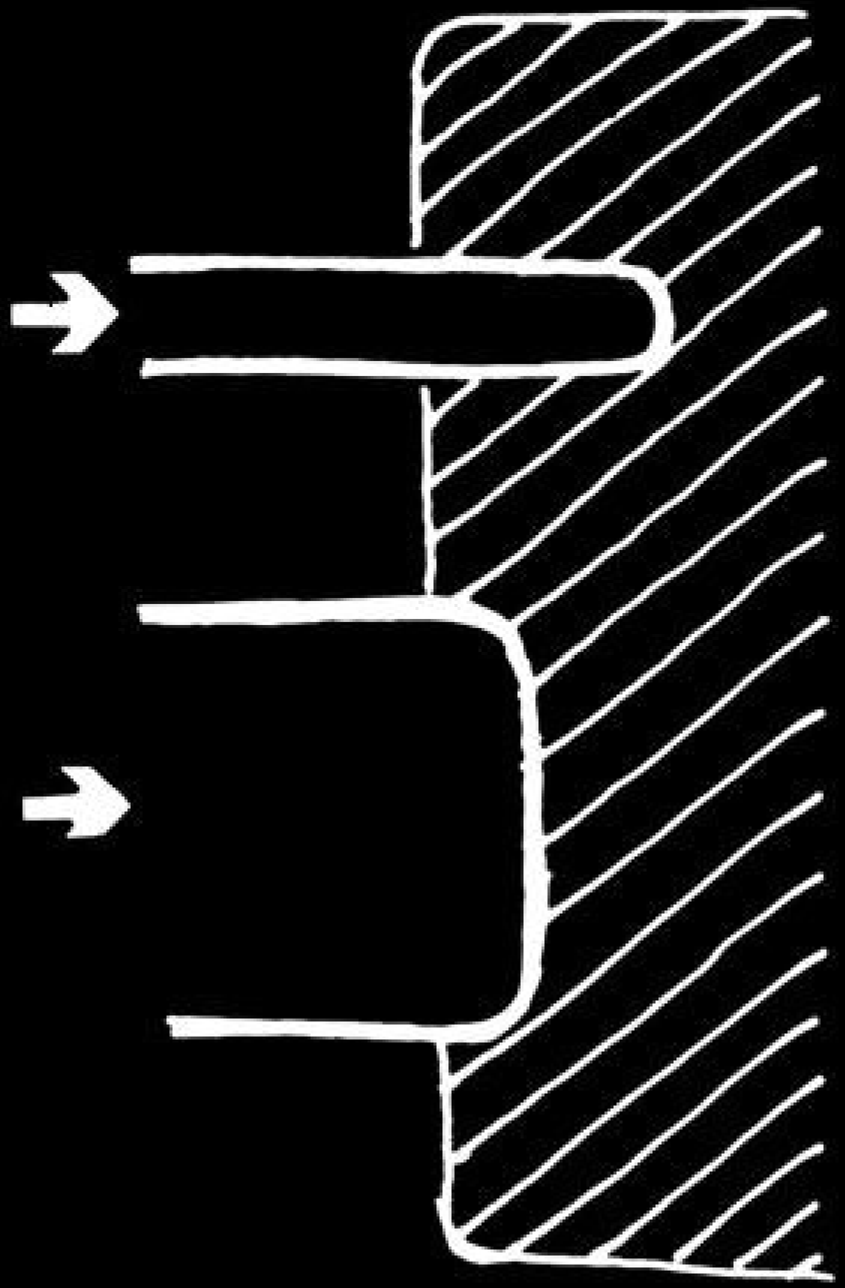
MODES OF CONSTRAINED CONSTRUCT FAILURE

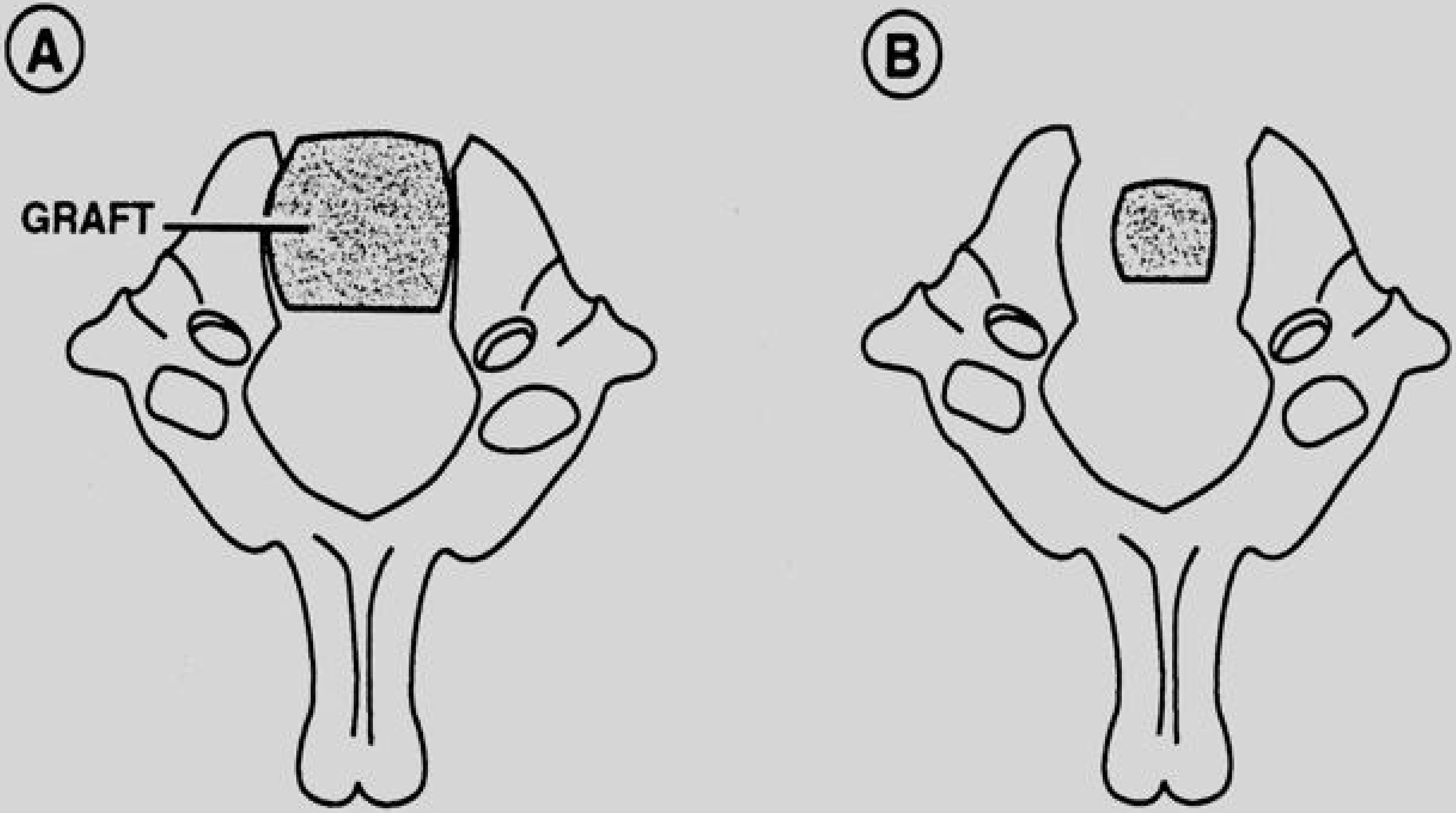
Construct Failure
Implant Failure
Stress Shielding

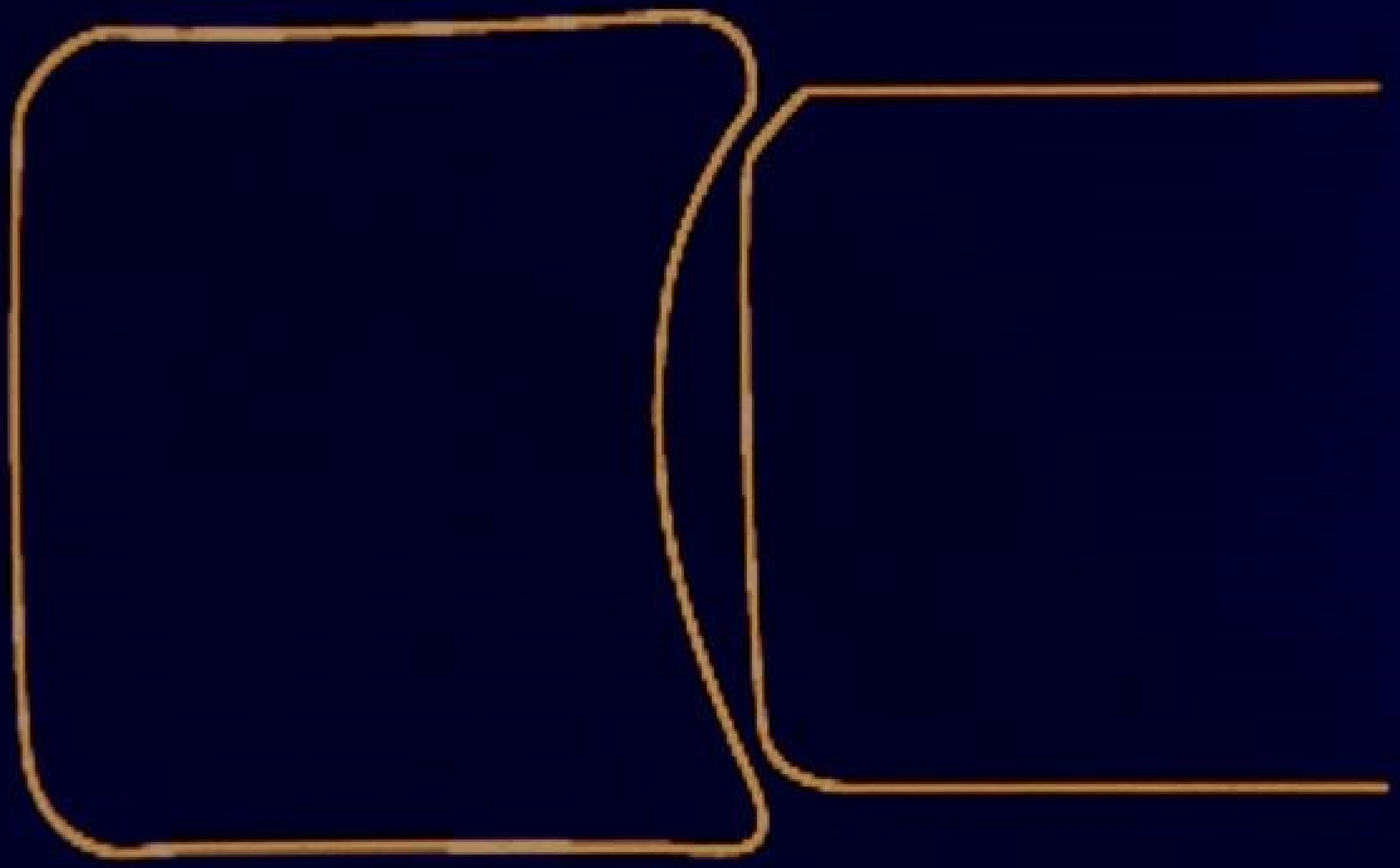


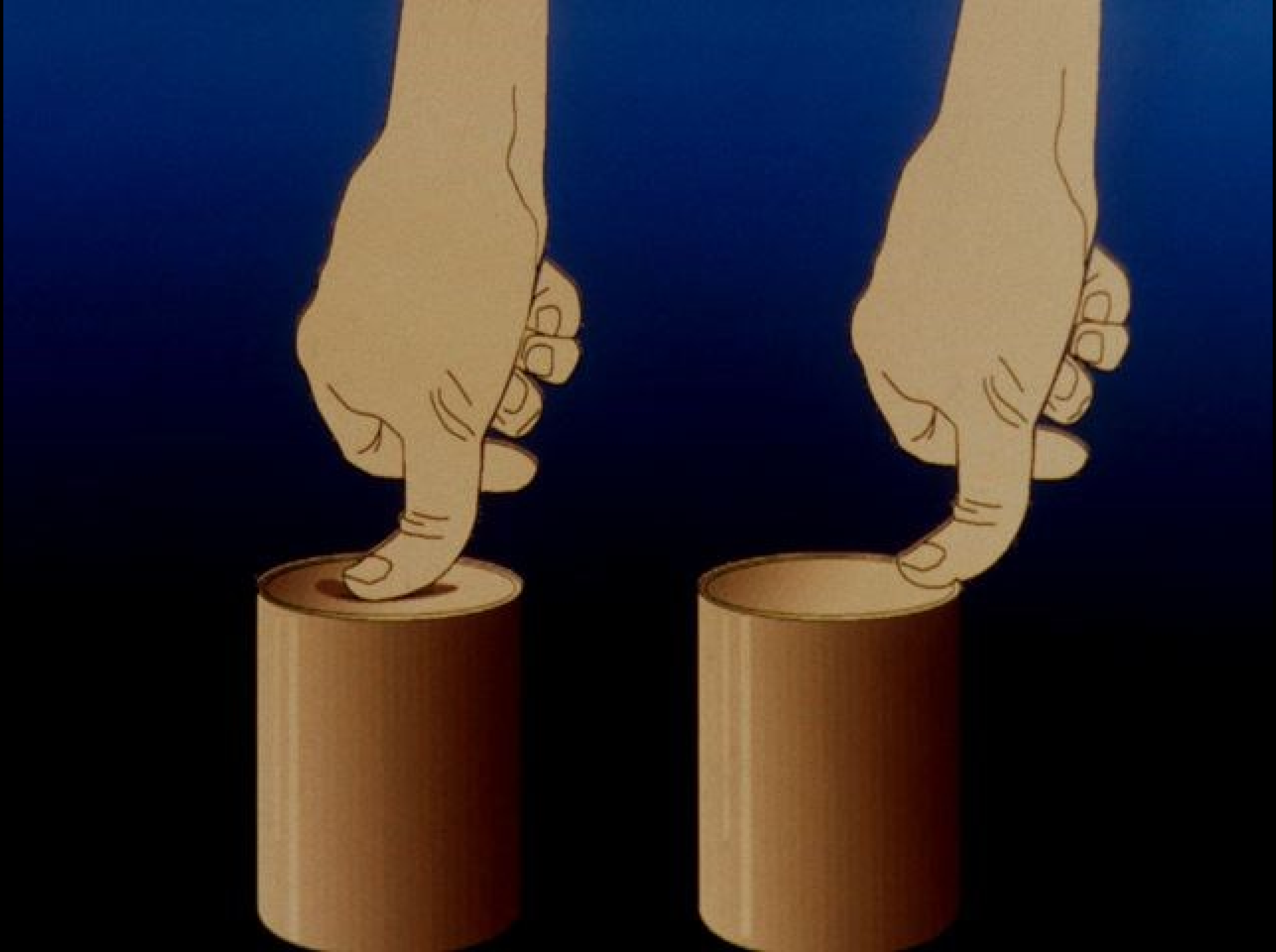
LOAD SHARING
versus
LOAD BEARING

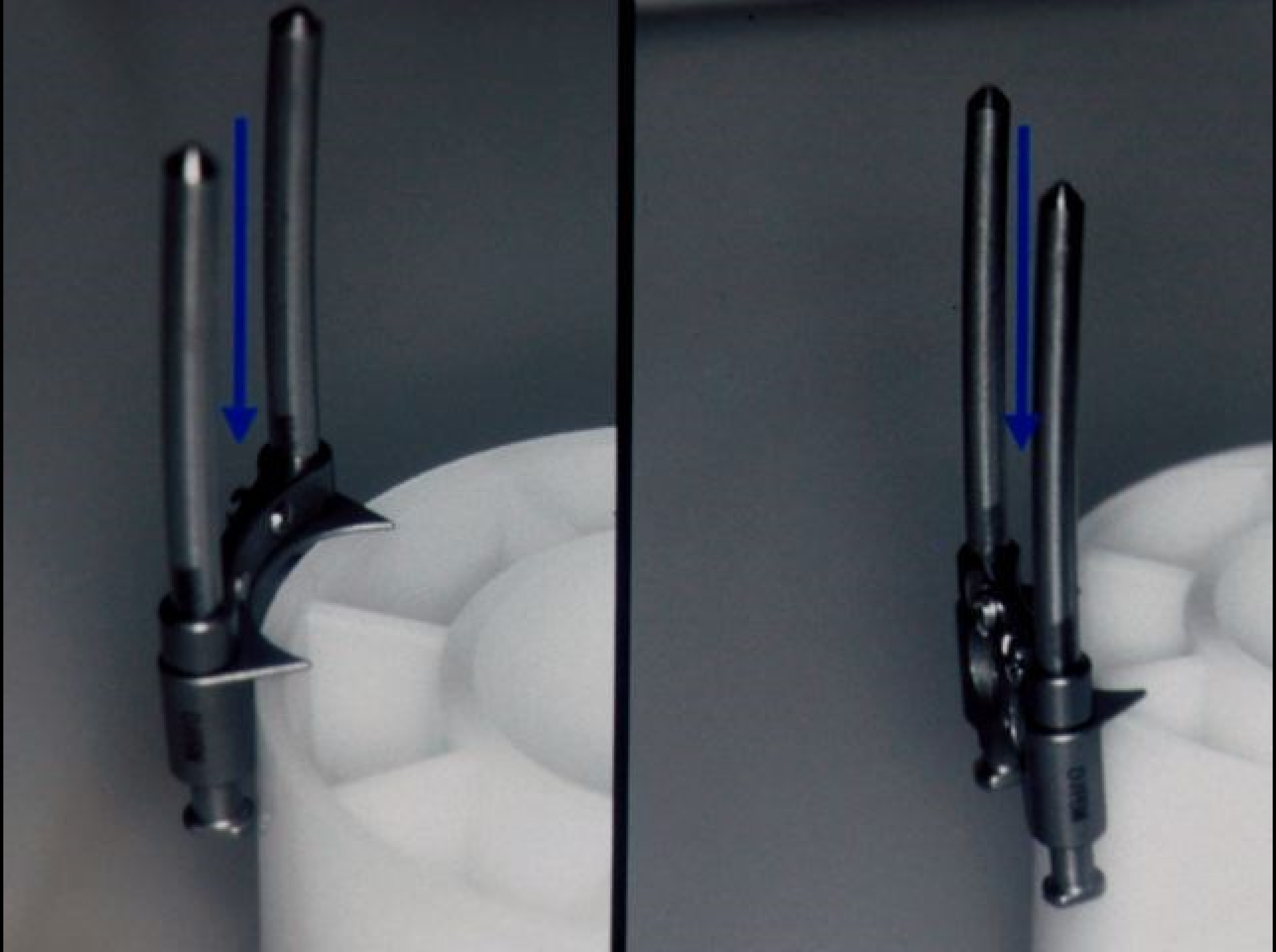
THE BIOMECHANICS OF FAILURE

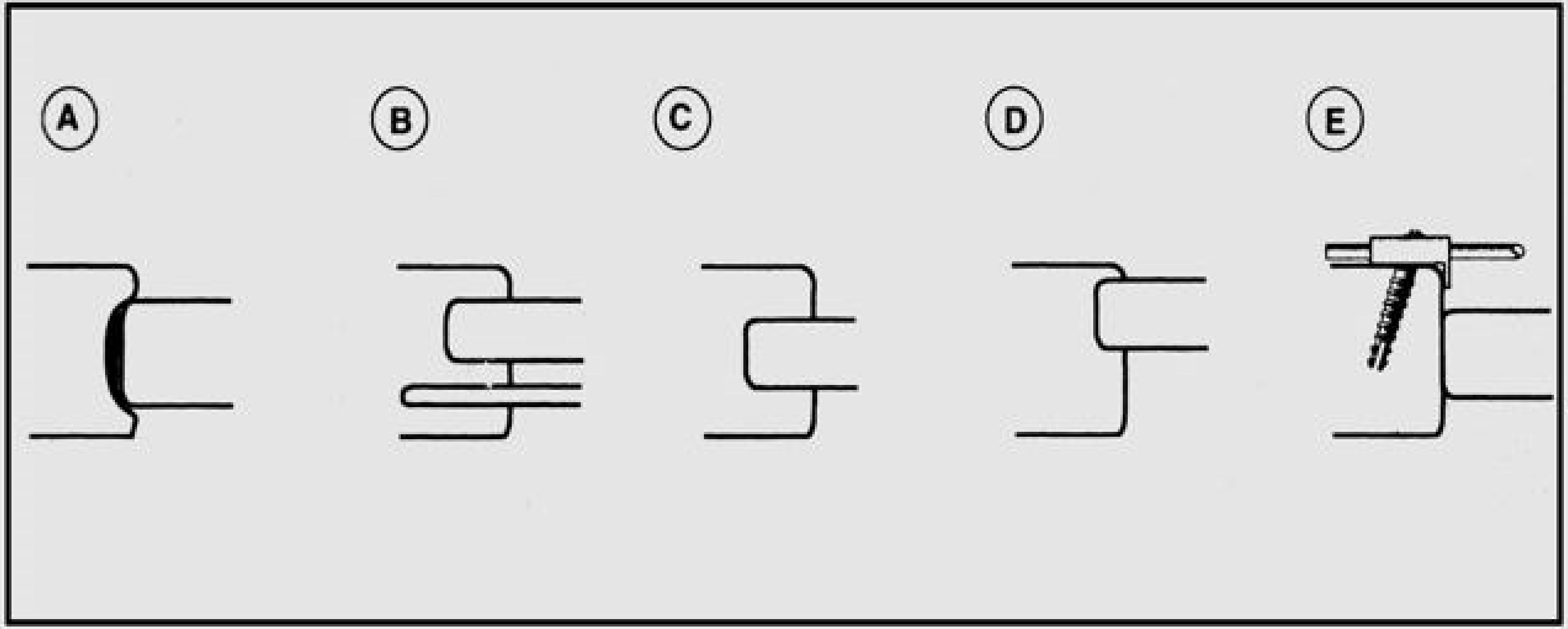



A
GRAFT
B



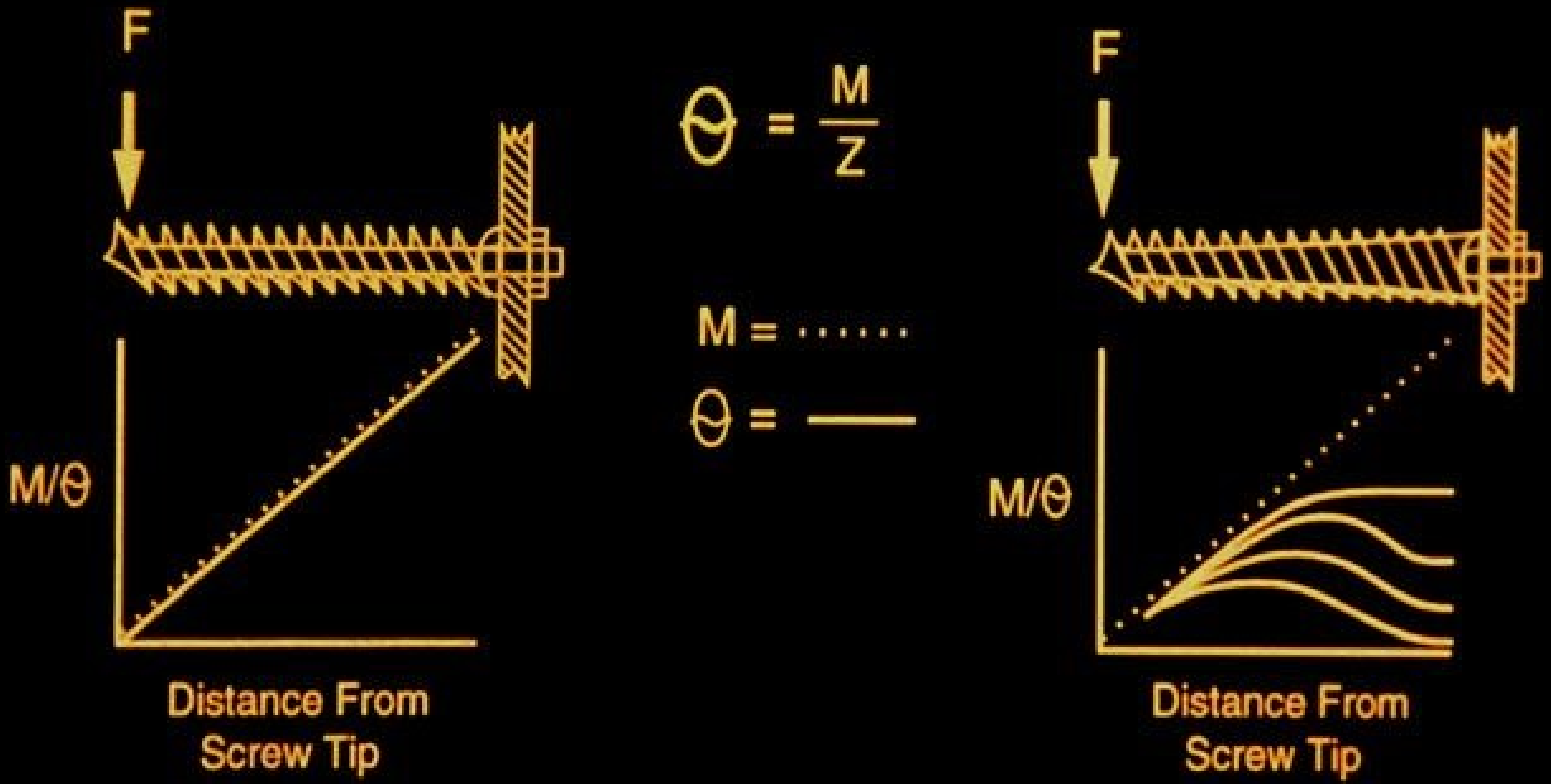


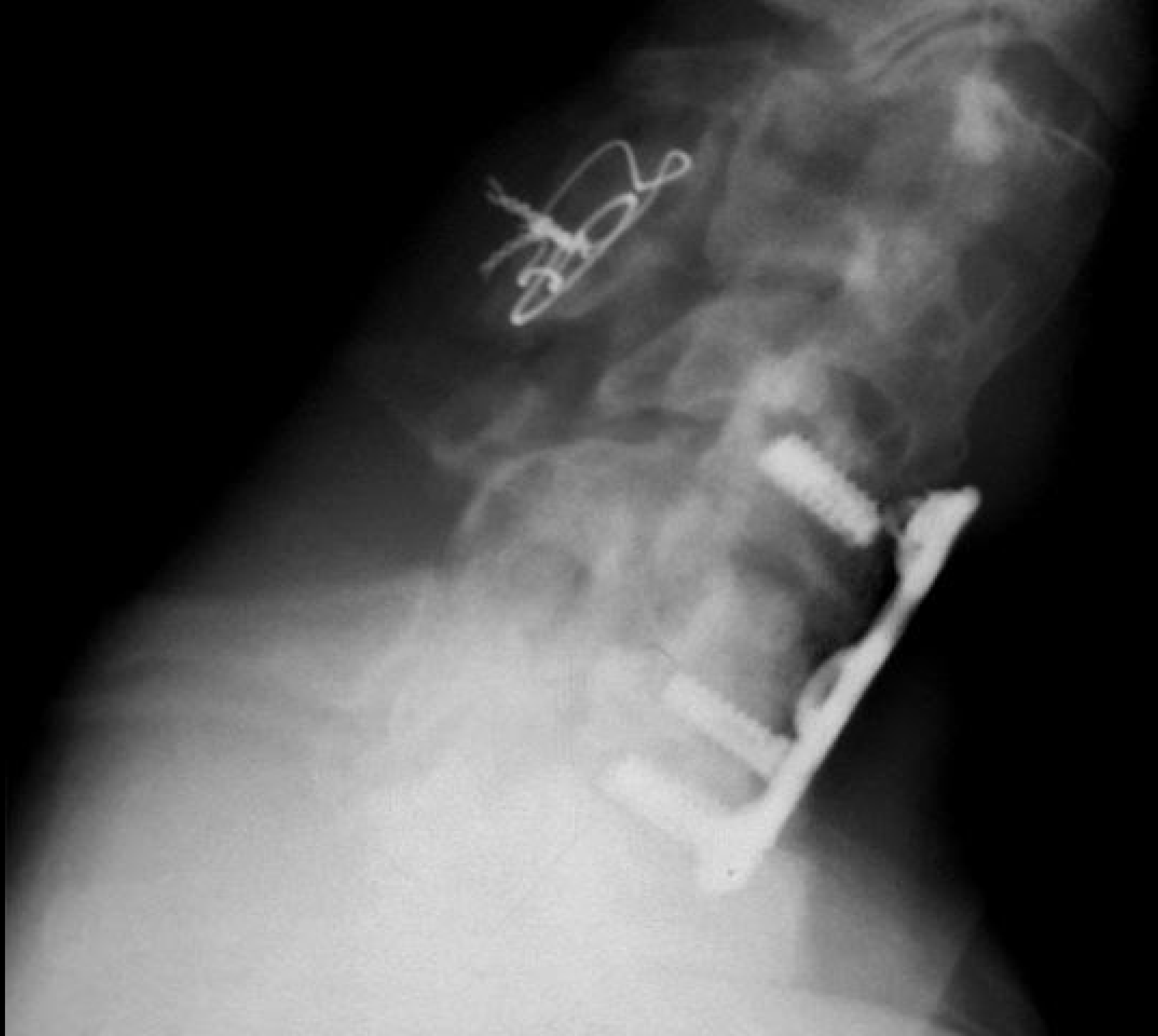


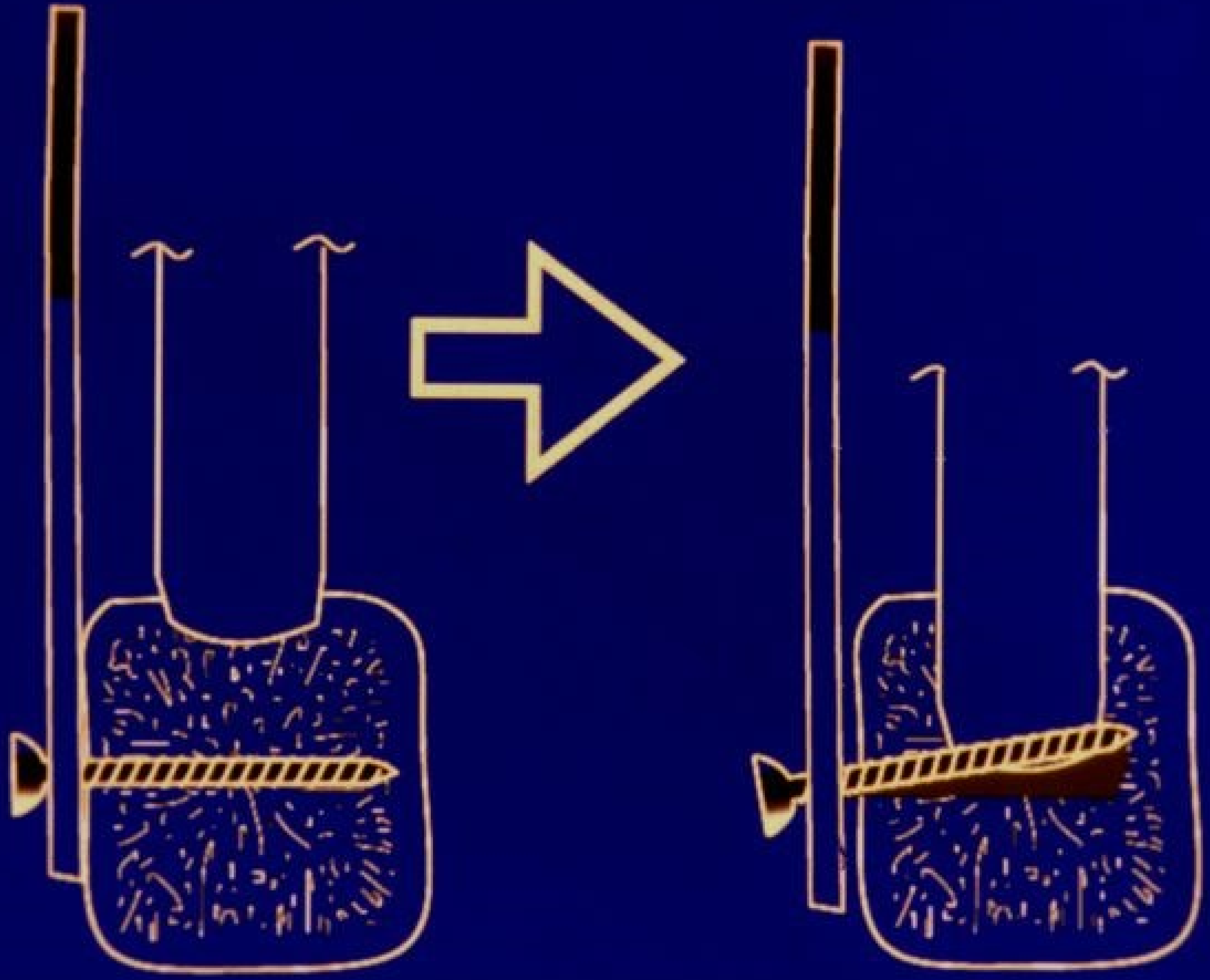

A
B
C
D
E

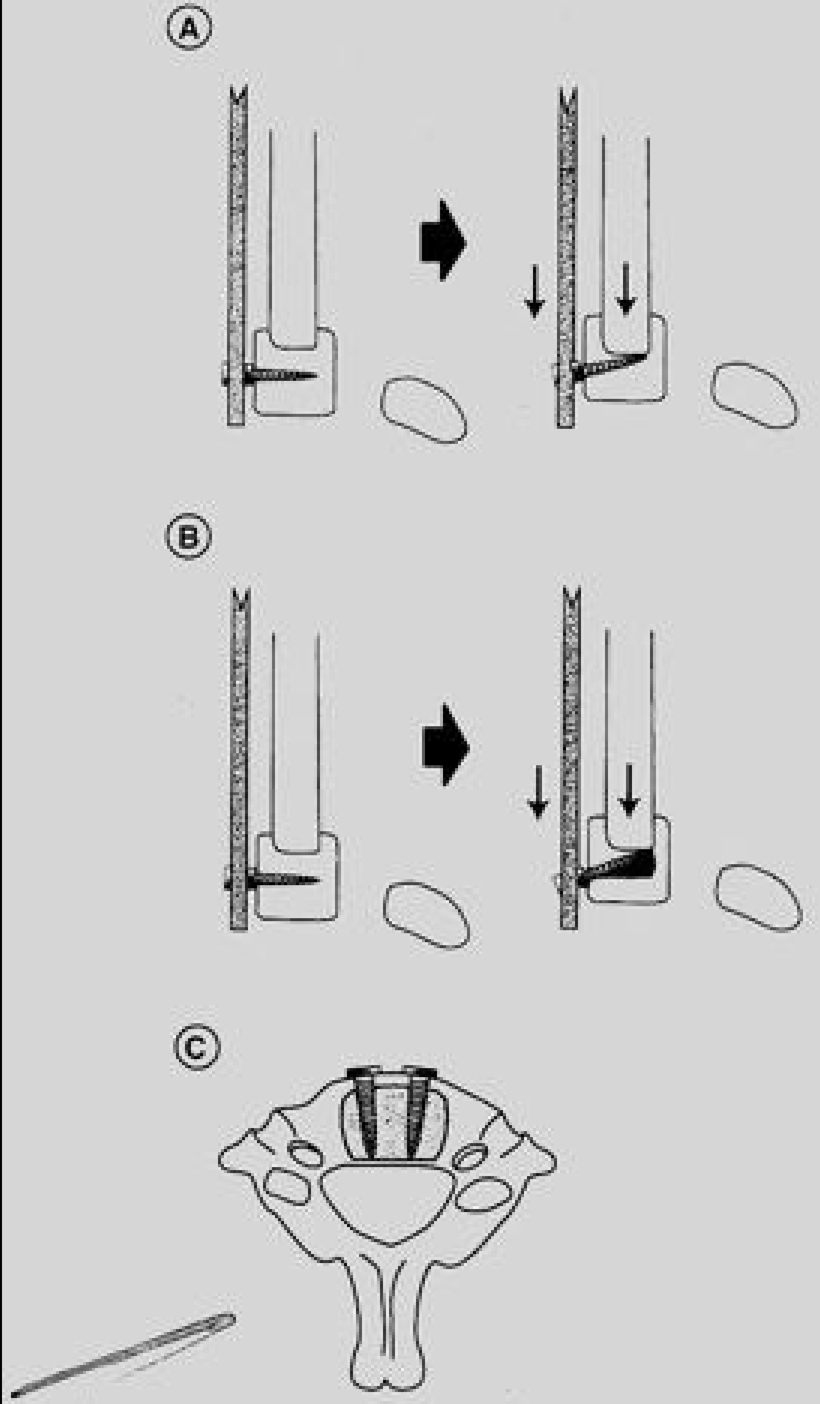
$$\text{Ƶ} \sim D^3$$

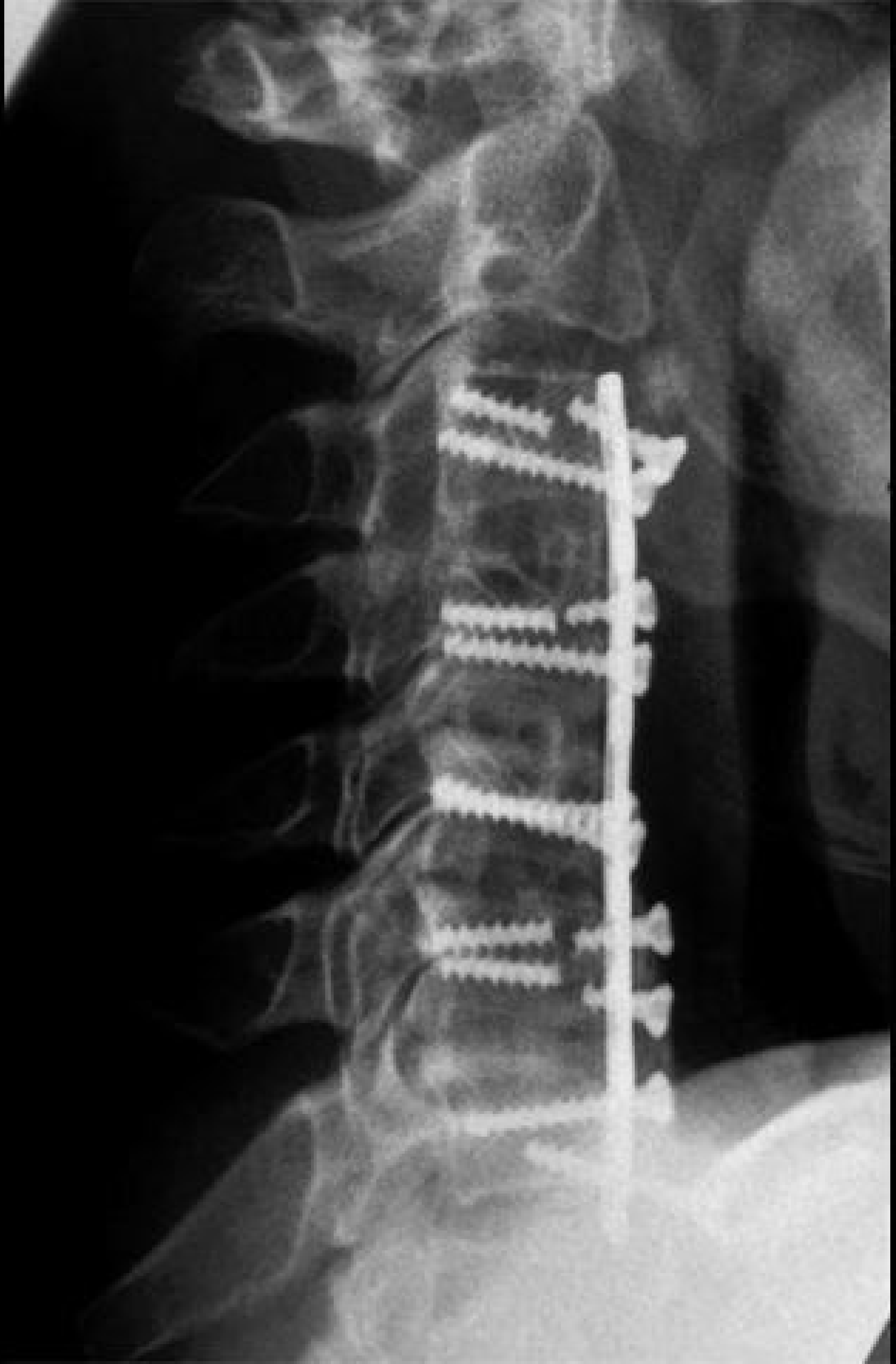
$$\theta = \frac{M}{Z}$$

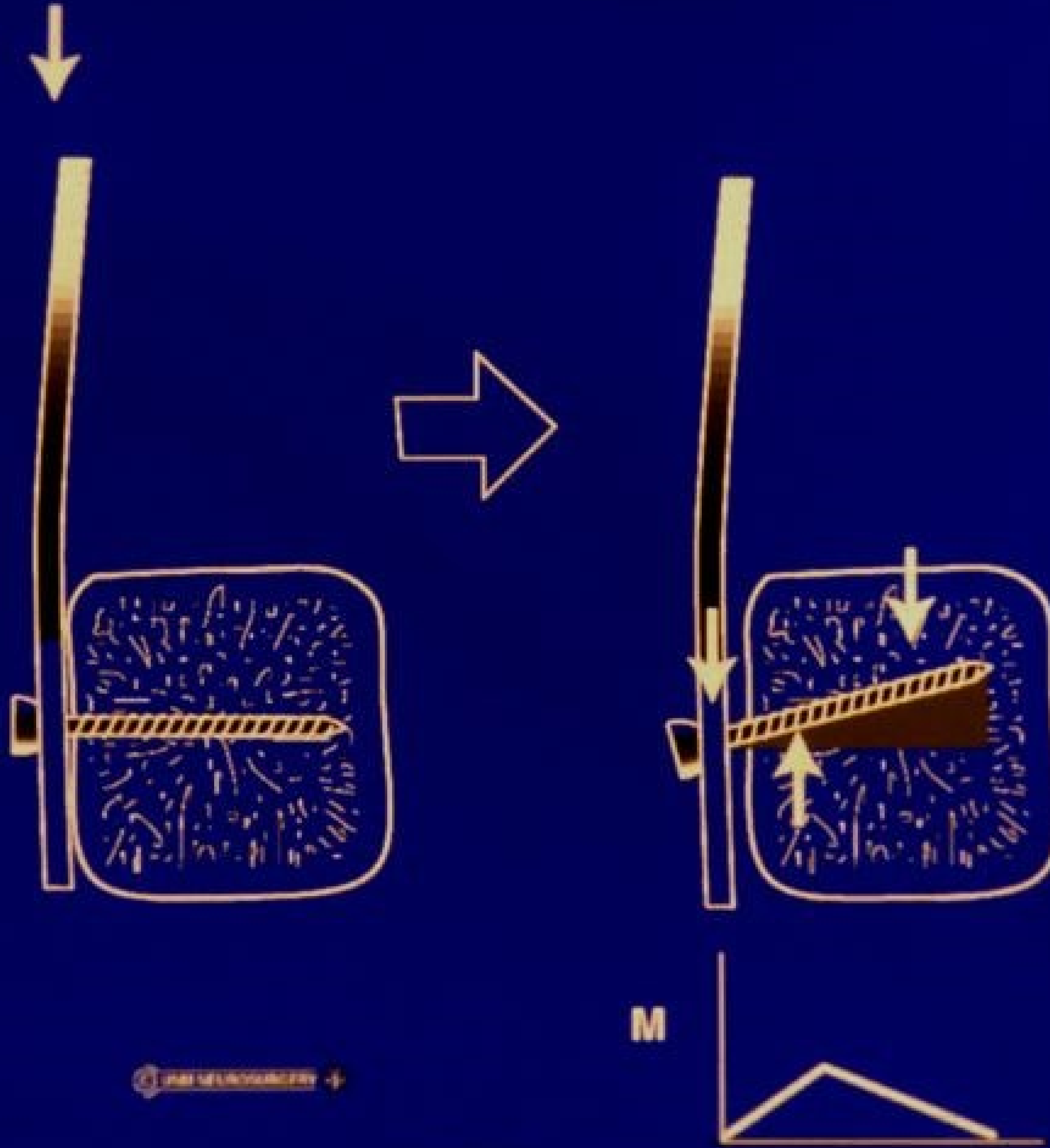

F
Θ = M/Z
M = ...
Θ = ——
M/Θ
Distance From Screw Tip
F
M/Θ
Distance From Screw Tip






A
B
C




M

TWO INFREQUENTLY CONSIDERED FACTORS

Bone Graft Loading and Unloading

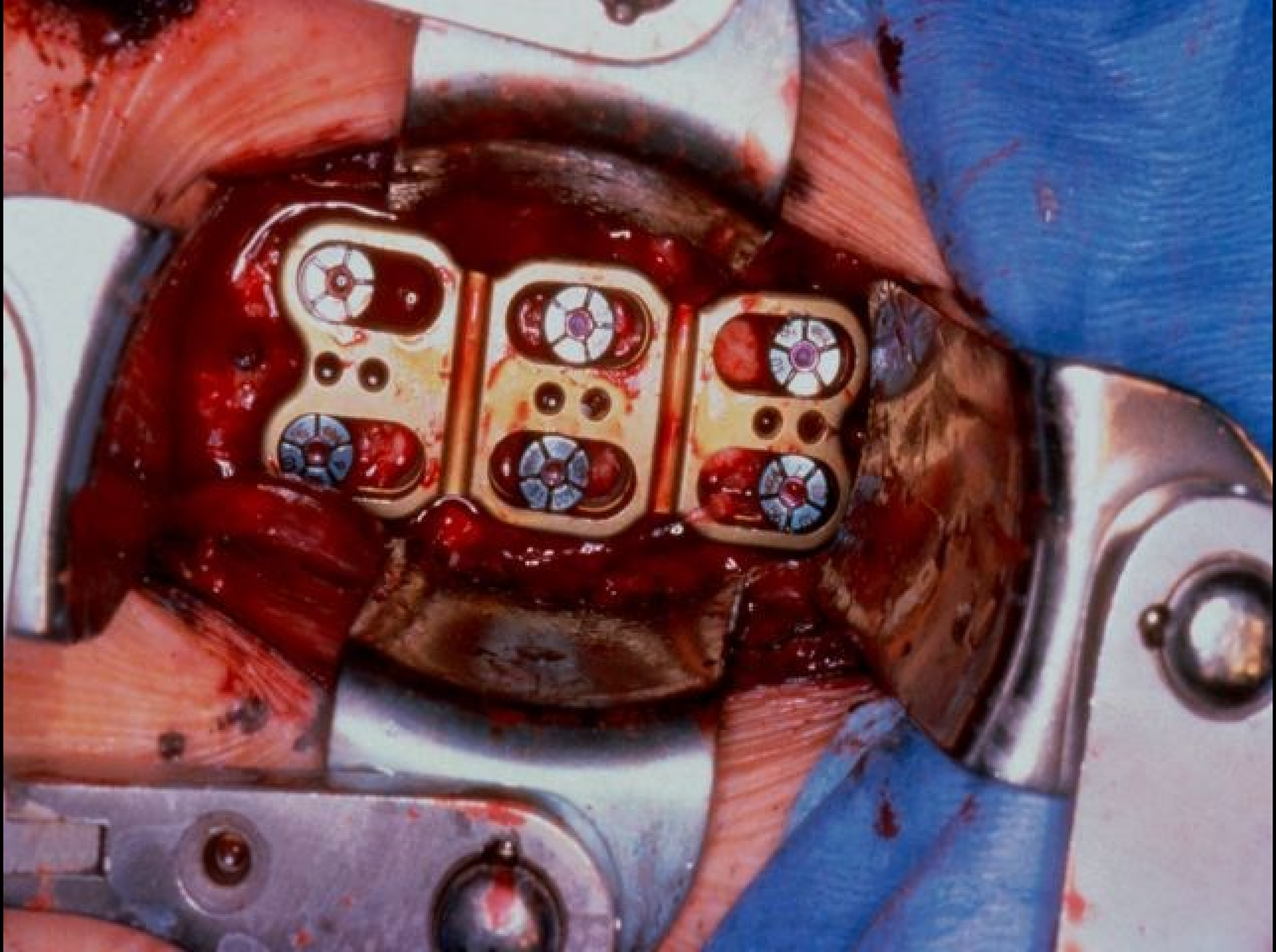
Exposure to Multiple Loading Patterns and Modes

LOADING THE BONE GRAFT

Significant Loading and Unloading
in
Flexion
and
Extension

Buffered by Dynamic Implant

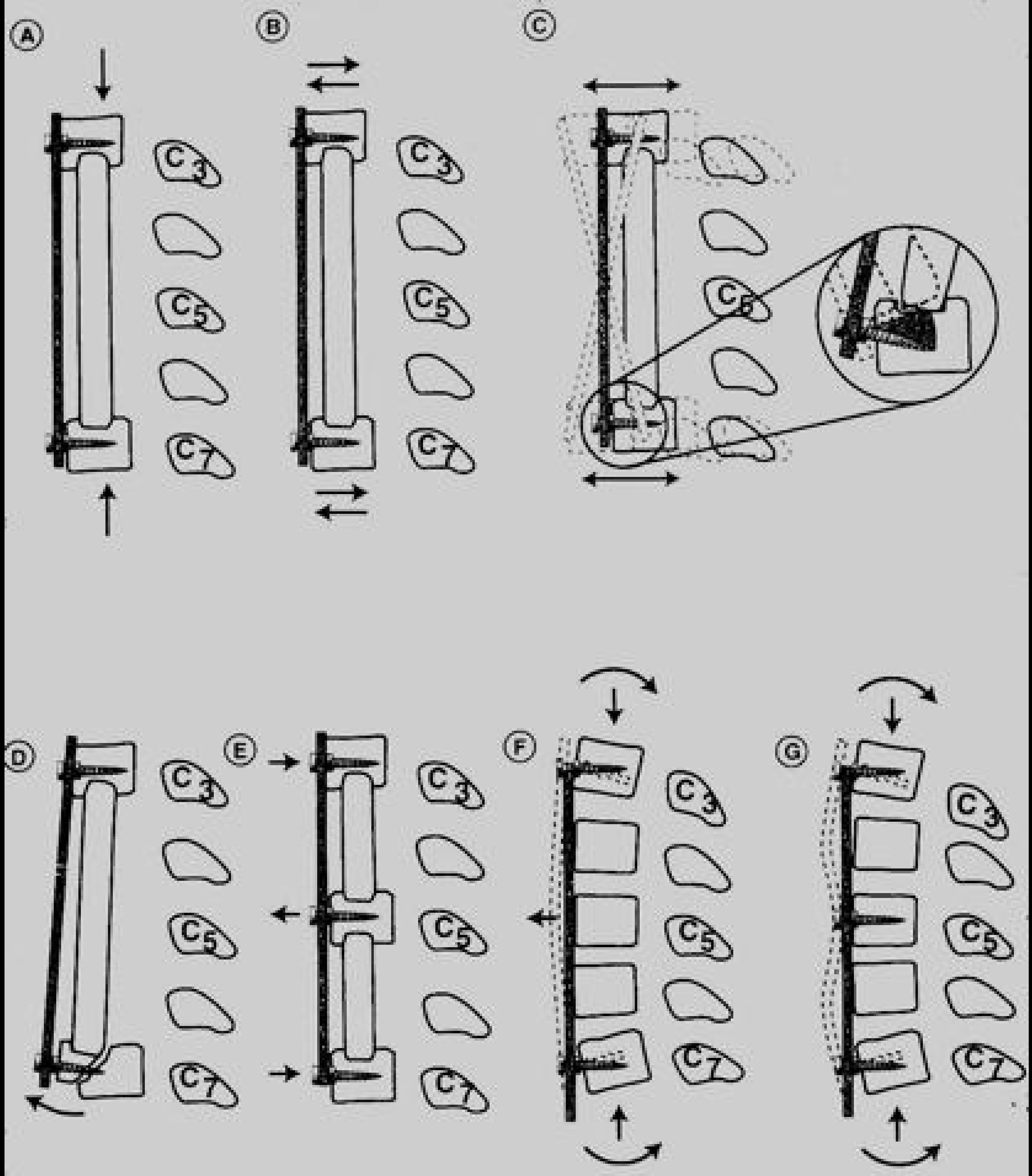
DiAngelo and Foley

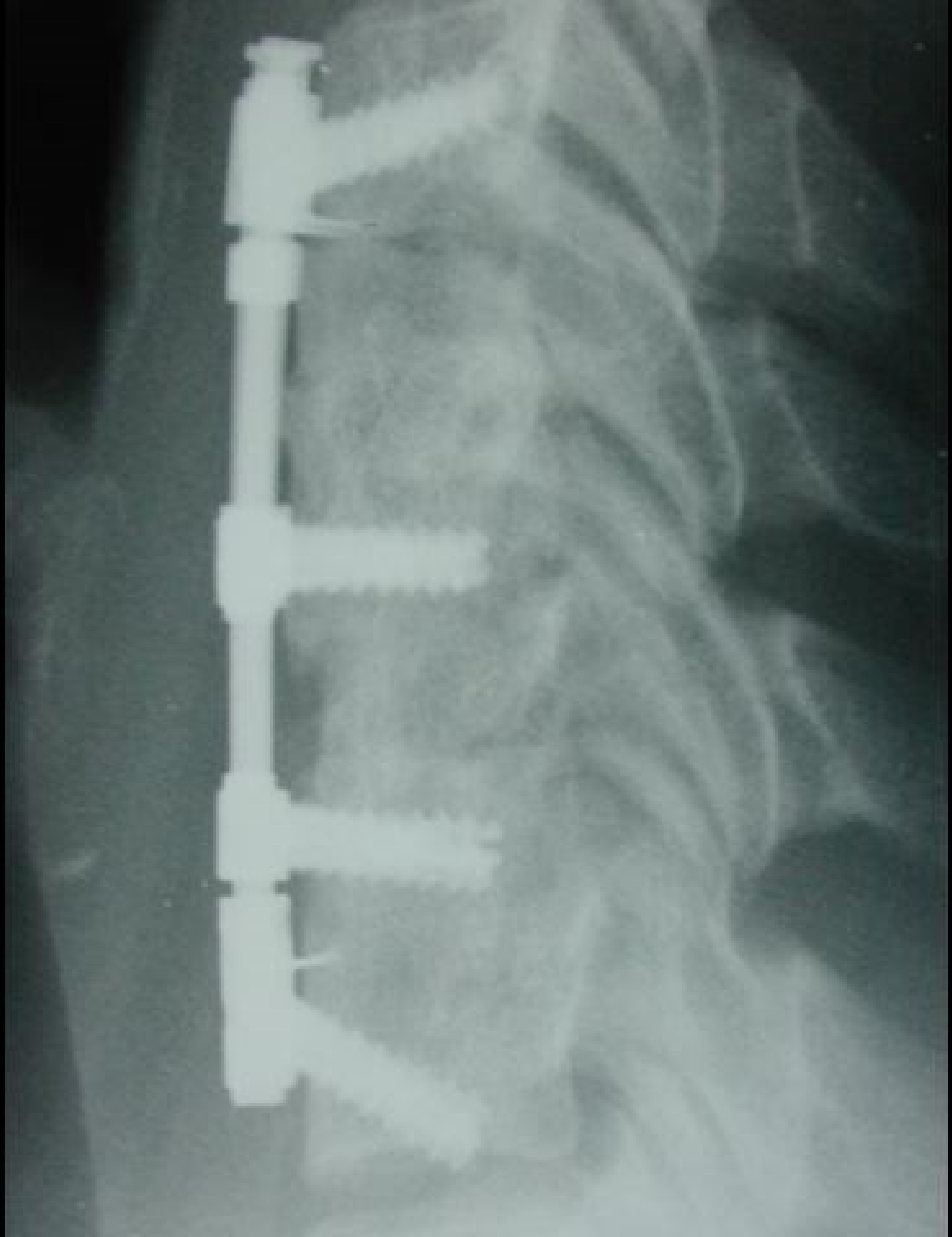


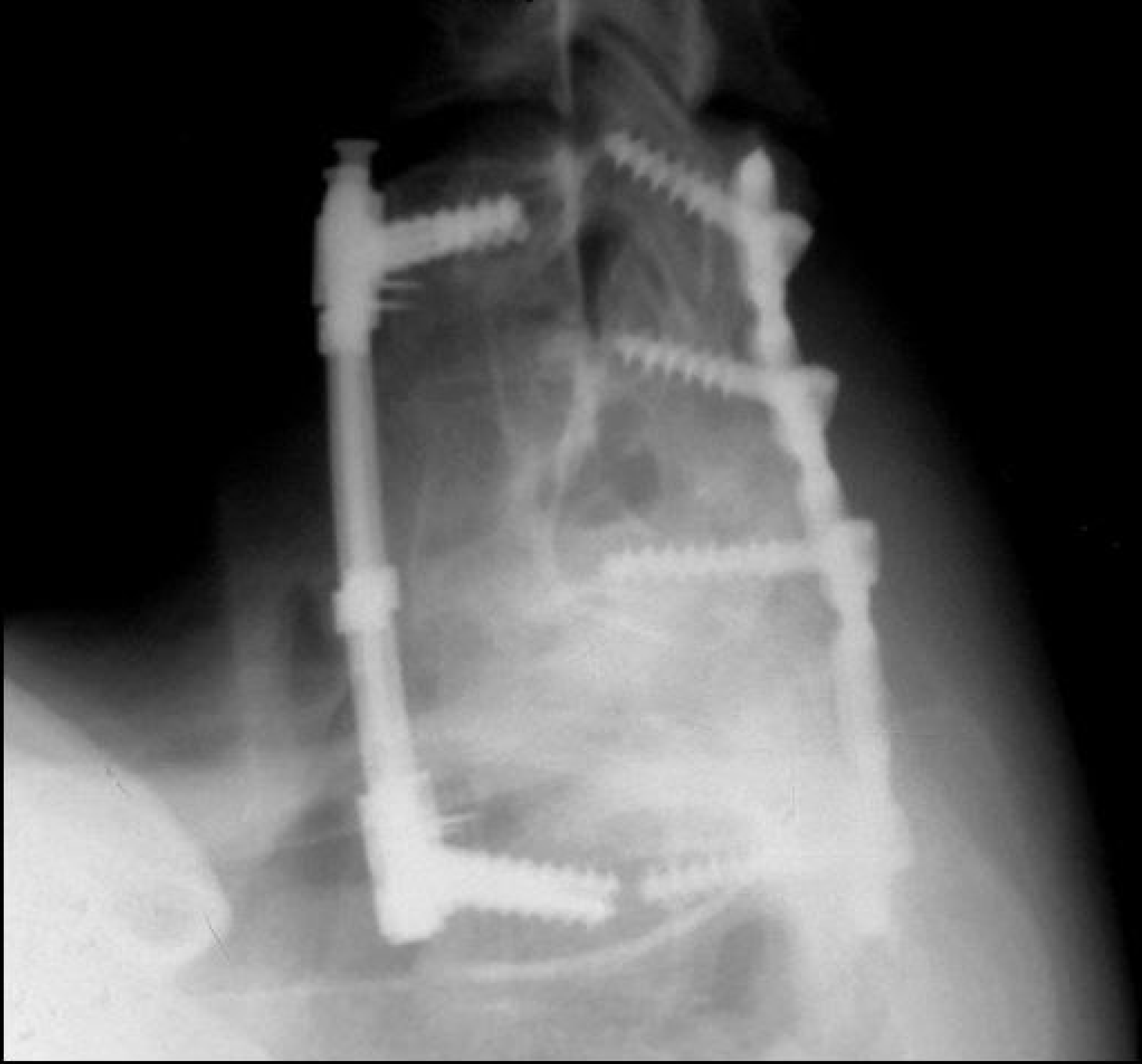
IMPLANTS FUNCTION
DIFFERENTLY
UNDER DIFFERING
LOADING CONDITIONS

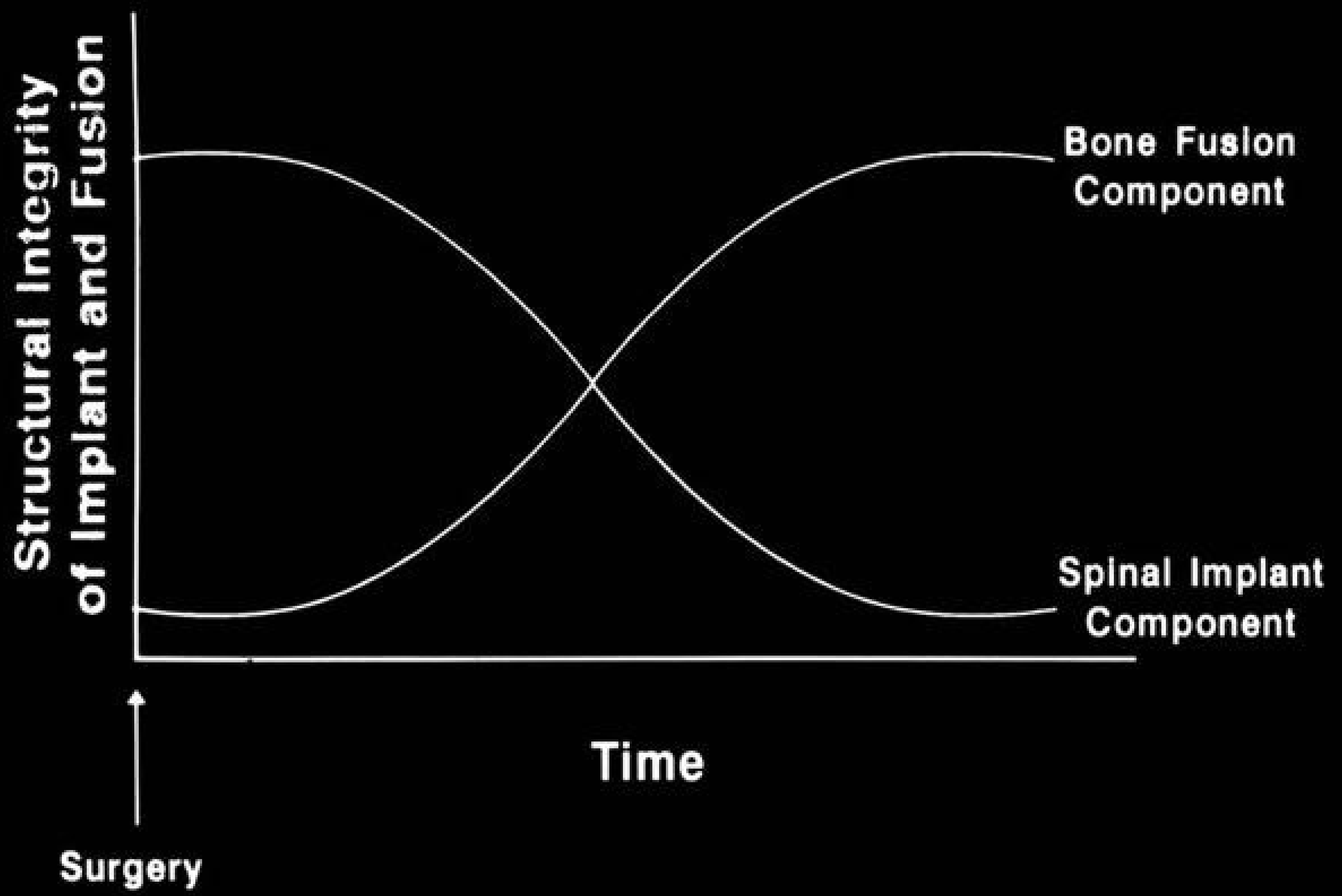
LOADING MODES

Distraction
Tension-Band Fixation
Three-Point Bending
Cantilevers


A
C3
C5
C7
B
C3
C5
C7
C
C5
D
C3
C5
C7
E
C3
C5
C7
F
C3
C5
C7
G
C3
C5
C7

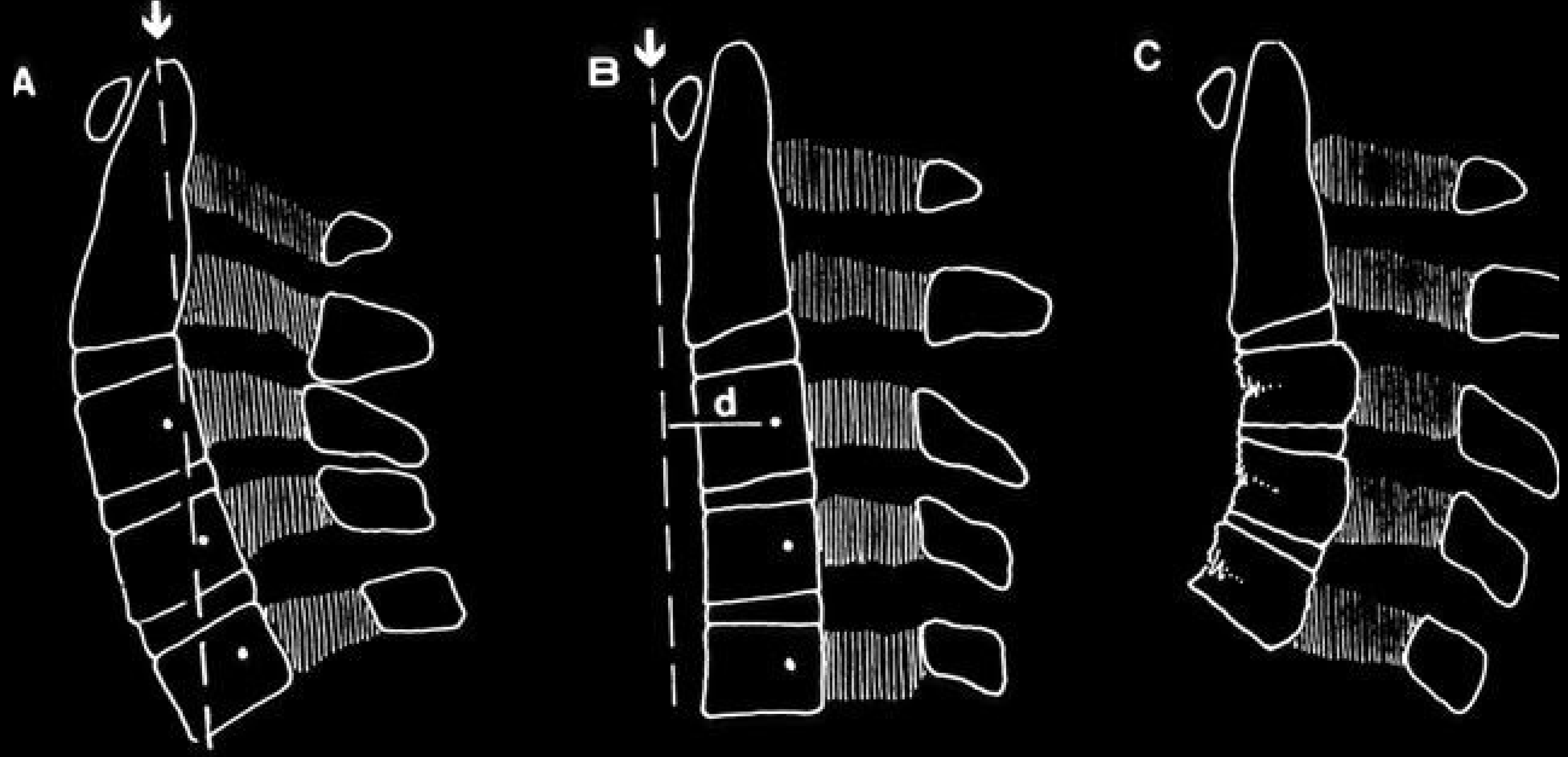





Structural Integrity
of Implant and Fusion
Bone Fusion
Component
Spinal Implant
Component
Time
Surgery

Cervical Spondylosis

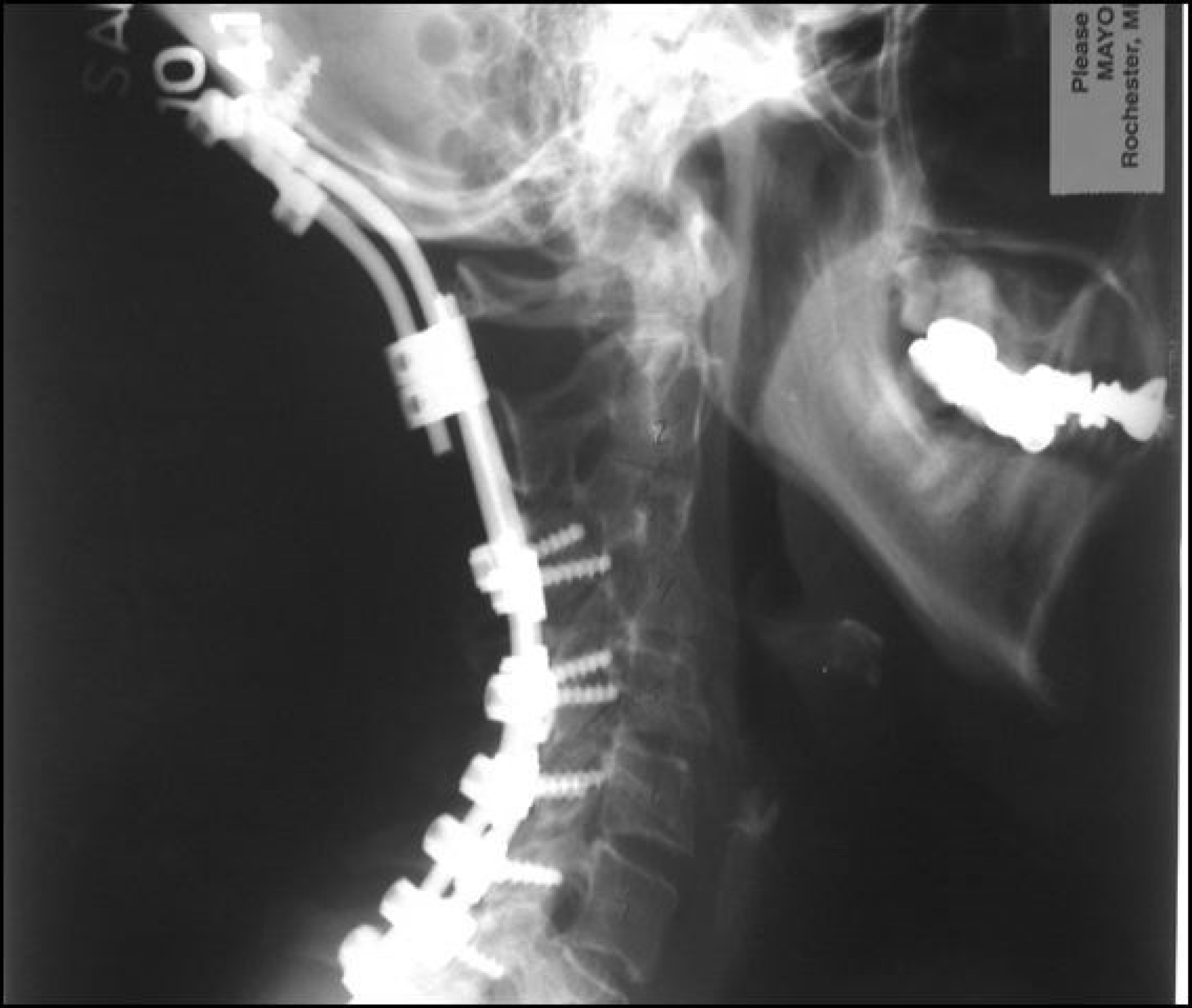
Myelopathy
Deformity


A
B
d
C

ENCROACHMENT
TETHERING

REPETETIVE TRAUMA

MATTER
OF
BALANCE


Please
MAYO
Rochester, M


PA

Intra-Operative Deformity Correction

Ventral
vs
Dorsal

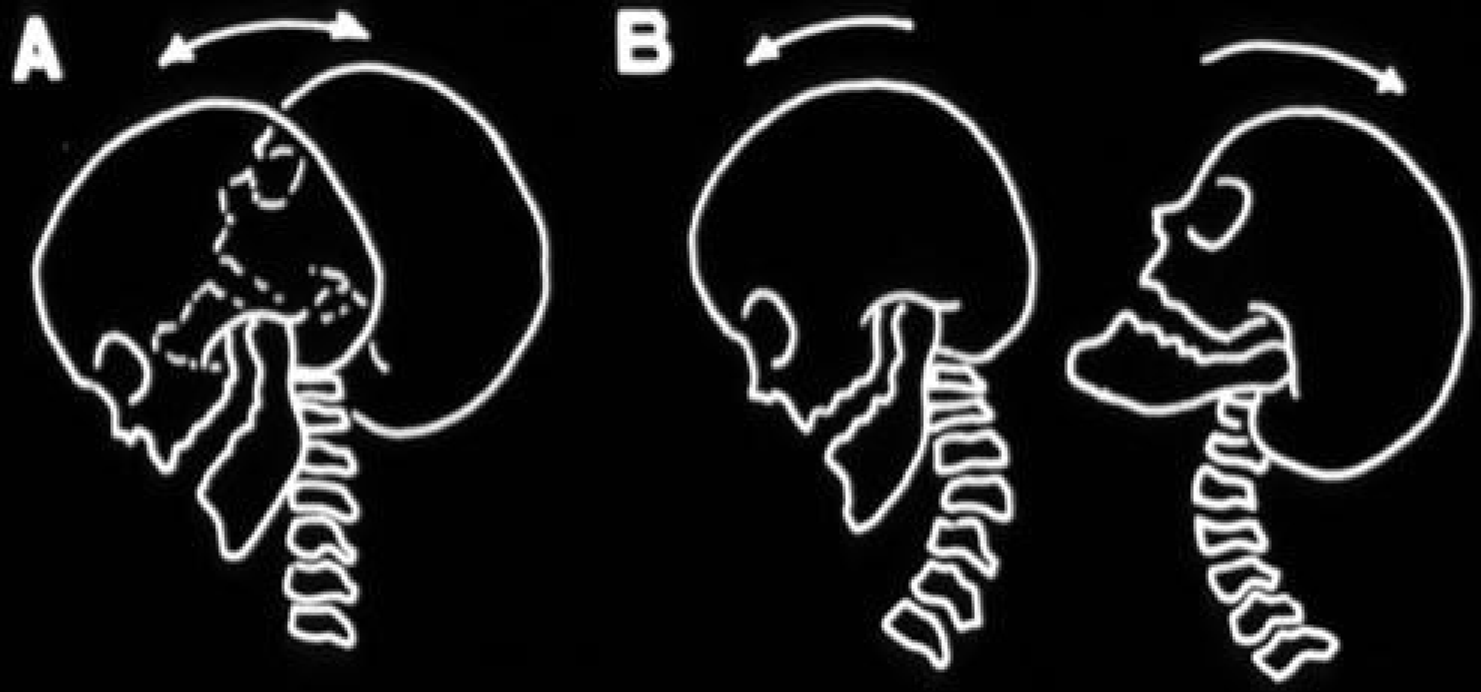
Its all about the leverage!!!

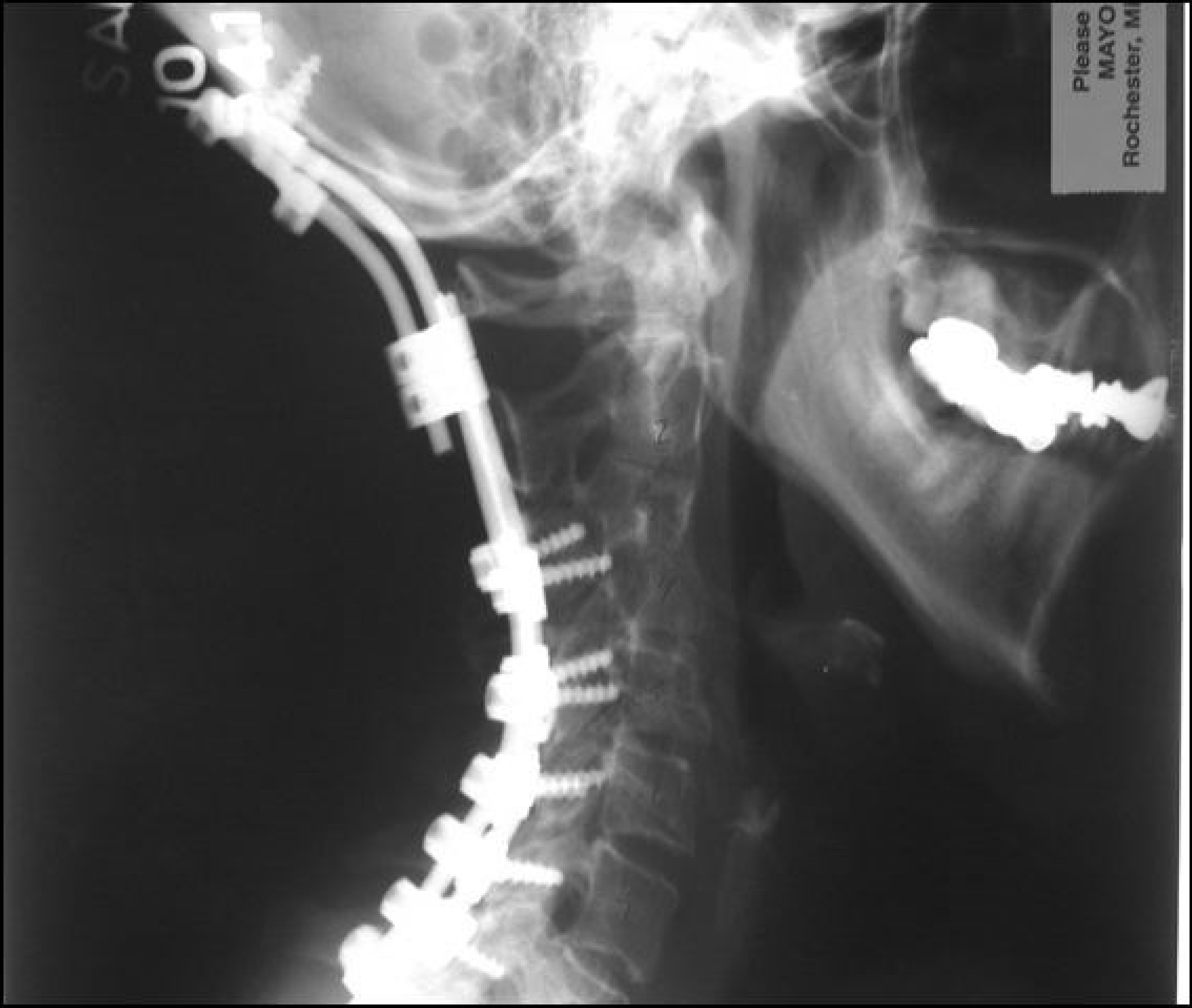
Dorsally, leverage is VEEEERRRYYYY difficult to achieve!!!

Polyaxial Screws

Exception

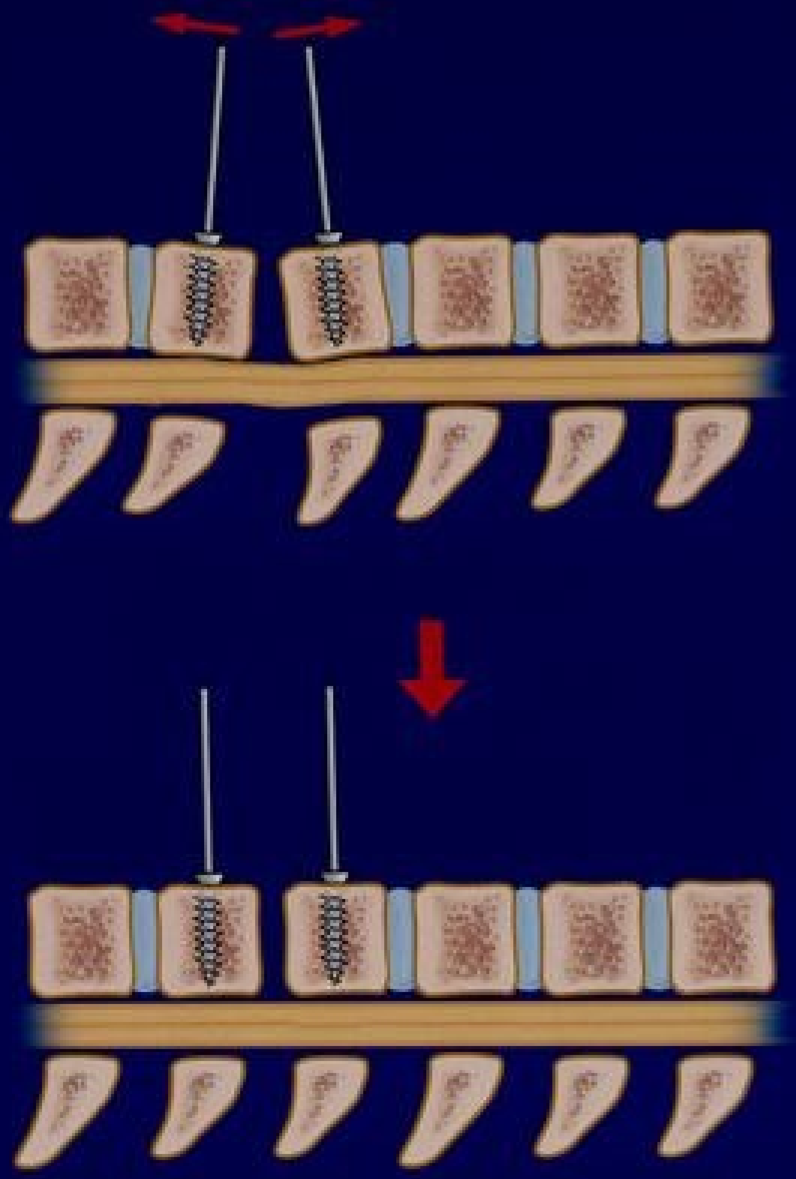
Capital Flexion and Extension

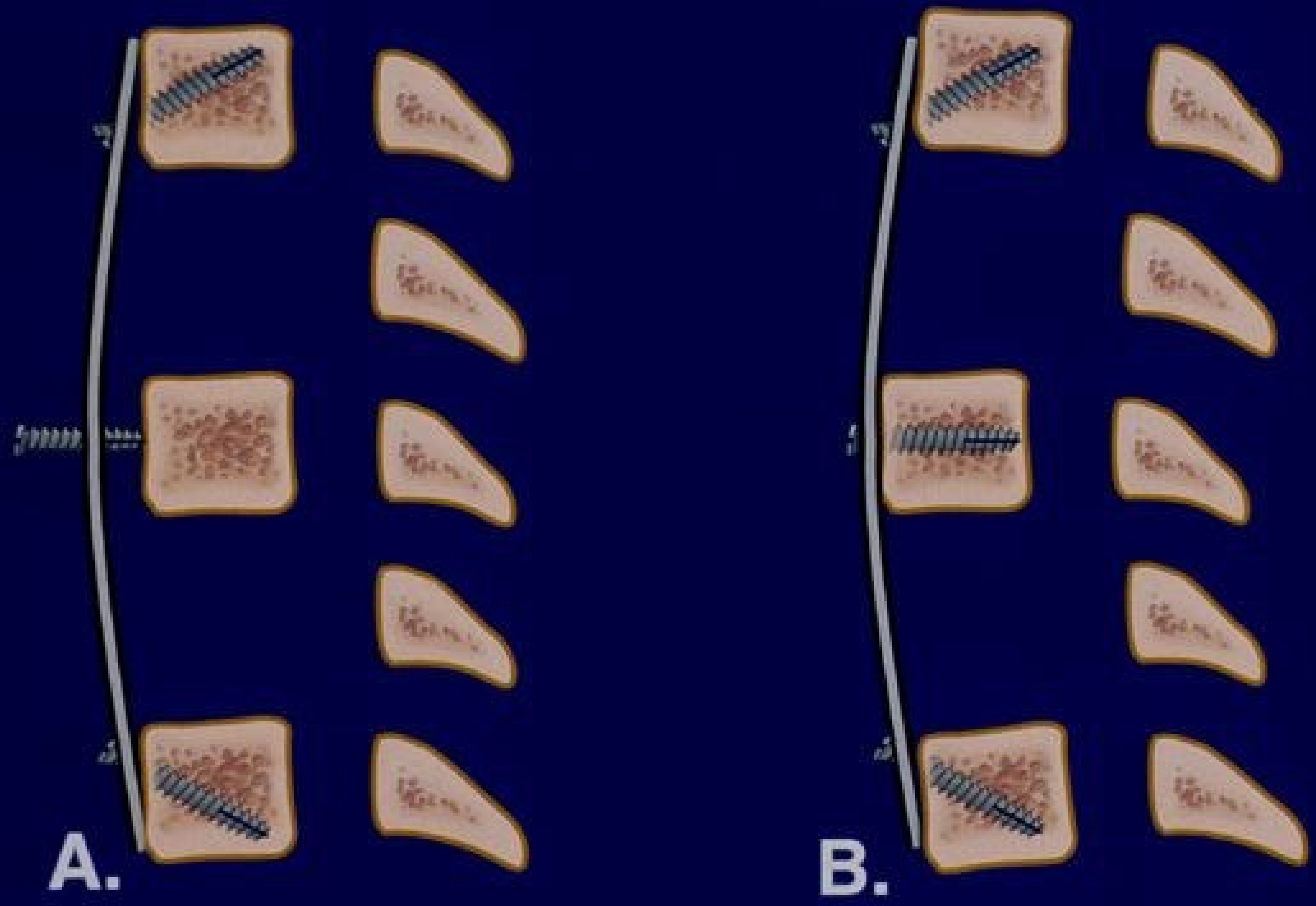



Please
MAYO
Rochester,

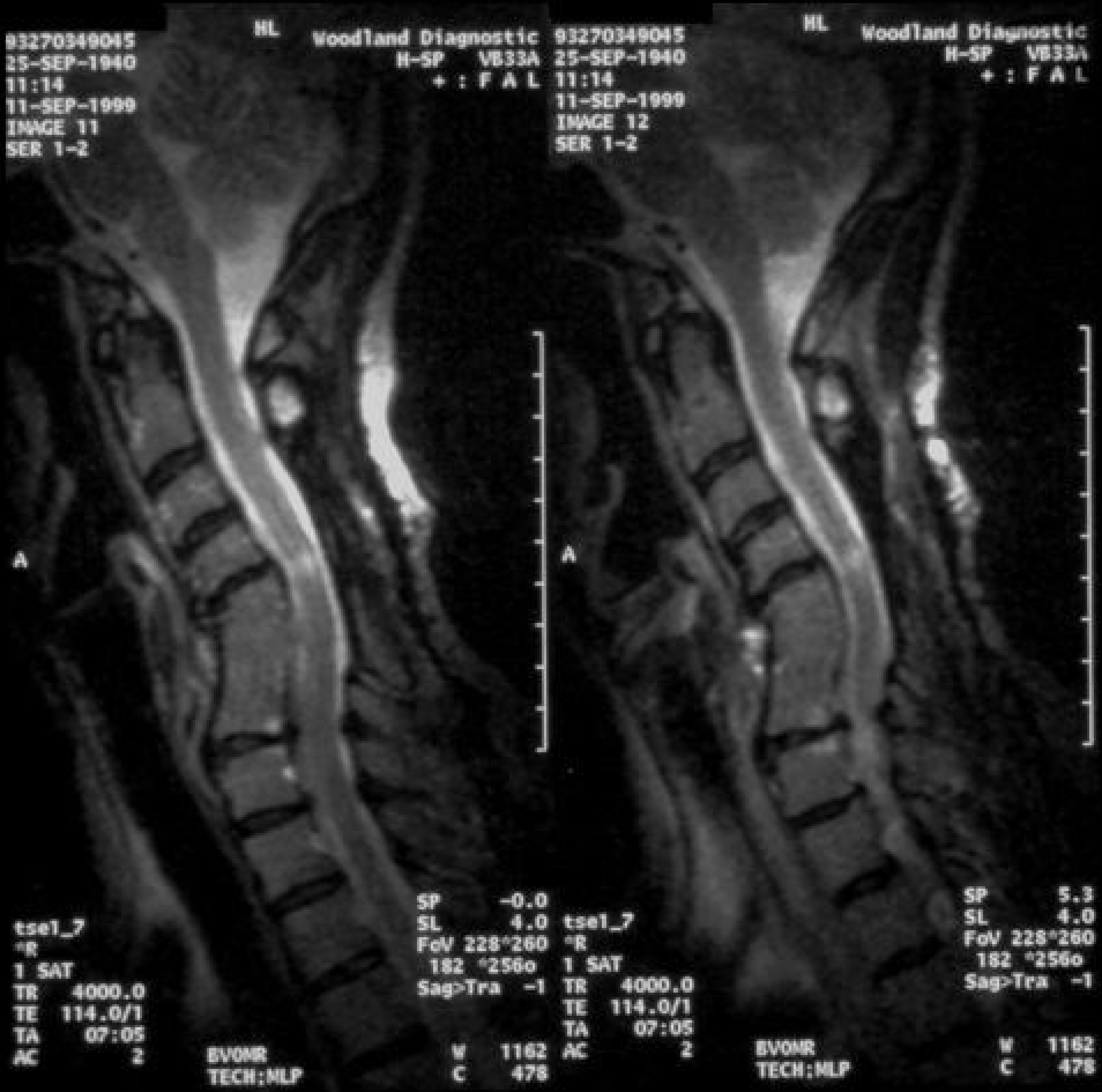
Ventral

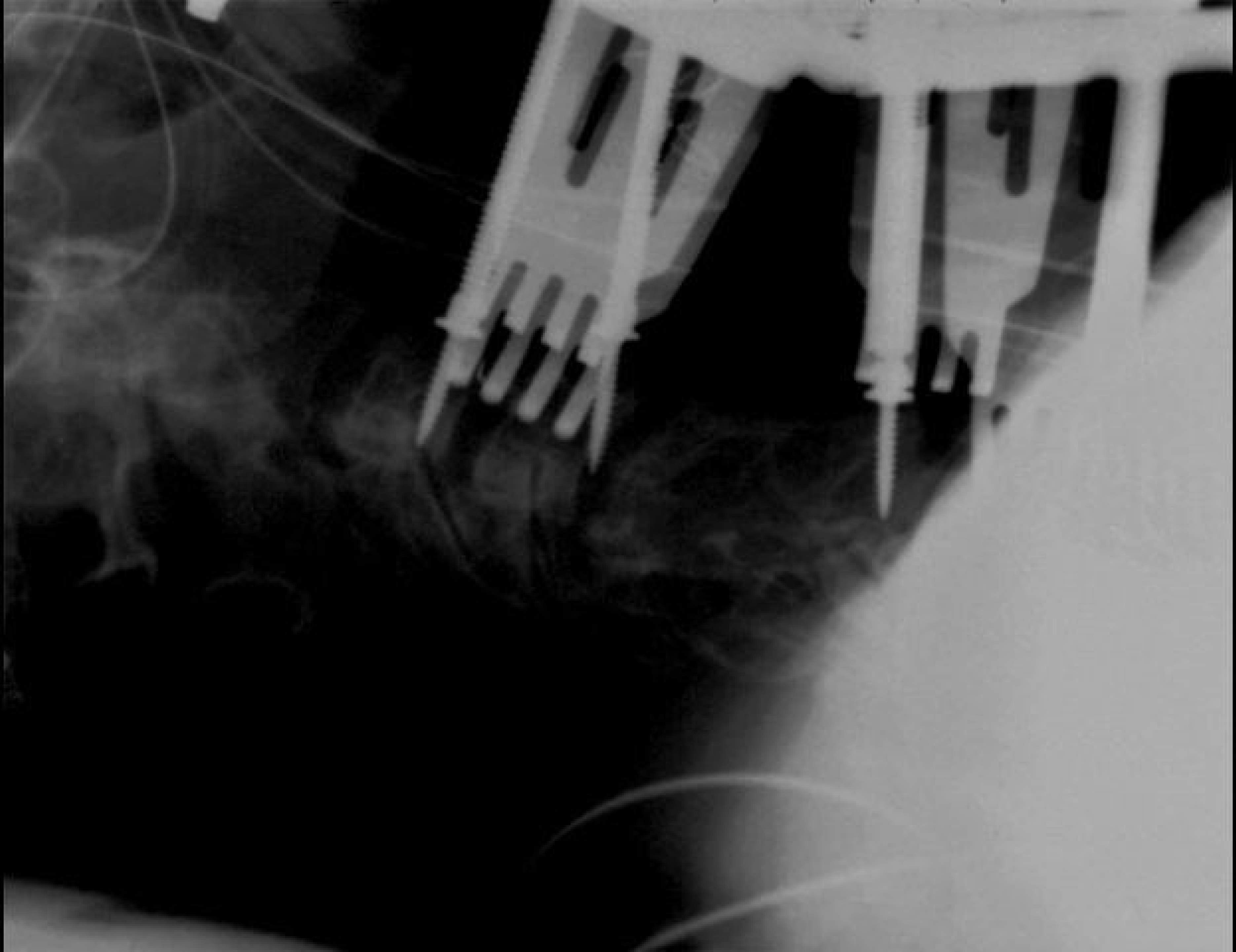
Another Story

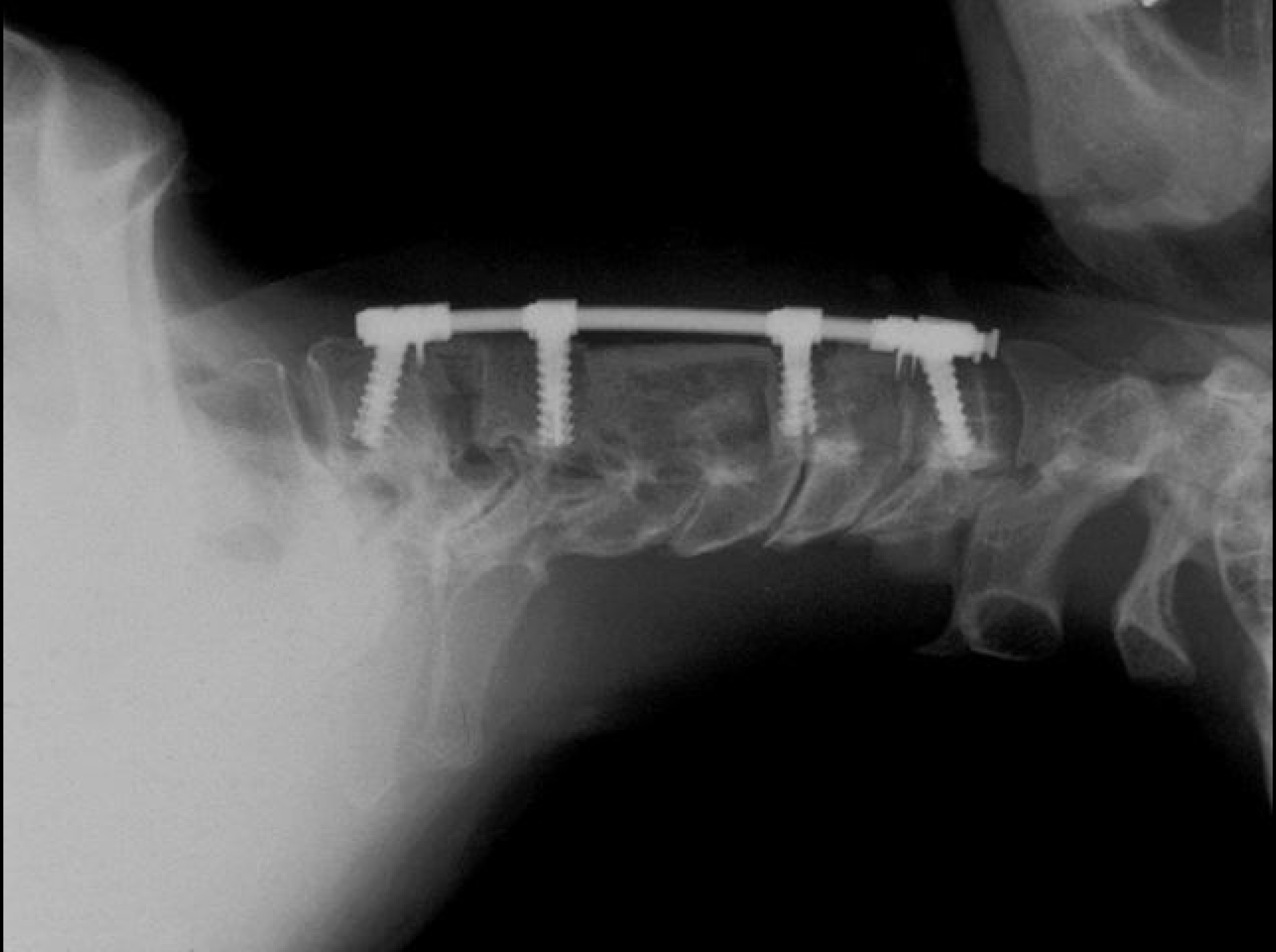



A.
B.

Gravity

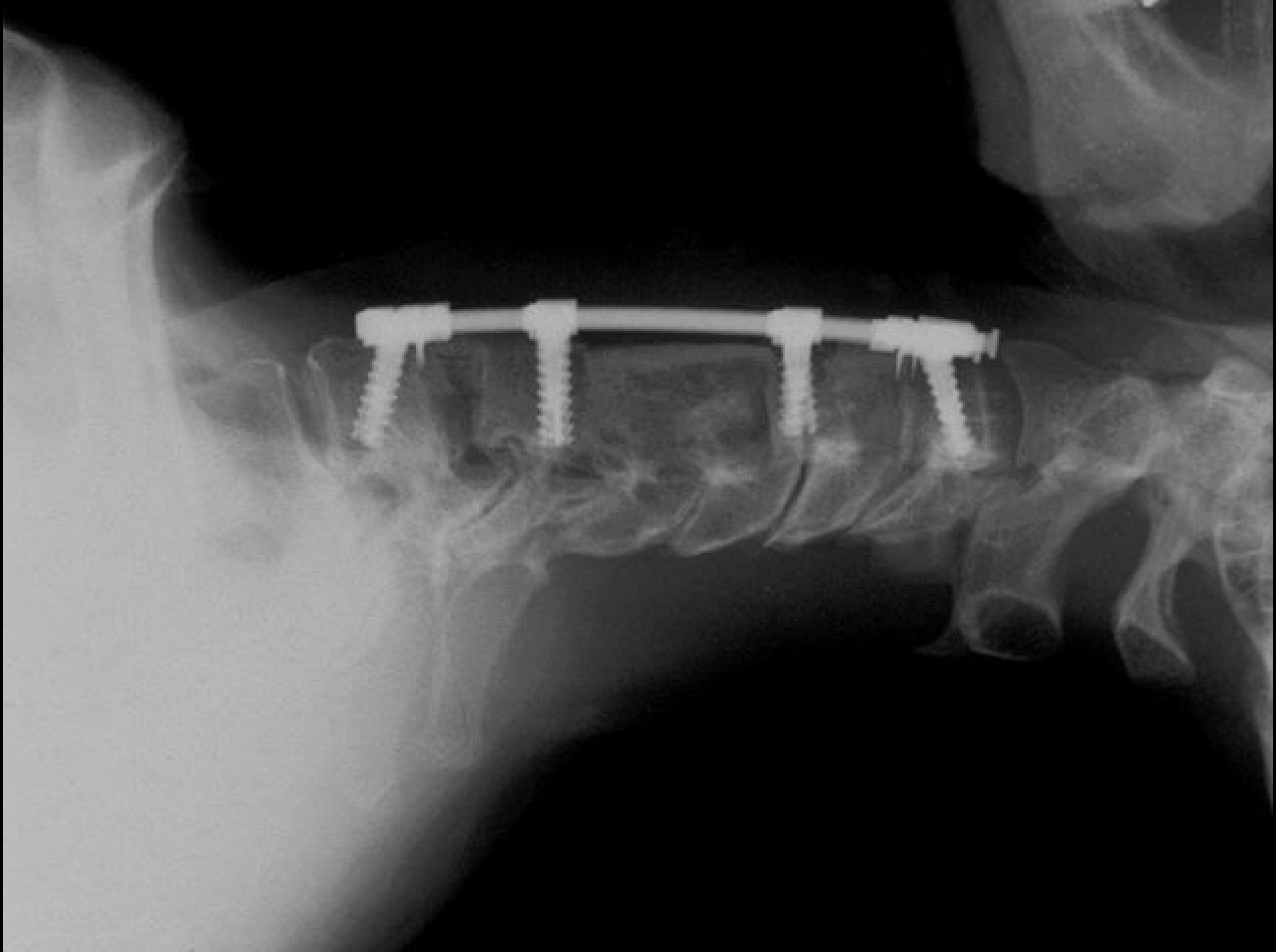

93270349045
25-SEP-1940
11:14
11-SEP-1999
IMAGE 11
SER 1-2
HL
Woodland Diagnostic
H-SP VB33A
+ : F A L
A
tse1_7
*R
1 SAT
TR 4000.0
TE 114.0/1
TA 07:05
AC 2
BVOMR
TECH;MLP
SP -0.0
SL 4.0
FoV 228*260
182 *256o
Sag>Tra -1
W 1162
C 478
93270349045
25-SEP-1940
11:14
11-SEP-1999
IMAGE 12
SER 1-2
HL
Woodland Diagnostic
H-SP VB33A
+ : F A L
A
tse1_7
*R
1 SAT
TR 4000.0
TE 114.0/1
TA 07:05
AC 2
BVOMR
TECH;MLP
SP 5.3
SL 4.0
FoV 228*260
182 *256o
Sag>Tra -1
W 1162
C 478

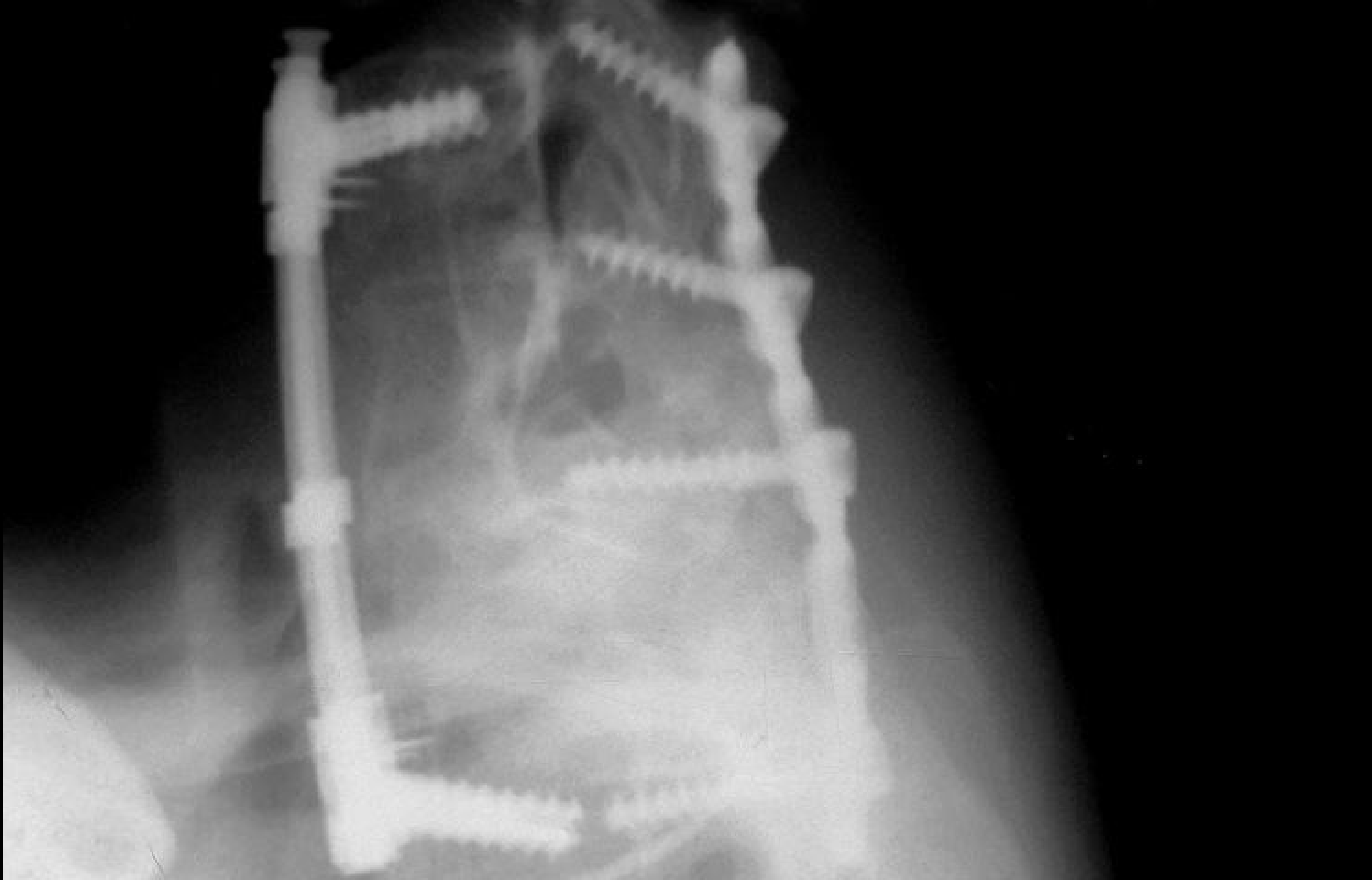


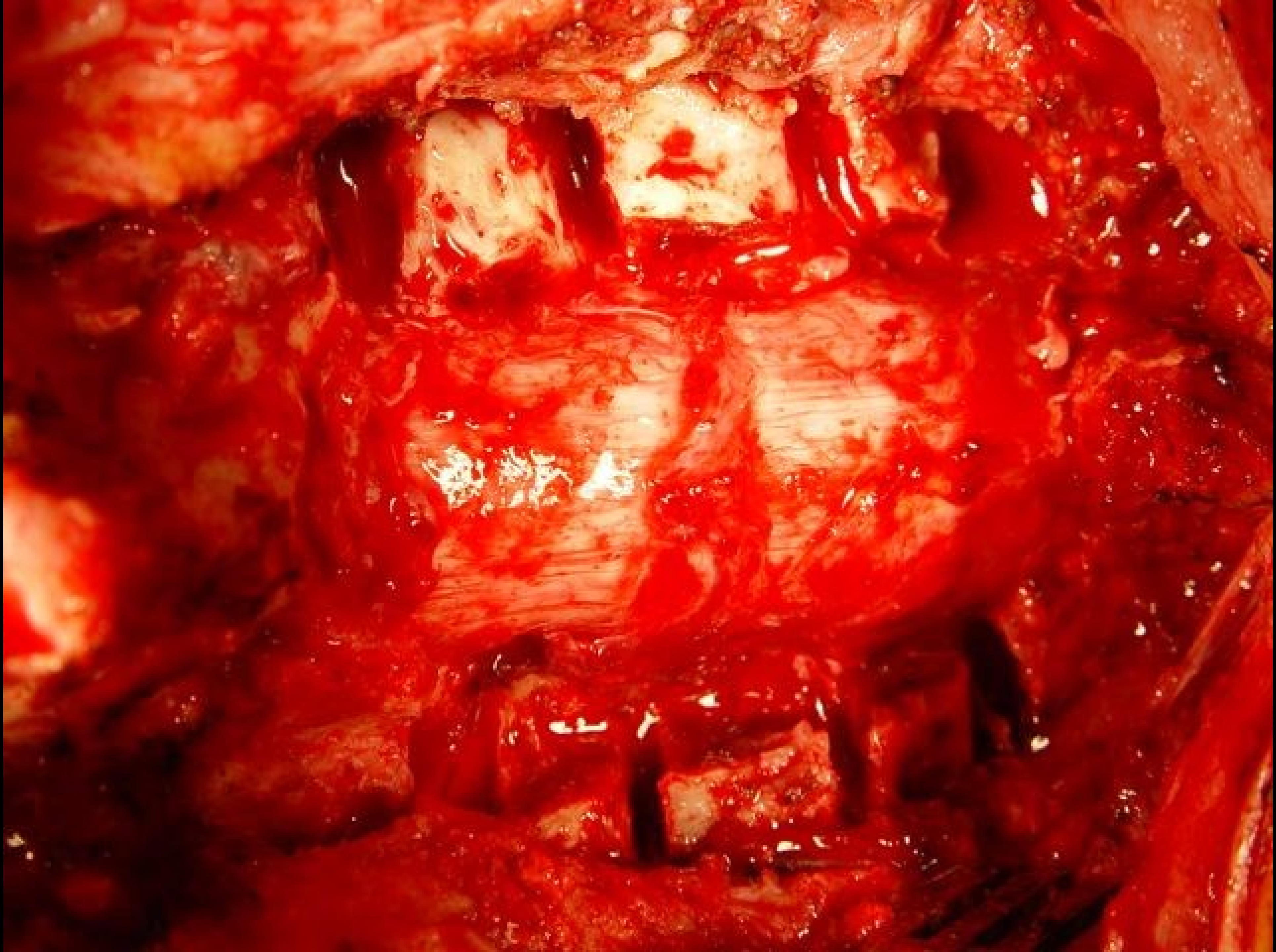


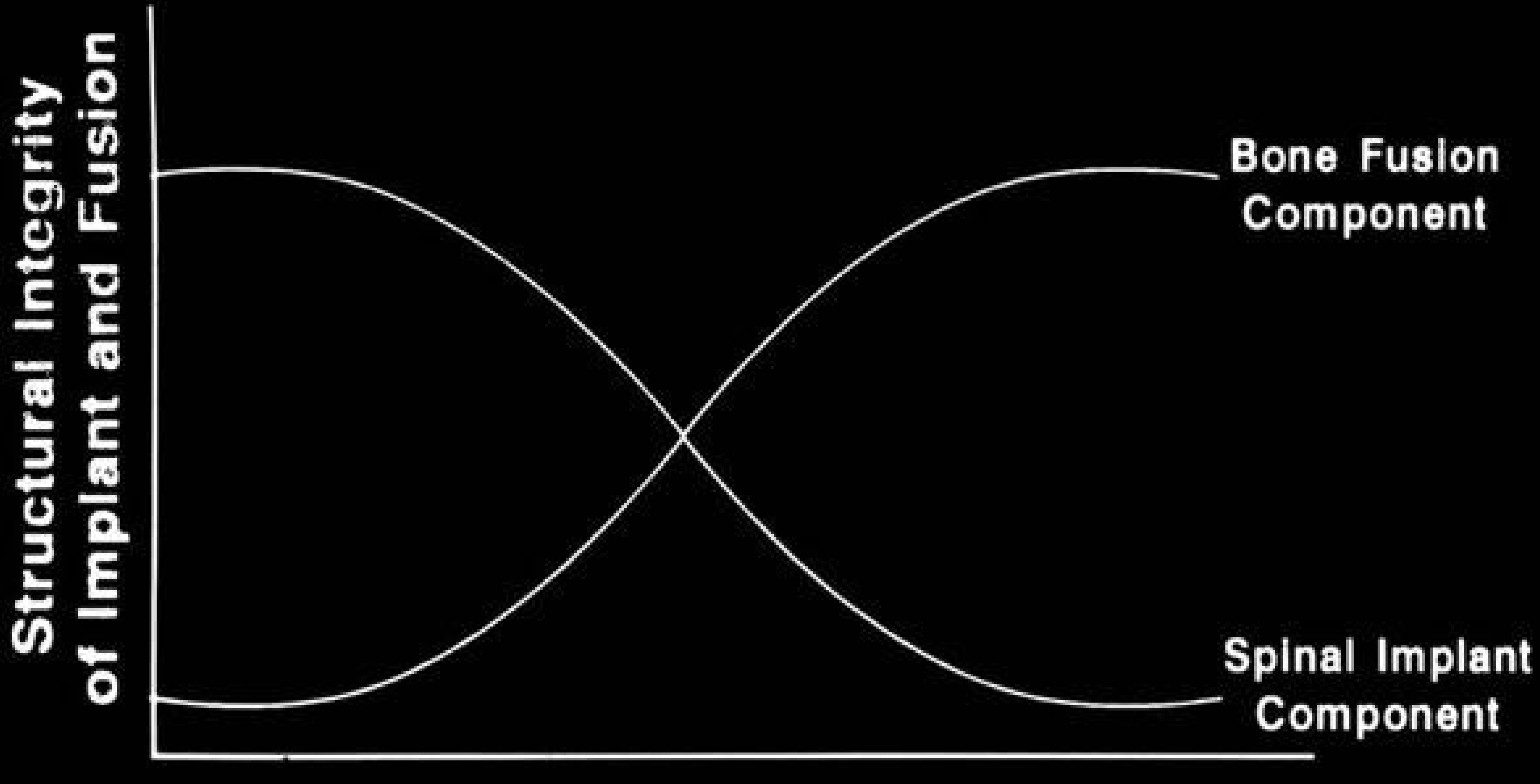
Its all about leverage!!!

Fixation Follows!!!

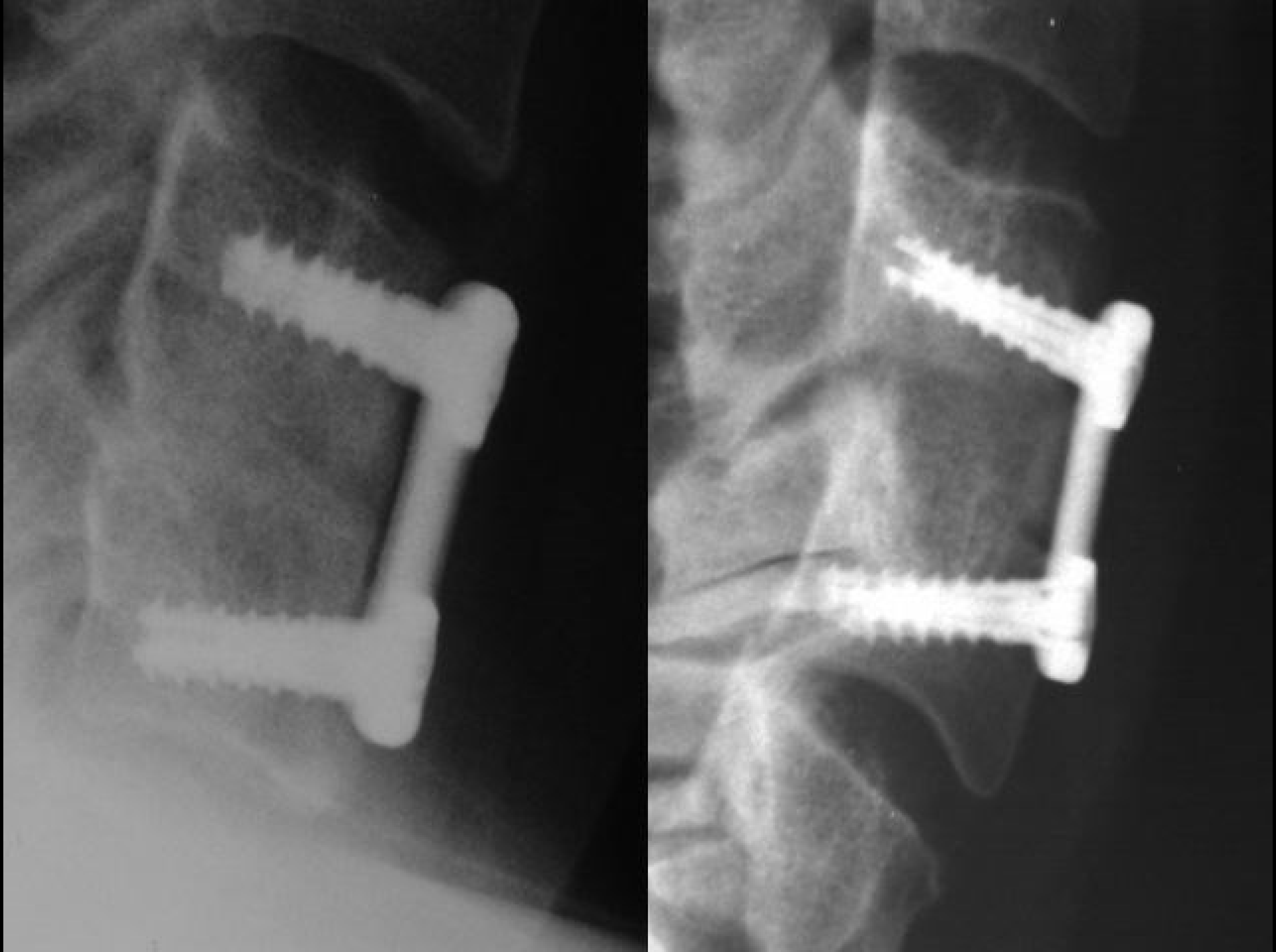







Structural Integrity
of Implant and Fusion
Bone Fusion
Component
Spinal Implant
Component
Time
Surgery

HOW IMPORTANT
is
POSTURE
and
BALANCE
?????



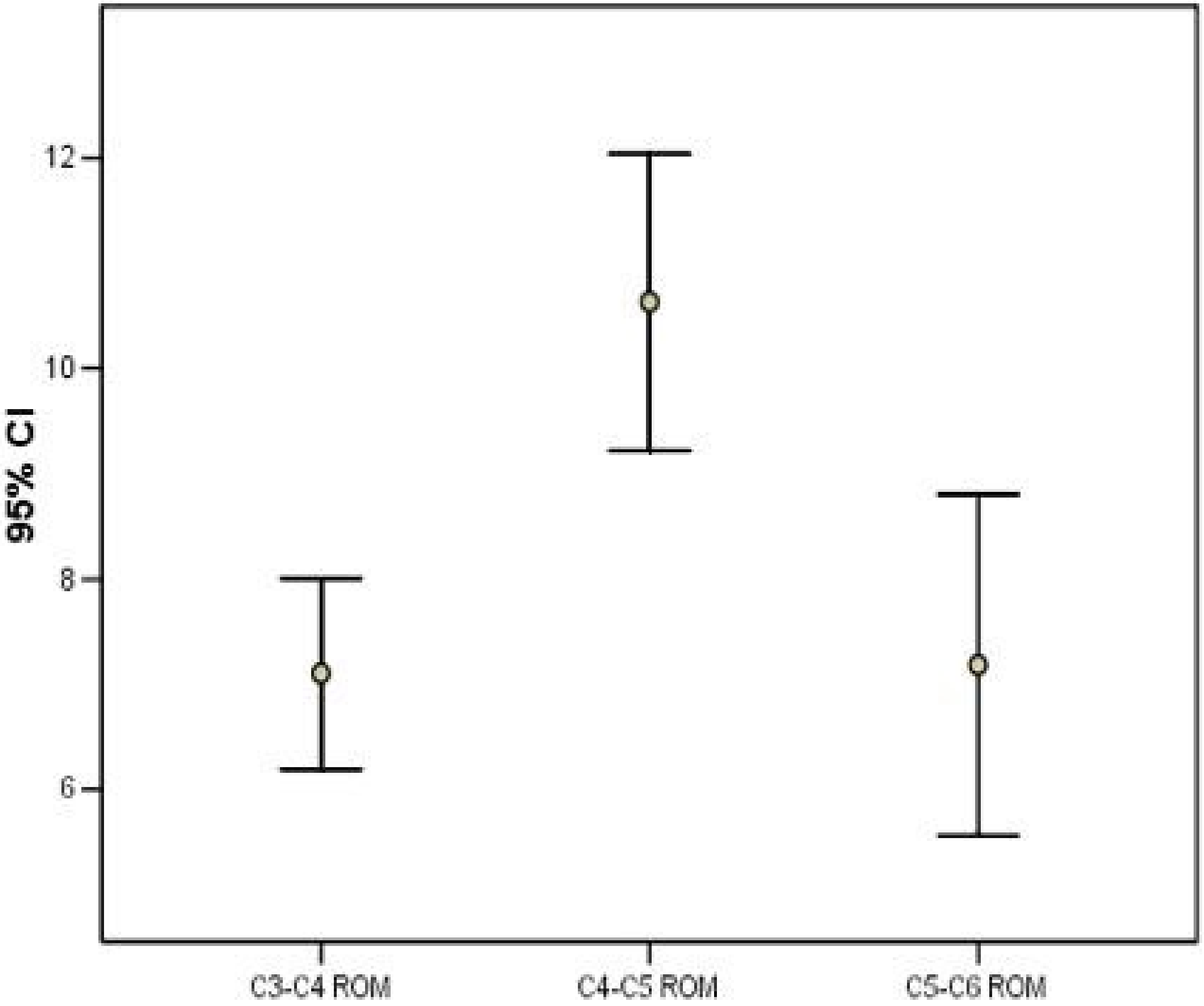
Cervical Spine Posture

State	Lordosis	ROM
Normal	±	24.9 degrees (-10.6 = 14.3 degrees)
Small Spacer	++	21.4 degrees
Large Spacer	+++	15.1 degrees

6 Cadavers; 10.6 degrees at C4-5: 0.7 Nm Flex and 0.5 Nm Ext

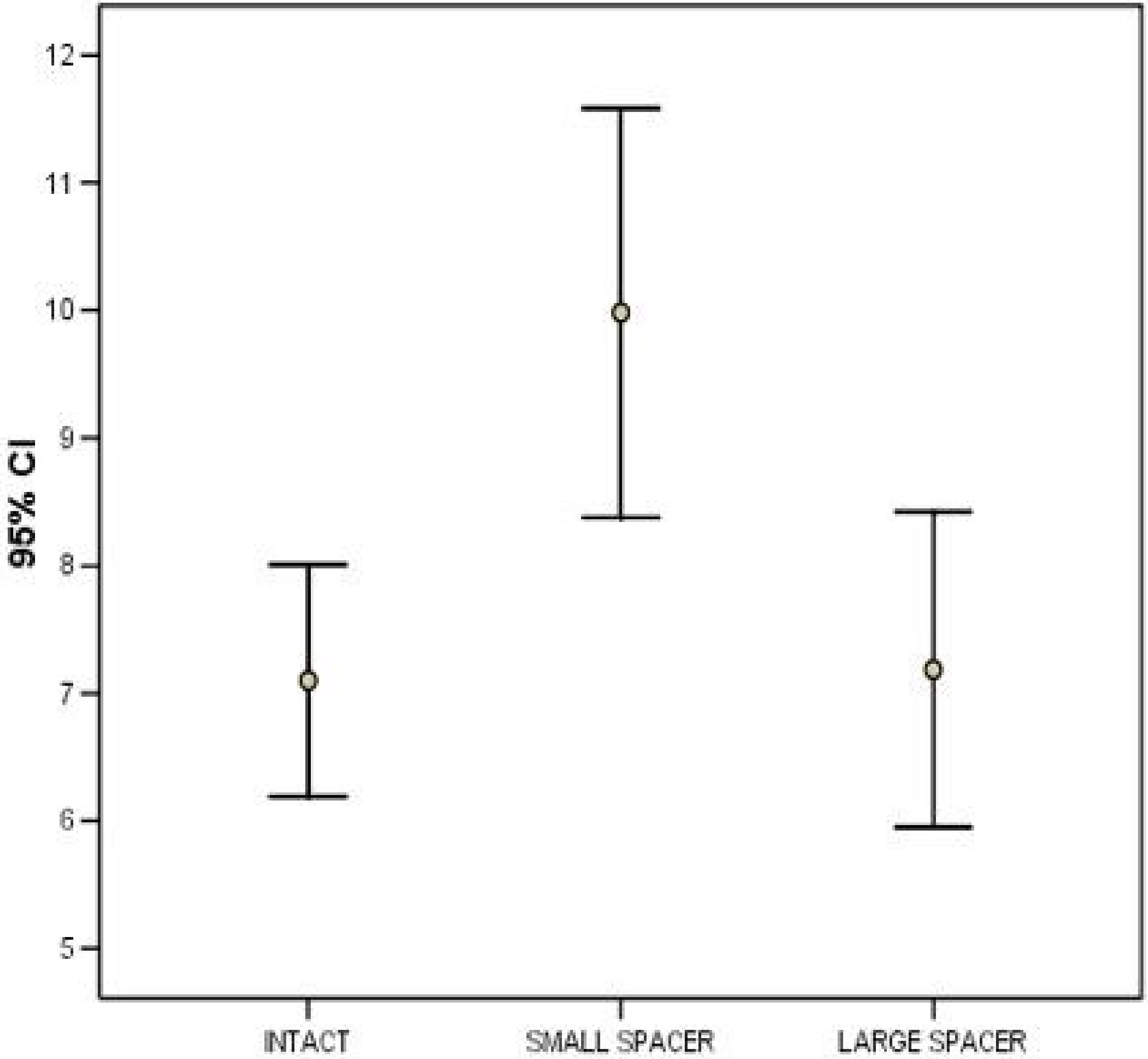
Under the conditions of this study, there is a significant increase in adjacent level segmental motion with the achievement of a neutral posture (small spacer) that is not observed with the achievement of a significant lordosis (large spacer).

Intact Range of Motion C3-C4, C4-C5 and C5-C6

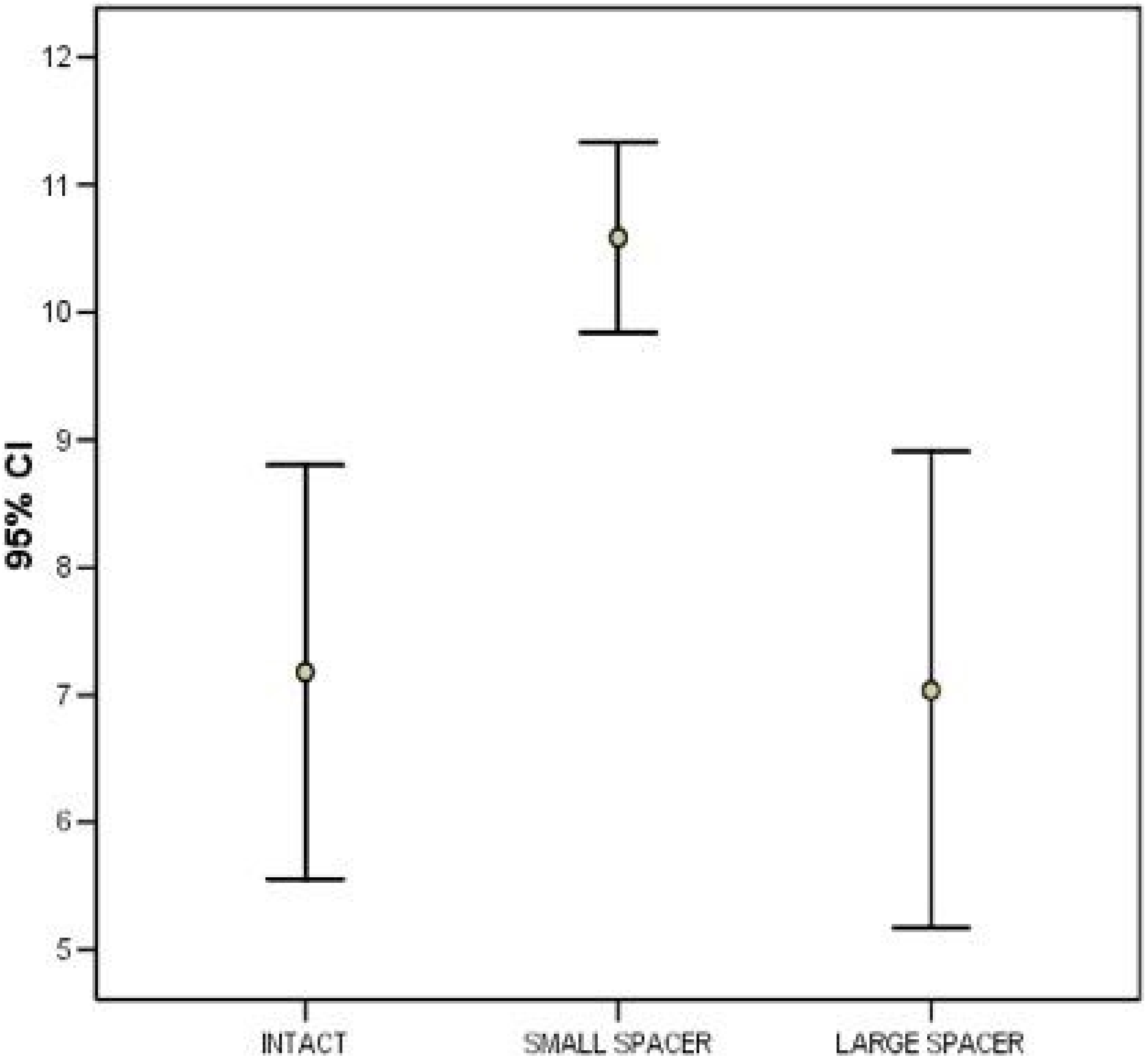


ROM = Range of Motion in degrees

Range Of Motion measured at C3-C4 disc space during flexion-extension



Range Of Motion measured at C5-C6 disc space during flexion-extension



TDA
Decreases Adjacent Segment
Degeneration
and
Disease

TDA
Decreases Adjacent Segment Degeneration and Disease

?????

44 patients – 4.5 years

ACDF – 41% ASDeg

PLF – 50% ASDeg

No Correlation with Symptoms

Herkowitz HN, Kurz LT, Overholt DP. Surgical management of cervical soft disc herniation: a comparison between the anterior and posterior approach. Spine 1990: 15(10): 1026-30

3 Studies – Ave Followup 4.5 Years

Prevelance of ASDis – 9-17%

Prevelance / years followed

Annual Incidence of ASDis Requiring Surgery

1.5 - 4% / year

Hilibrand AS, Robbins M. Adjacent segment degeneration and adjacent segment disease: the consequences of spinal fusion? The Spine Journal 4 (2004) 190S-194S

846 Patients – PLF – f/u 2.8 yrs

Prevalance ASDis - 9%

Annual Incidence ASDis - 3%

Henderson CM, Hennessy RG, Shuey HM, Shackelford EG. posterior lateral foraminotomy as an exclusive operative technique for cervical radiculopathy: a review of 846 consecutively operated cases. Neurosurgery 1983: 13(5):504-12

253 Patients ACD w and w/o F
f/u 3 years

Prevelance ASDis – 7%
Annual Incidence ASDis – 2.5%

No Difference - w and w/o

Lunsford LD, Bissonette DJ,Jannetta PJ, Sheptak PE, Zorub DS. Anterior surgery for cervical disc disease, part 1: treatment of lateral cervical disc herniation in 253 cases. J Neurosurg 1980:53:1-11

Hilibrand AS, Carson GD, Palumbo MA, Jones PK, Bohlman HH. Radiculopathy and myelopathy at segments adjacent to the site of a previous anterior cervical arthrodesis. J Bone Joint Surg 1999; 81A(4):519-28

409 ACDF

f/u 2-21 years

Prevelance ASDis – 14%

Annual Incidence ASDis – 3%

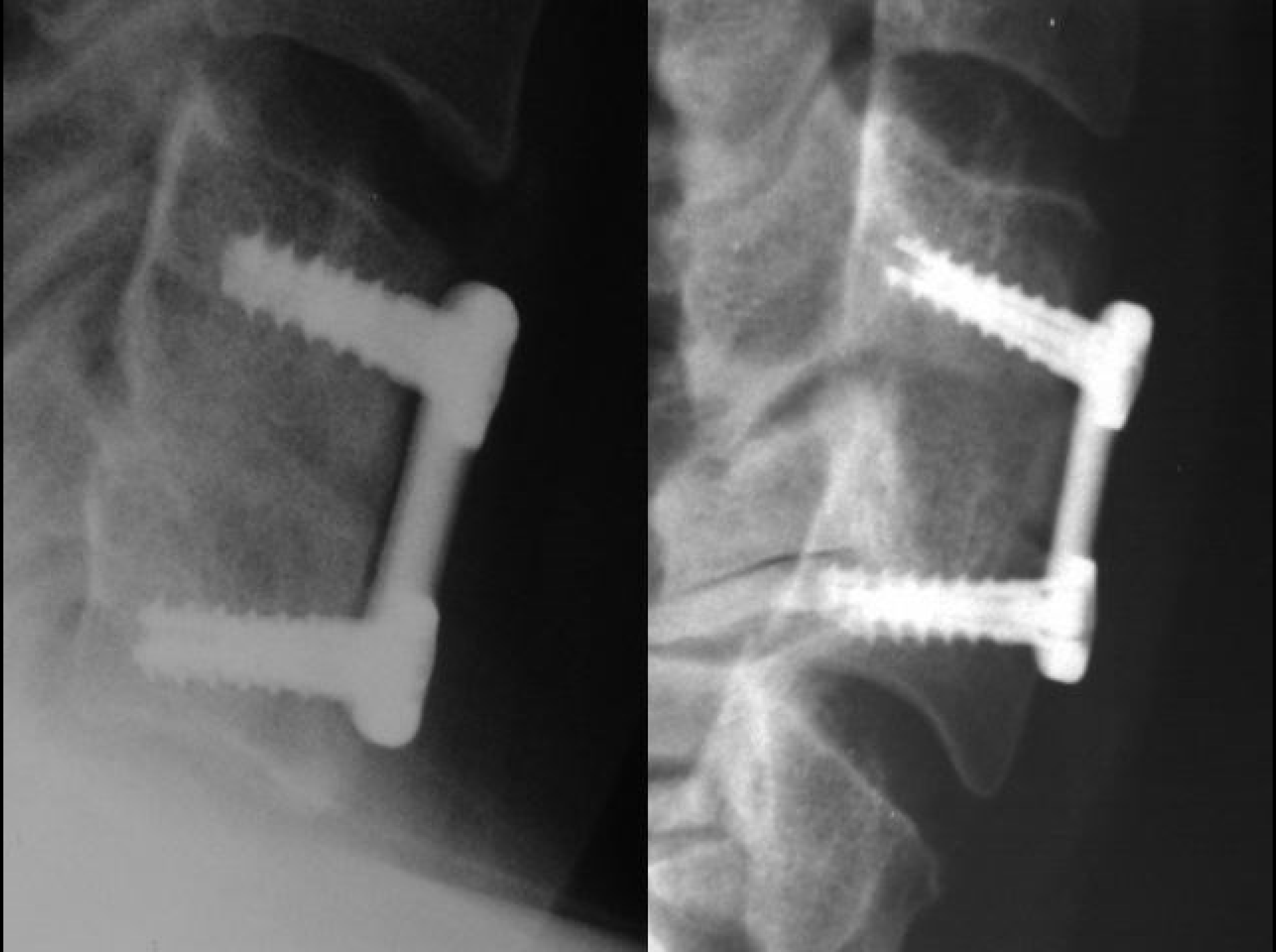
Risk Factors

Neural Element Compression at Adjacent Levels

Surgery Adjacent to C56 or C67

Multilevel ACDF Lower Incidence of ASDis

(12% vs 18%, $p \leq 0.001$)

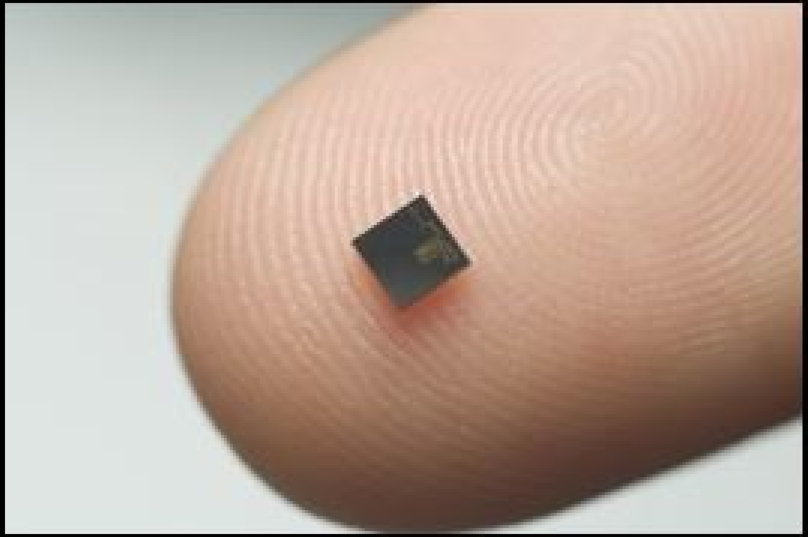


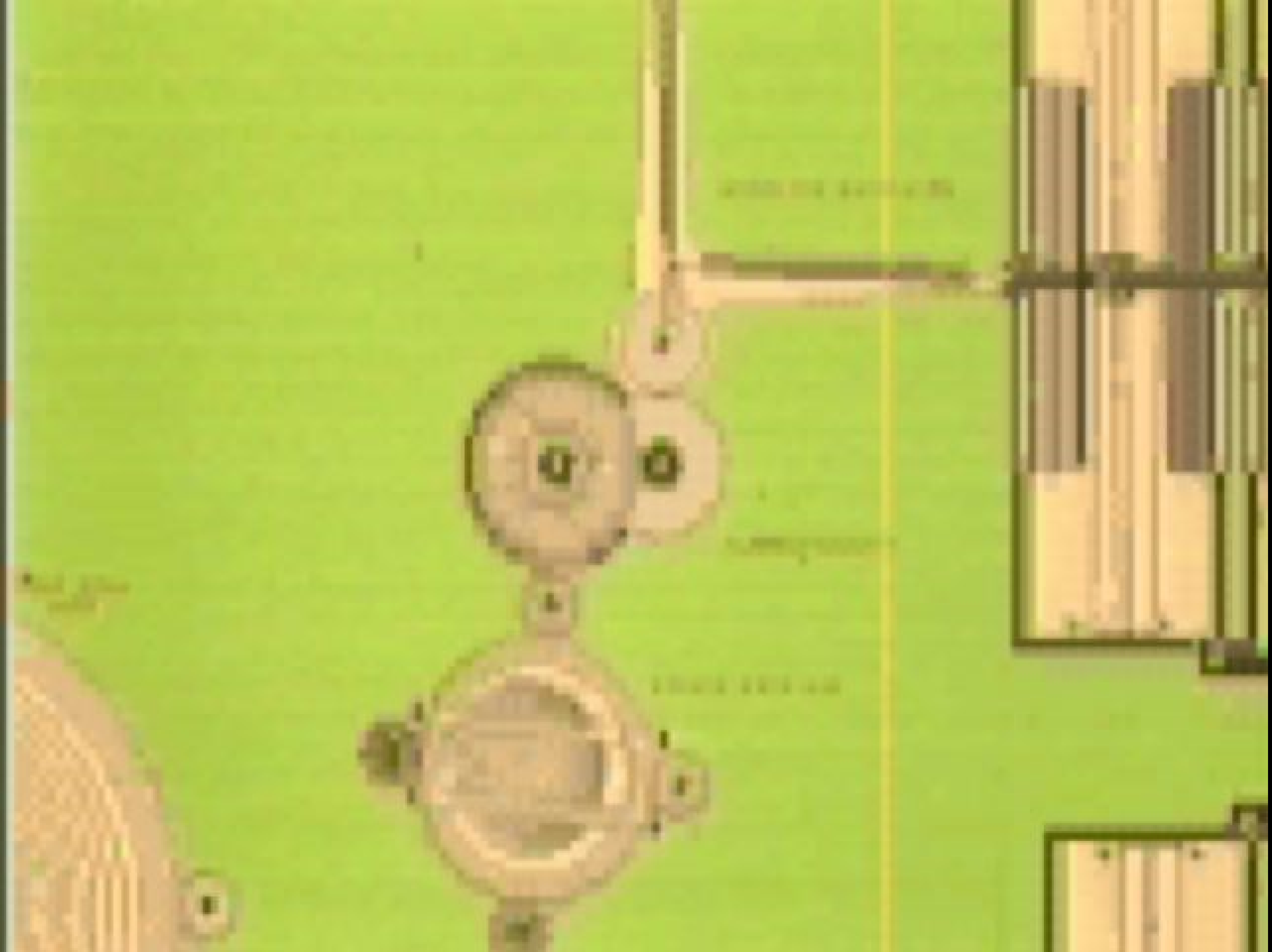
MicroElectroMechanical Systems

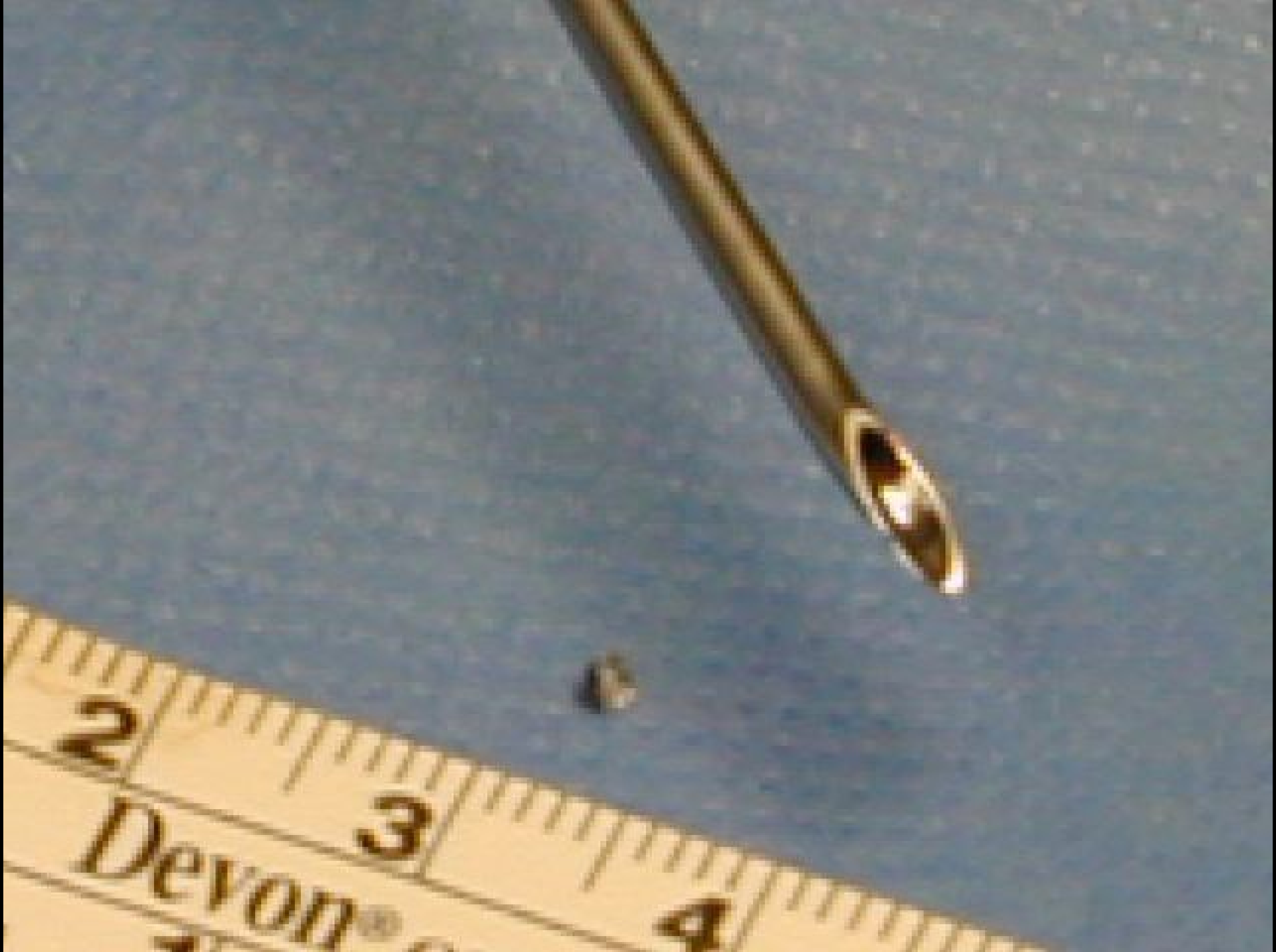
- Integrated micromachines
- "Systems-on-a-Chip"
- Gears, motors, levers, etc…
- Perform complex tasks
- Size of chip = μm - mm

MEMS

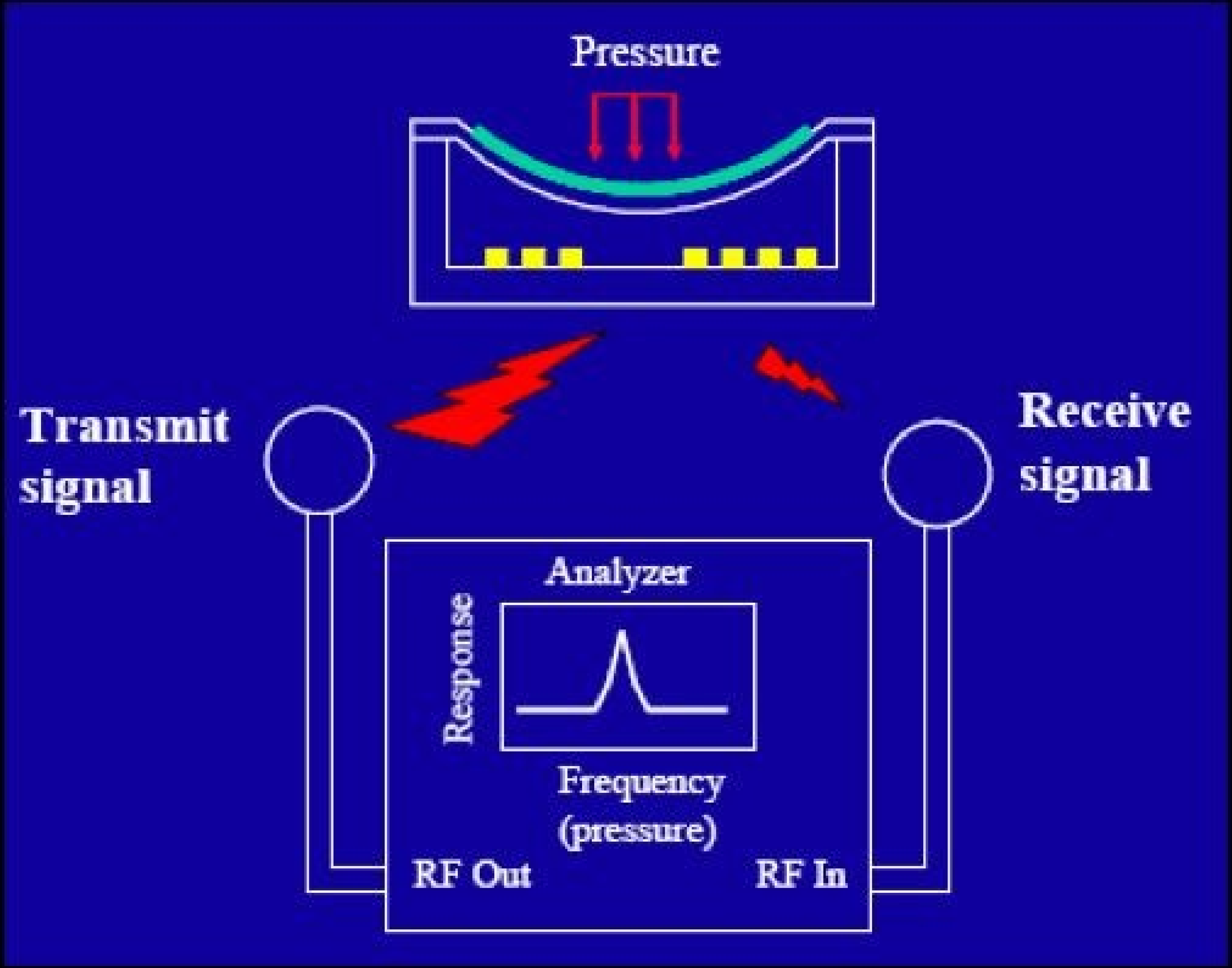
- Enabling Technology
- Ability to Read and Respond to Environment
- Stand-Alone or Combined with Implants






2
3
4
Devon®

Wireless Telemetry Principle

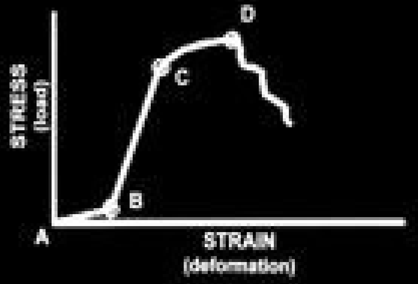


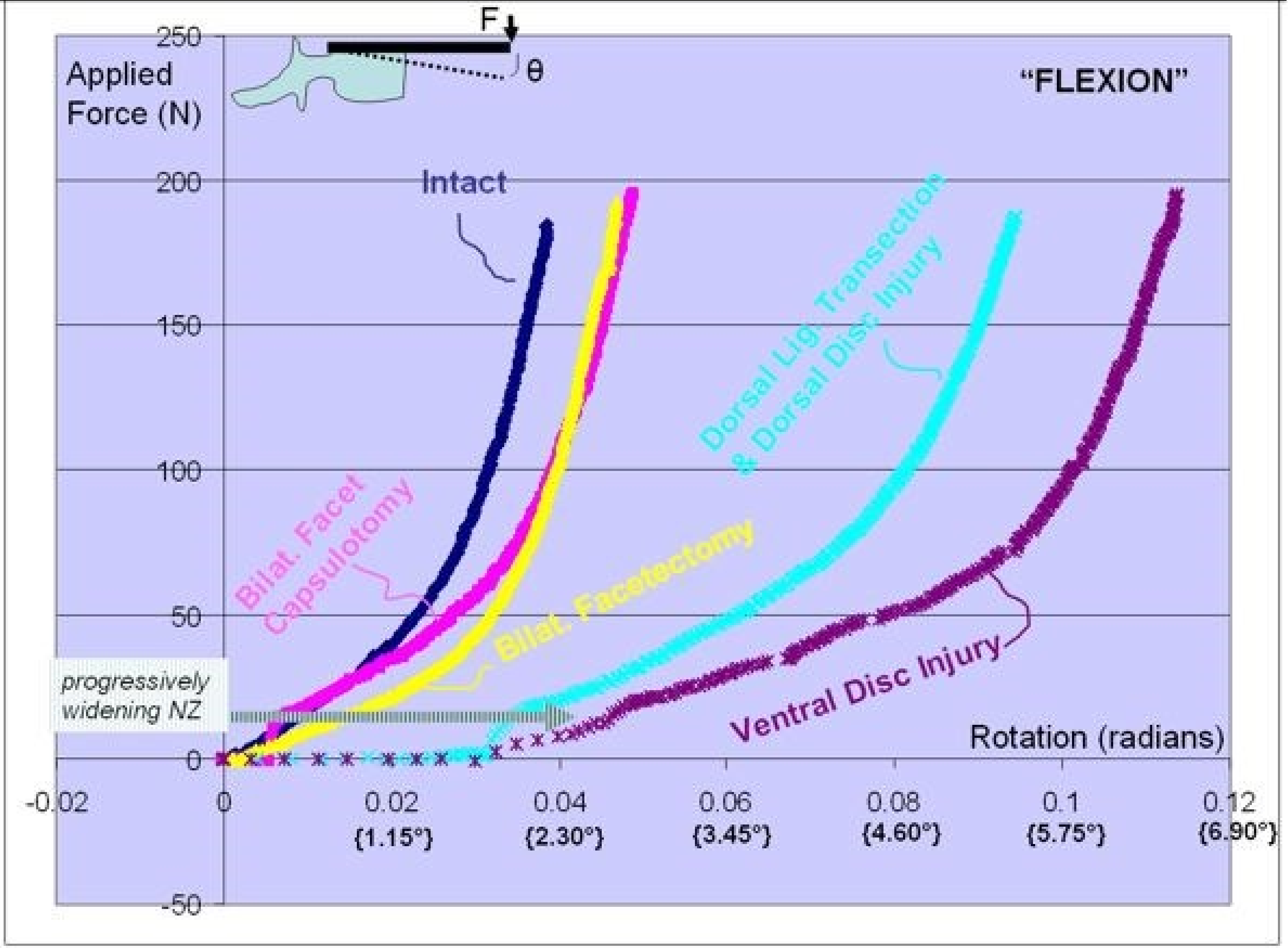
The Biomechanical Correlate of Mechanical Back Pain

Widened Neutral Zone

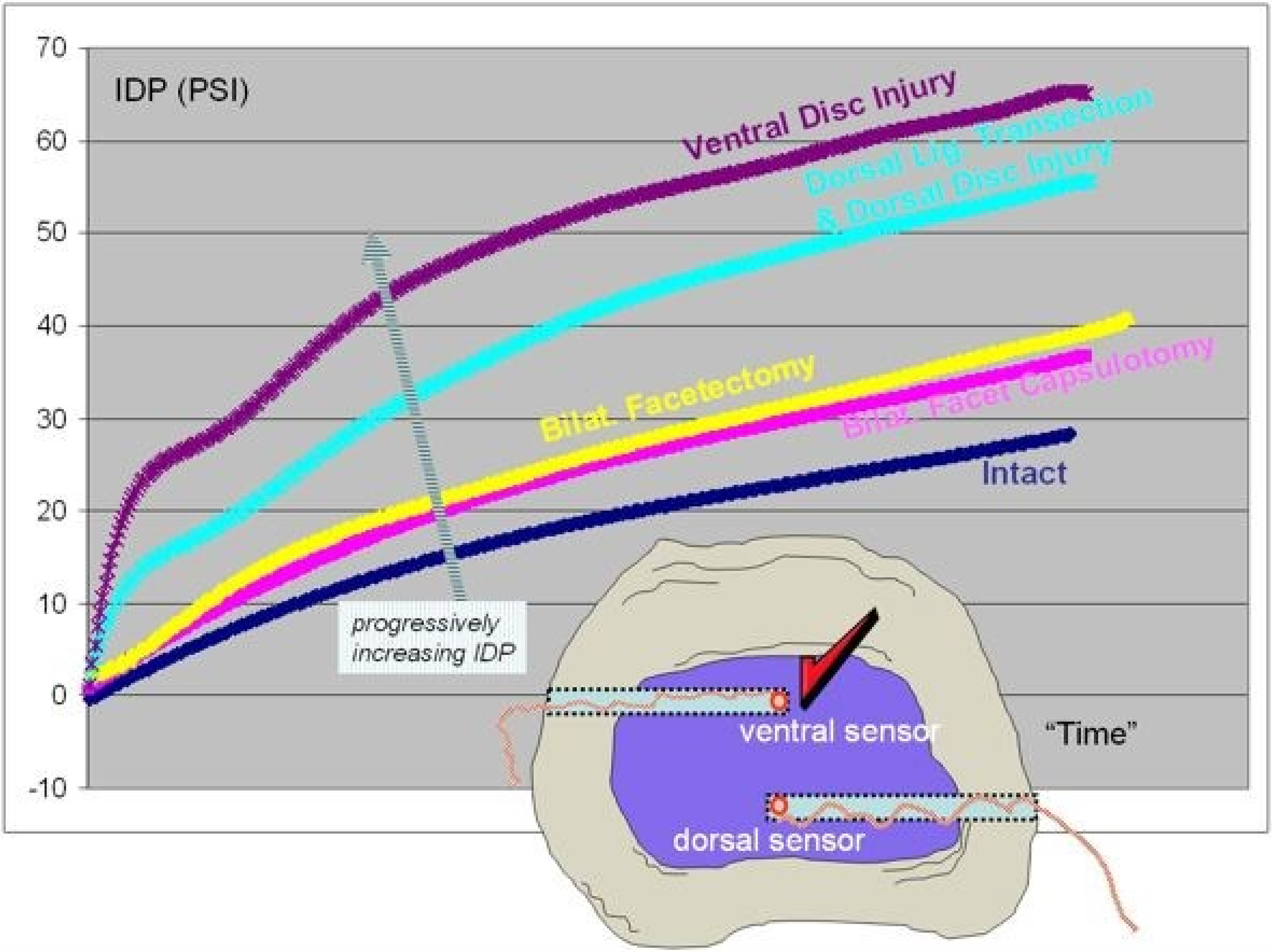
and

Altered COR





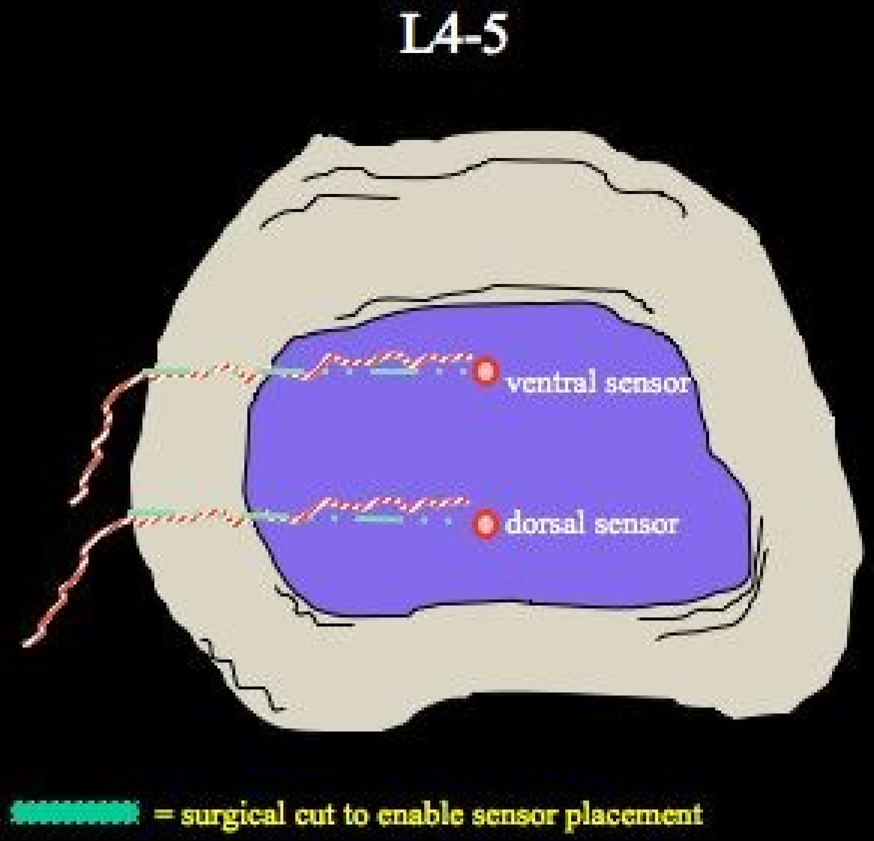
"FLEXION"
Applied Force (N)
F
θ
250
200
150
100
50
0
-50
Intact
Bilat. Facet Capsulotomy
Bilat. Facetectomy
Dorsal Lig. Transection & Dorsal Disc Injury
Ventral Disc Injury
progressively widening NZ
Rotation (radians)
-0.02
0
0.02 {1.15°}
0.04 {2.30°}
0.06 {3.45°}
0.08 {4.60°}
0.1 {5.75°}
0.12 {6.90°}

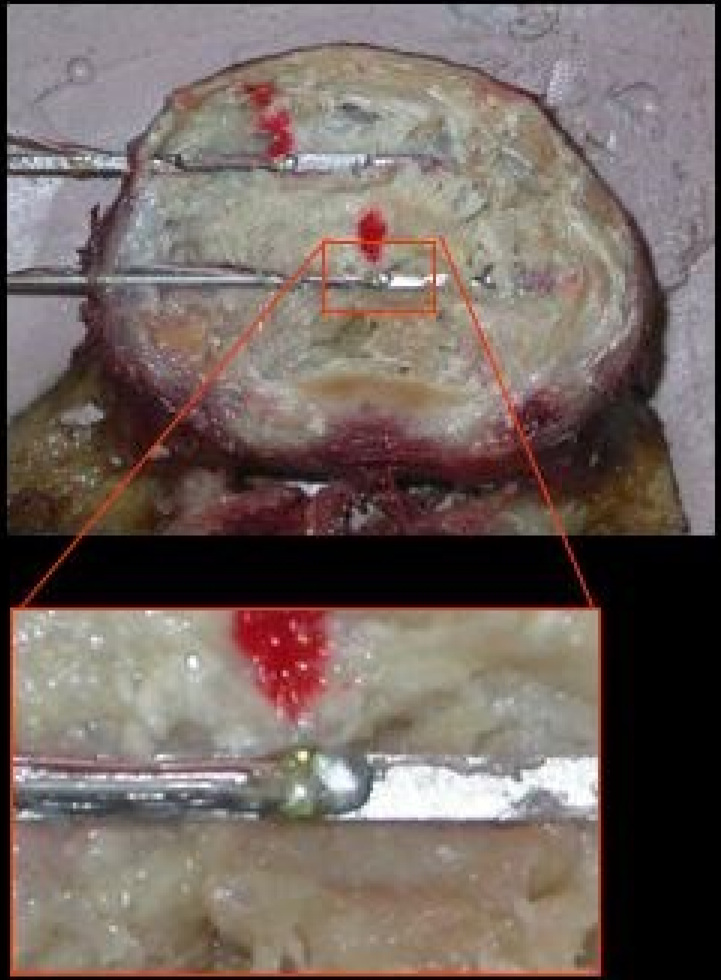


IDP (PSI)
70
60
50
40
30
20
10
0
-10
Ventral Disc Injury
Dorsal Lig. Transection
& Dorsal Disc Injury
Bilat. Facetectomy
Bilat. Facet Capsulotomy
Intact
progressively
increasing IDP
ventral sensor
dorsal sensor
"Time"

IDP Detection of Neutral Zone

(Cleveland Clinic - *In Vitro* Study at using Wired Sensors)

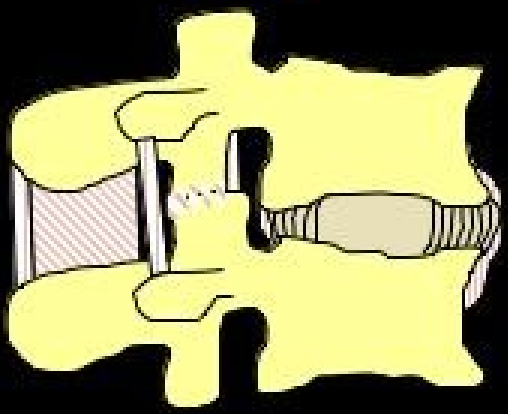




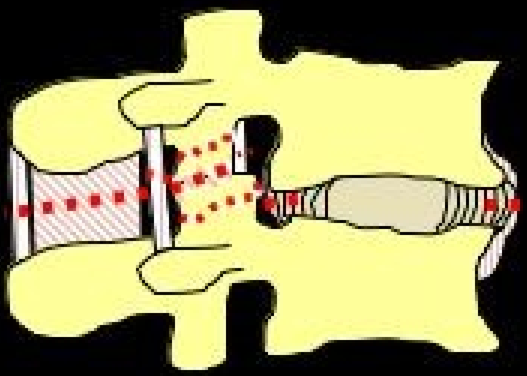
IDP Detection of Neutral Zone

(*In Vitro* Study – Instability Model)

"INTACT"



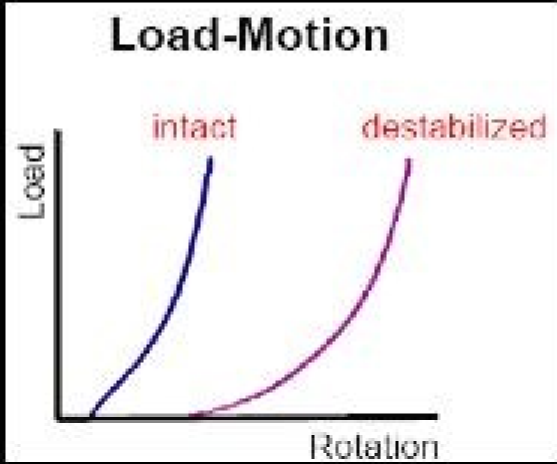
"DESTABILIZED"

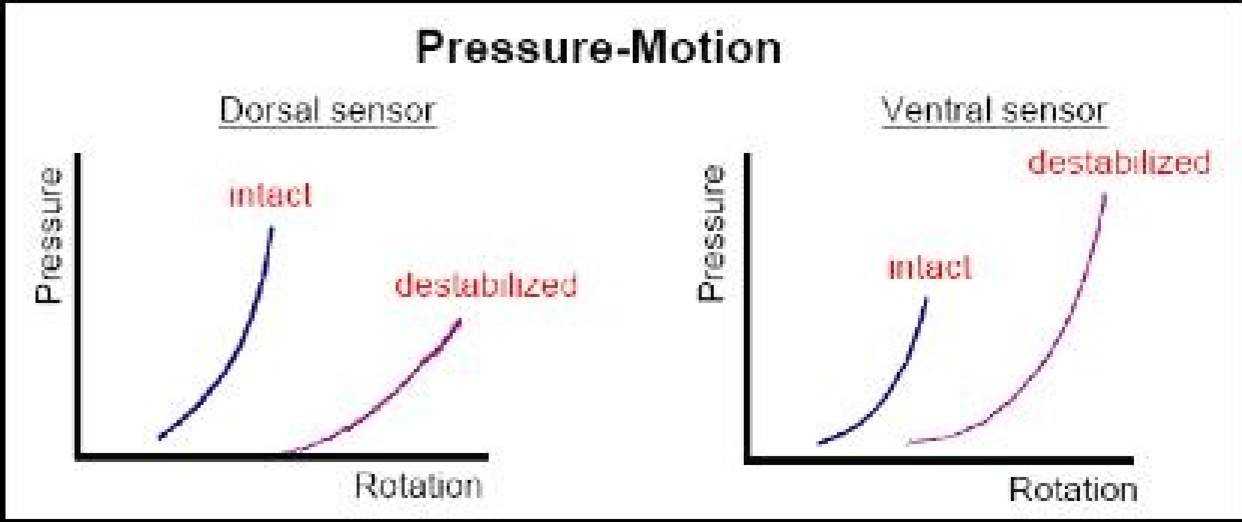


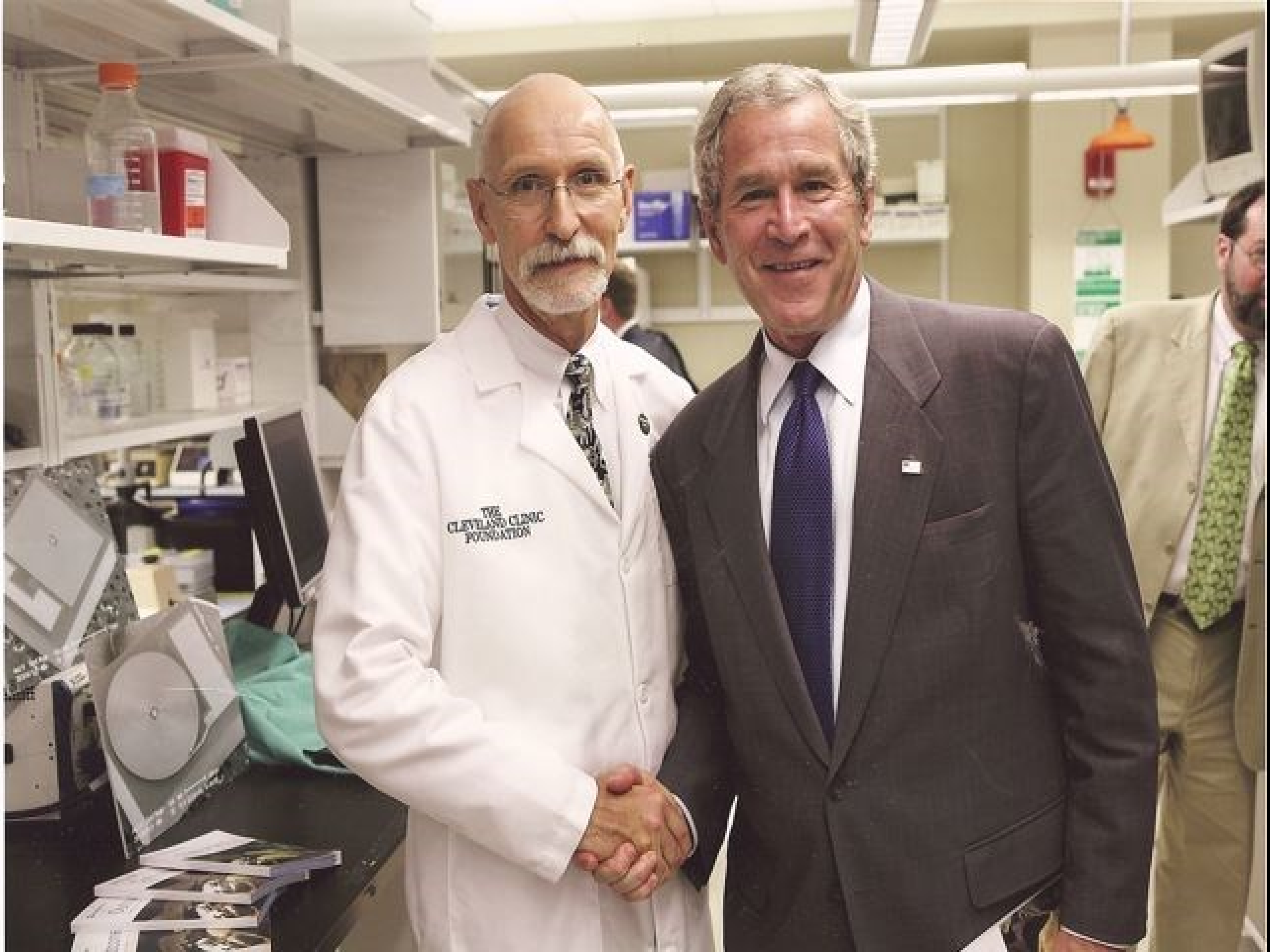
- Destabilized cases
  - Facet capsule
  - Bilateral facetectomy
  - Posterior ligament destabilization
  - Ventral disc destabilization
  - Dorsal disc destabilization
- Same loads for each injury
  - Cantilever Loading

IDP Detection of Neutral Zone

(Early Results – Flexion example)



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Baxter

THANK YOU!!!

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