FIGHTER PILOT CERVICAL SPINE INJURIES

CLINICAL AND BIOMECHANICAL STUDY AND THE NEED TO RE-EVALUATE PHYSICAL FITNESS PROGRAMS

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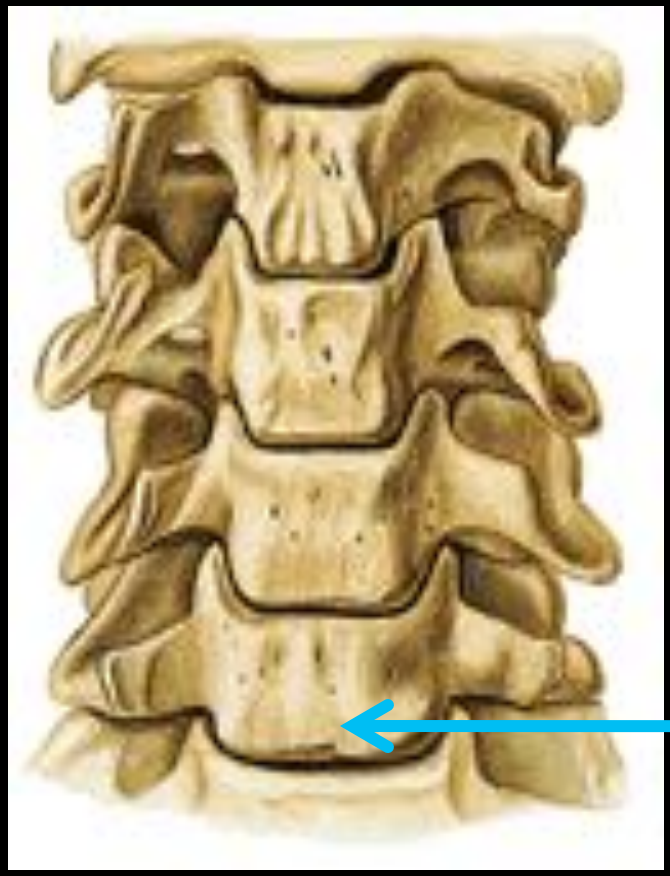
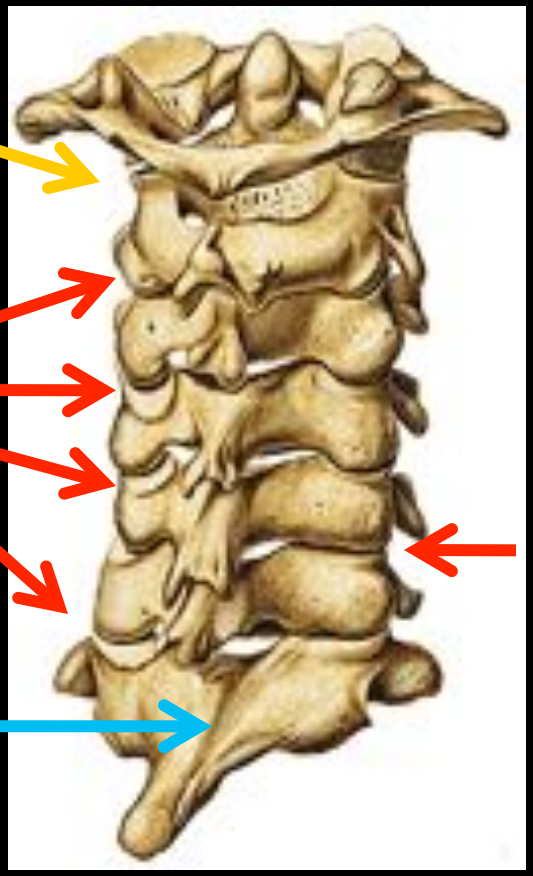
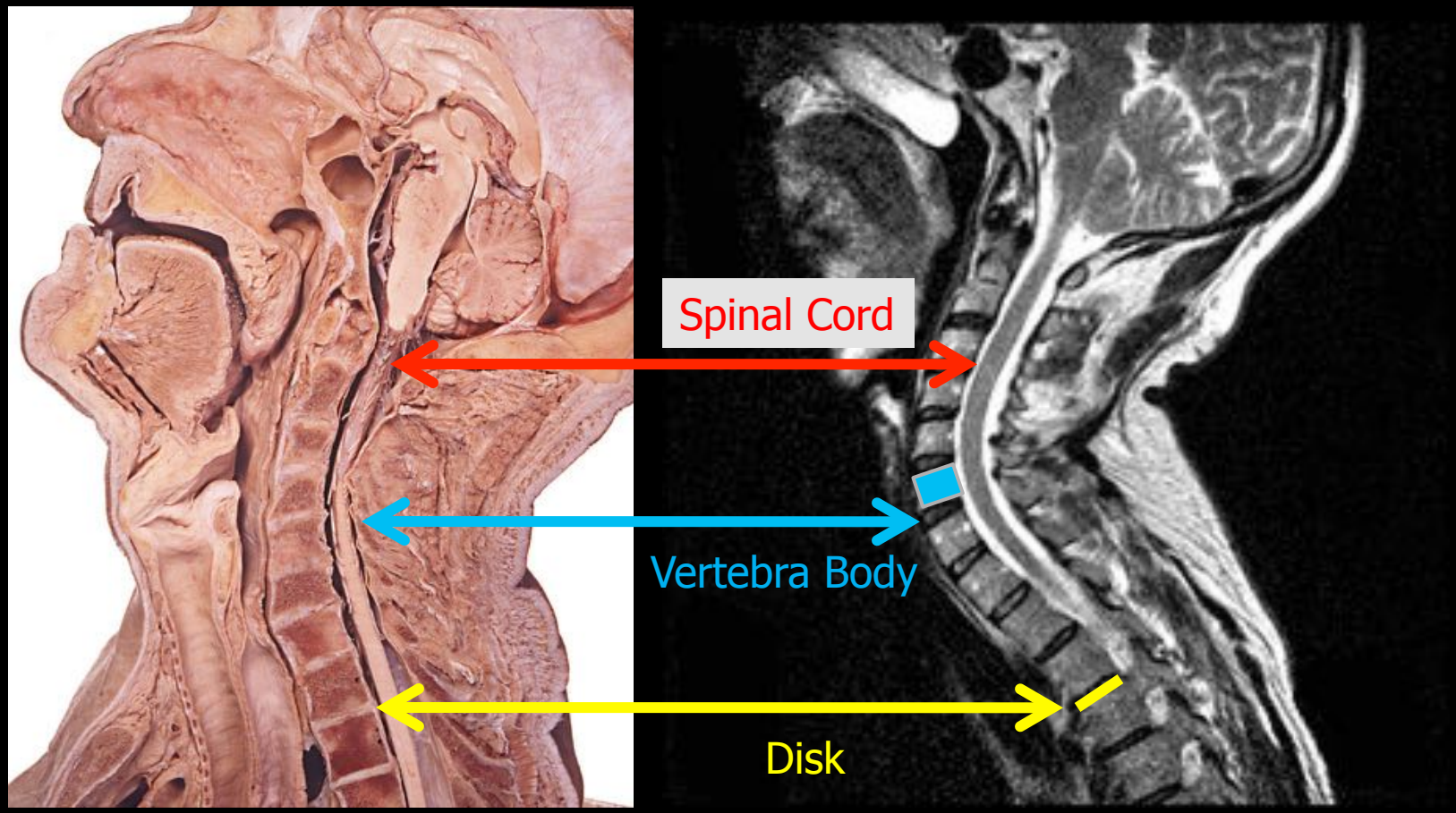
Cervical Spine Anatomy





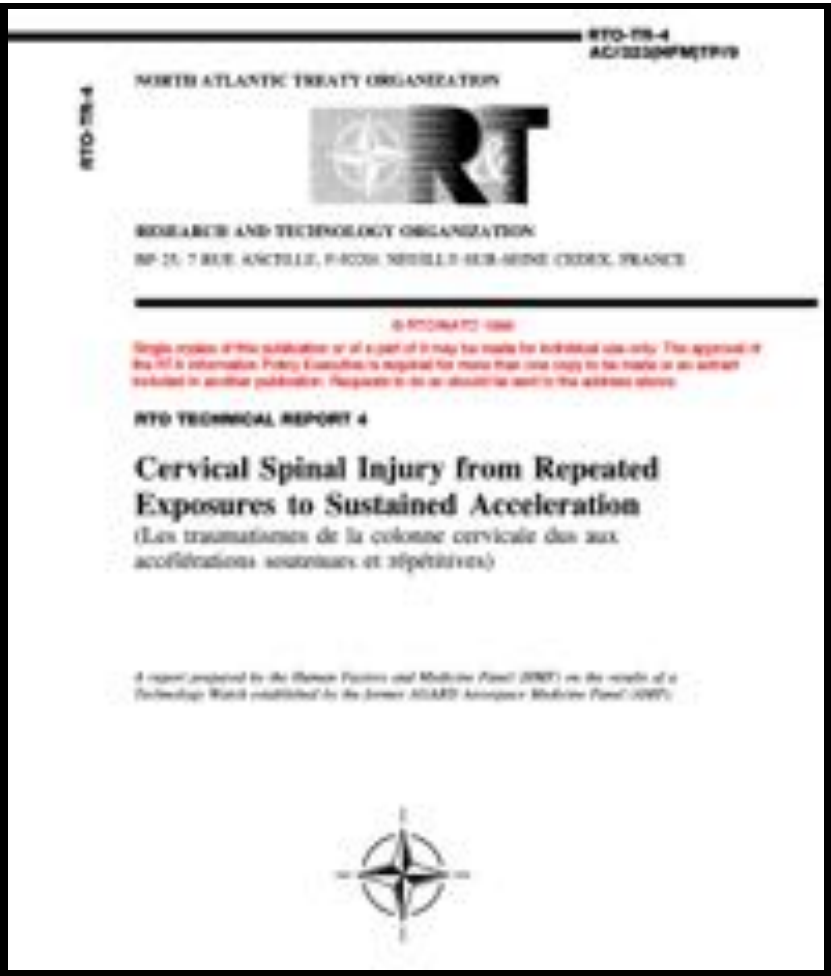
Cervical Spine Anatomy



In-Flight Spine Injuries

- 1948 (Shaw)
  - 2 lumbar disk ruptures
  - 5 Gs and 9 Gs
- 1964 (Mayers)
  - 66 spine surgeries on pilots
  - Concluded: 4-5 Gs safe
- 1970 AGARD Report AR-140
  - One in-flight neck injury

In-flight Neck Injuries



RTO-TR-4

NORTH ATLANTIC TREATY ORGANIZATION

RESEARCH AND TECHNOLOGY ORGANIZATION

RTO TECHNICAL REPORT 4

Cervical Spinal Injury from Repeated Exposures to Sustained Acceleration

(Les traumatismes de la colonne cervicale dus aux accélérations soutenues et répétitives)

- 1982 AGARD : Pathophysiology and pathology of spinal injuries
- Loss of cervical lordosis
  - Pilots 60%
  - Non-pilots 5%

- 1999 RTO-TR-4 NATO
- Comprehensive review
- Documented the problem

In-flight Disk Ruptures

- 1990 Clark (ASEM)
  - F-14 pilot
  - C3-4 disk

- 1994 Hamalainen (ASEM)
  - 3 cases during ACM
  - 7.0 Gs

- 1996 Newman (ASEM)
  - F-111C pilot
  - C6-7 disk (4 Gs)

In-flight Neck Fractures

- 1988 Andersen (ASEM)
  - Flight surgeon back seat F-16B
  - C5 compression fx
  - Treated conservatively

- 1989 Schall (ASEM)
  - Report of 3 cases
  - 5-9 Gz

Acute vs Chronic Neck Injuries

- Acute
  - Aircraft type related
  - Age not factor
- Chronic pain
  - Age Related
  - >35 yo - 300% increase

Epidemiology of Neck Pain

- 38%
- MiG-21
- Alpha Jet

(Hamalainen, ASEM 1994)

Epidemiology of Neck Pain

- **90%** F-15

  (Kikukawa, ASEM 1995)

- ***75% -85%*** F/A-18

  (Knudson, ASEM 1988)
  (Newman, ASEM 1996)

Epidemiology of Neck Pain

- 35-50% F-16

  (Vanderbeek, ASEM 1988)

  (Paola Verde ICASM 2009)

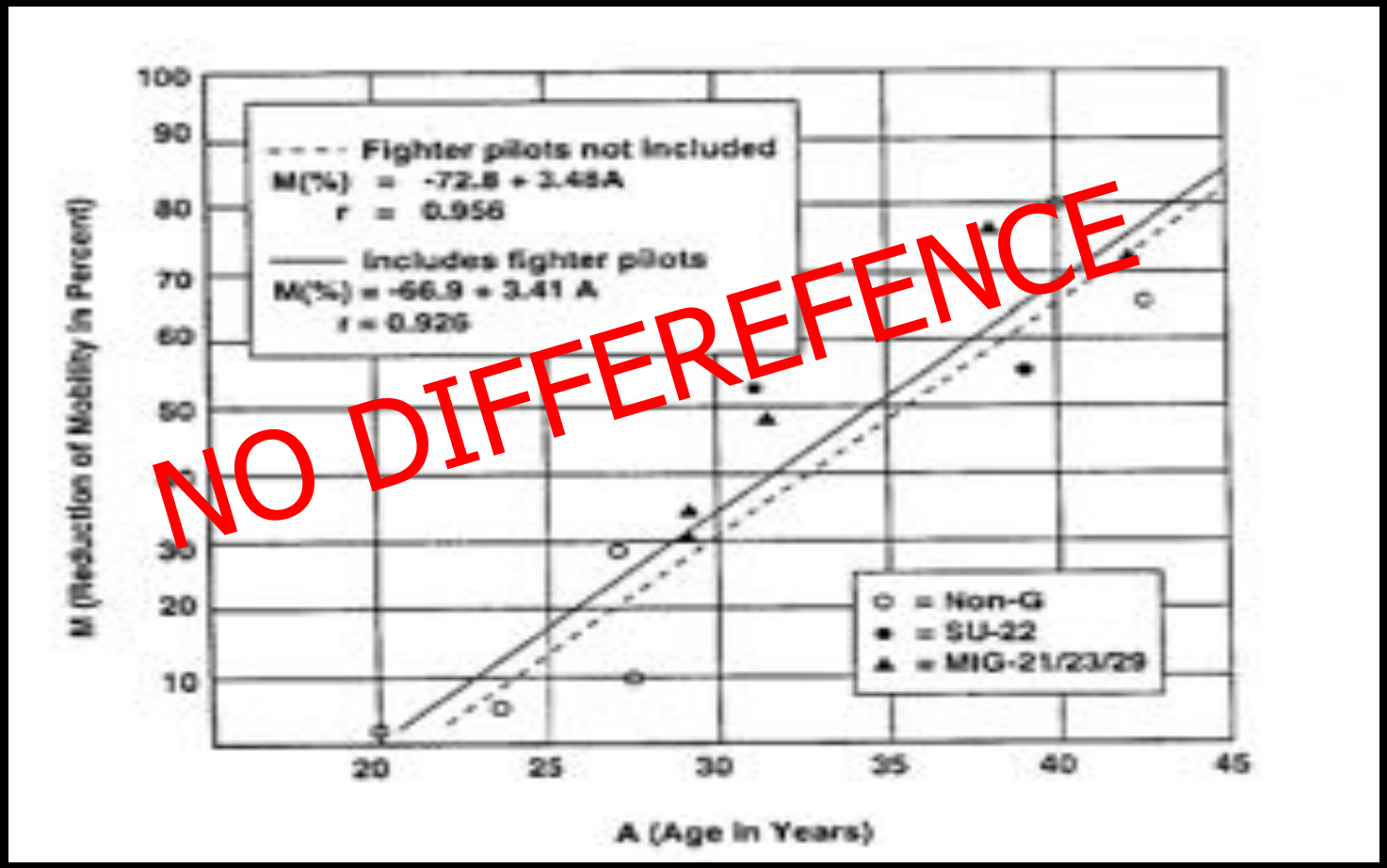
- 3% EF-2000

  (Paola Verde ICASM 2009)

Clinical Studies

- Kinematic Studies
  - High vs low G
- Radiographic changes
  - Pilots vs non-pilots
  - Pilots vs age
- MRI studies

Cervical Kinematics – Age and Aircraft Type



Talal J RTO RT -4 1999

Review of the Vertebral Column Pain Problems in Polish Air Force Fighter Pilots

MRI: Pilots vs non-pilots

Table 3-1: Occurrence of Inter-vertebral Disk Degeneration in Pilots and Non-flying Controls (37).

	All Disk Changes (%)[1]		Mild Disk Changes (%)[2]		Moderate Disk Changes (%)[3]		P <
Disk	Pilots	Controls	Pilots	Controls	Pilots	Controls	
C_{2-3}	25	18	0	5	[illegible]	14	n.s.
C_{3-4}	88	64	0	7	88	36	0.01
C_{4-5}	67	50	[illegible]	32	29 (38)[4]	18	n.s.
C_{5-6}	79	86	8	36	67	50	n.s.
C_{6-7}	79	68	13	9	58 (64)	45 (59)	n.s.
Mean	68	57	10	22	53	33	

[1] include mild, moderate, and severe; [2] include mild; [3] include moderate; [4] in parenthesis includes severe.

NO DIFFEREFENCE

Hamalainen, O., Vanharanta, H., Kuusela, T.
Degeneration of cervical intervertebral disks in fighter pilots frequently exposed to high +Gz forces. Avia. Space Environ. Med. 64:692-696, 1993.

MRI: Transport vs Fighter Pilots

Groups	CAP	%	HPAP	%
N[1]	24		24	
Age (yrs)	31.4		32.5	
Flying Time (hrs)	1272		[illegible]	
Signal Intensity[2]	0	[illegible]	[illegible]	**12.5**
Osteophytes	2	12.5	2	12.5
Signal Intensity[3]	4	16.6	10	41.7
Disk Height	8	33.3	6	20
Disk protrusion	9	41.3	12	50
Deformities[4]	1	4.2	1	4.2

[1] Number of subjects per group; [2] vertebrae; [3] Disk; [4] Spinal column; [5] Bold indicate values > in HPA

NO DIFFEREFENCE

Radiological Evaluation of the Cervical Spine of High Performance Aircraft Pilots of the Spanish Air Force (SPAF) F R Tehada, RTO RT – 4 1999

Reliability of Imaging Studies

- Not reliable in predicting neck pain
- Radiographs
  - Age related changes
- MRI
- CT Scan
  - Fair to moderate reliability


Assessment of Neck Pain and Its Associated Disorders

Results of the Bone and Joint Decade 2000–2010 Task Force on Neck Pain and Its Associated Disorders

Reliability of Clinical Examinations

- Cervical flexor endurance good predictor
- Poor specificity
  - Range of motion
  - Trigger Points
  - Provocation tests
    - Specific for nerve root


Assessment of Neck Pain and Its Associated Disorders

Results of the Bone and Joint Decade 2000–2010 Task Force on Neck Pain and Its Associated Disorders

G Load and Neck Pain

G Level	Low	Medium	High		
AIRCRAFT TYPE	**F-1**	**A7, A-4, F-4, F-5**	**F-15**	**F-16**	**F-18**
Vanderbeek (1988)		30.7%	51.2%	57.6%	
Knudson et al (1988)		30-50%			74%
Newman (1997)		82%			85%
Kikukawa (1994)	14.8%	30%	95%		
Hamalainen et al (1997)		38%			

Neck Pain and Extensor Strength

- 3 groups
  - F pilots with pain
  - Asymptomatic pilots
  - Pain free controls
- Lower MVC in extensor muscles in fighter pilots with neck pain

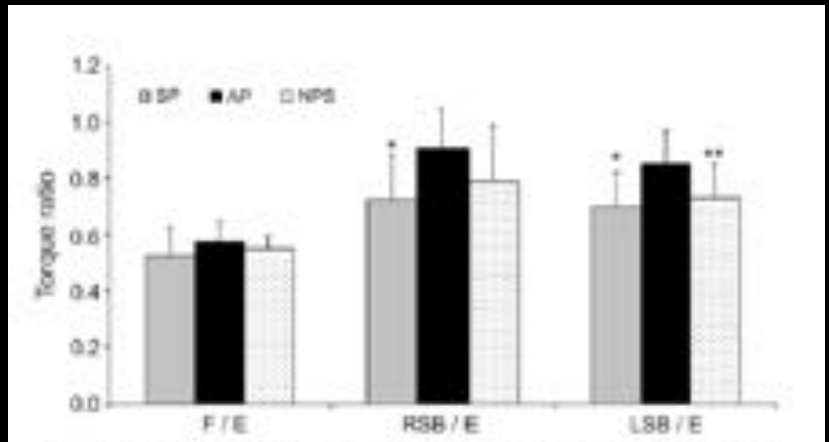
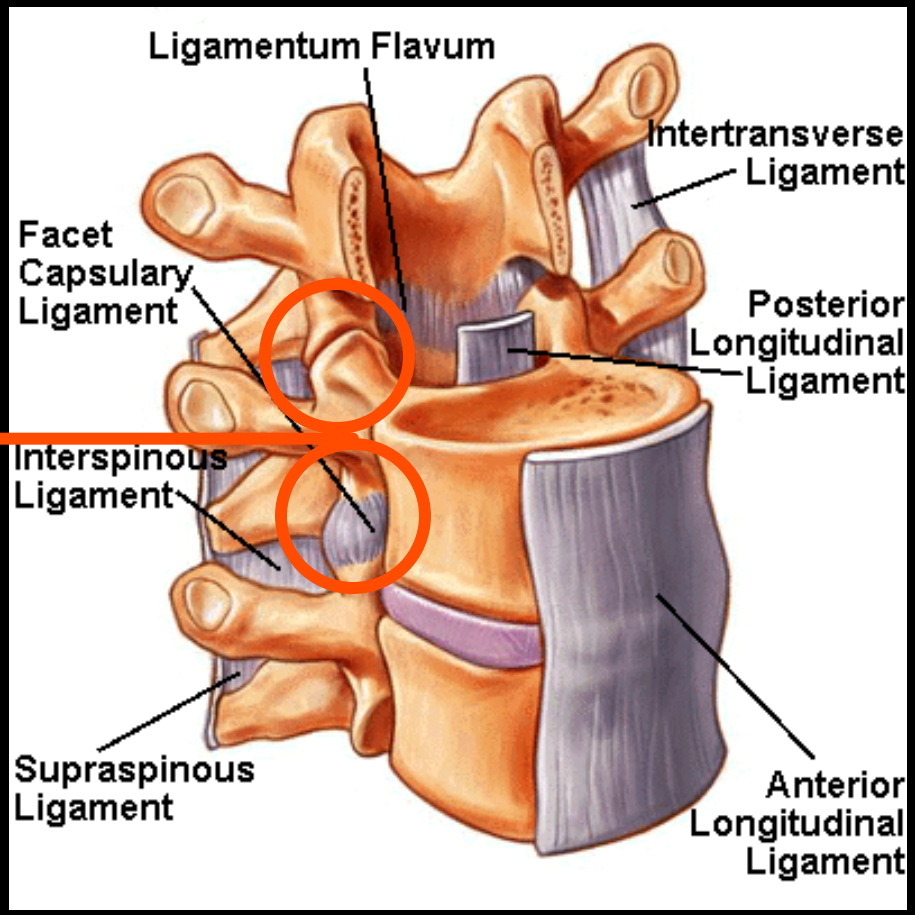


Fig. 1. Right and left side bending (RSB and LSB) and flexion (F) torques to extension (E) torque ratio in symptomatic pilots (SP, $N = 9$), asymptomatic pilots (AP, $N = 10$), and non-pilot subjects (NPS, $N = 8$). ** $P < 0.01$, * $P < 0.05$: significant differences compared with AP. Values are mean (SD).

Lecompte et al Neck strength and EMG activity in fighter pilots with episodic neck pain. ASEM 2008; 79: 947 – 52 .
Ang et al. Neck strength and myoelectric fatigue in fighter pilots with a history of neck pain. ASEM 2005; 76:375– 80.

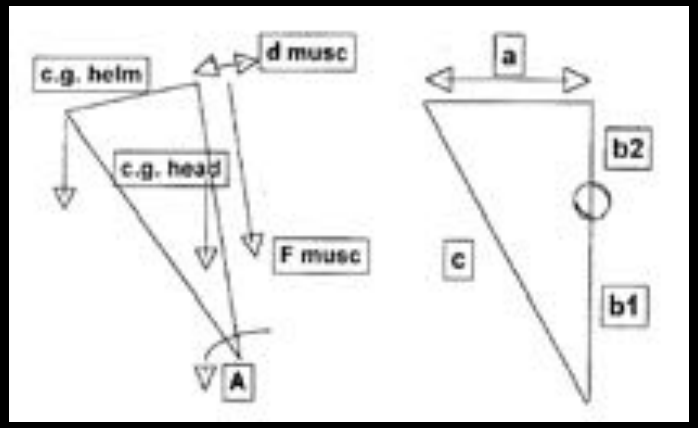
Where comes the pain from?

- Disk
- Ligaments
  - Great Strength
- Muscle
- Bone
- Facet

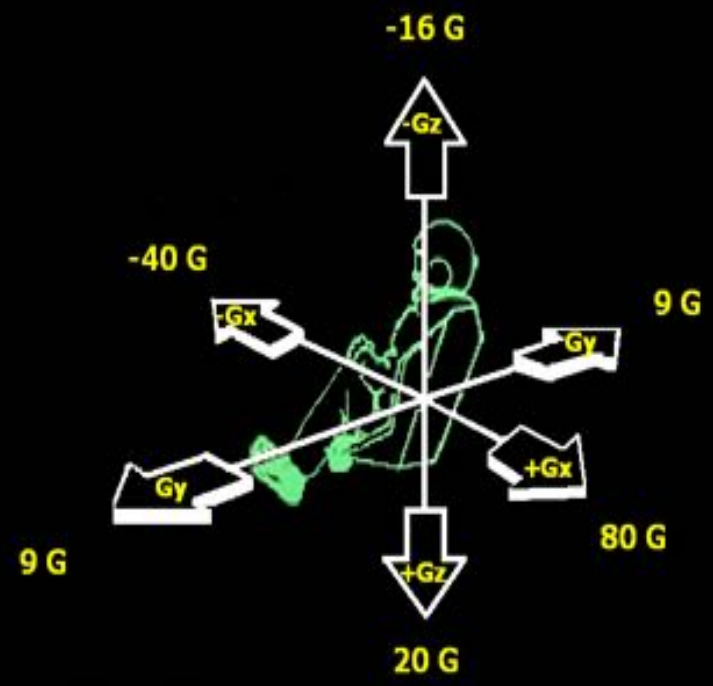


Biomechanical Studies

- Mostly impact studies
- Few acceleration studies
  - In vivo
    - In flight EMG: MVC %
    - Fatigue after static loading
    - Anthropometric data
    - Centrifuge studies
  - In vitro
    - Finite element studies



Human G tolerance: In Vivo Experiment



Finite Element Studies

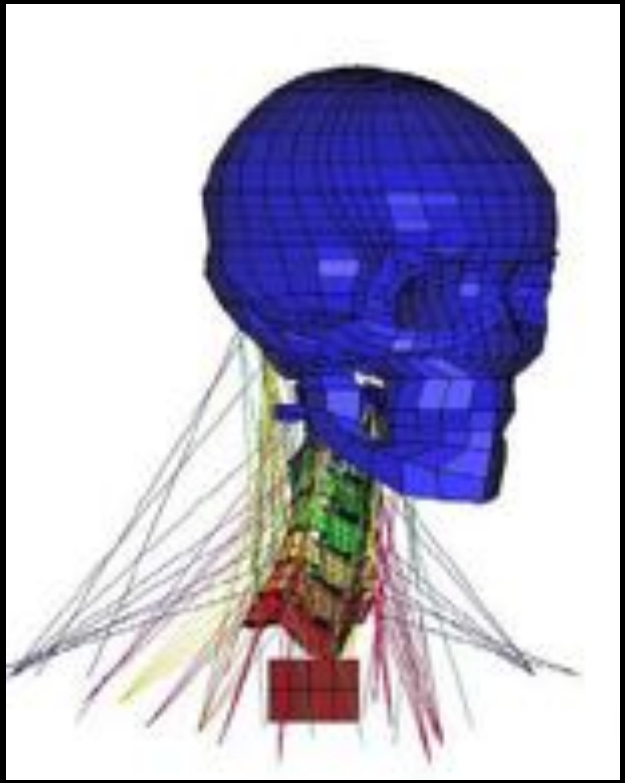
- Flexion Increases Neck Muscle force from 40 to 90 N

  (Snijders et al J. Biomech 1991)

- Safe Gz limits for different postures

Neutral	30 Gz
Flexion	25 Gz
Extension	15 Gz
Extens/lat. bend.	7 Gz

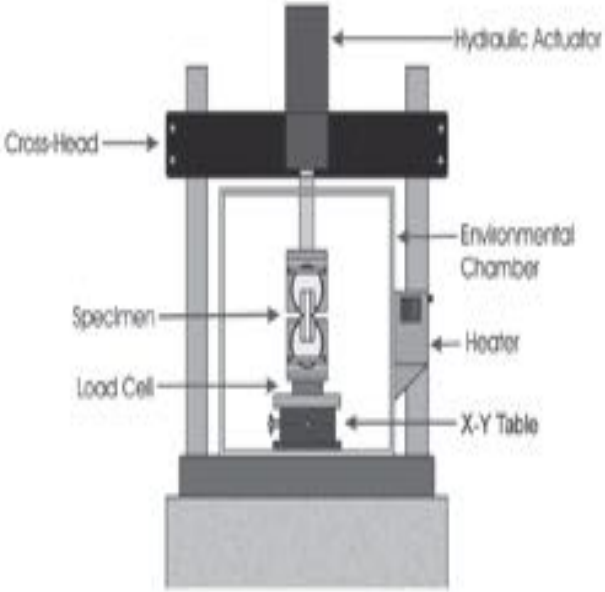
(Helleur et al ASEM 1984)



Cervical Spine Ligaments Failure

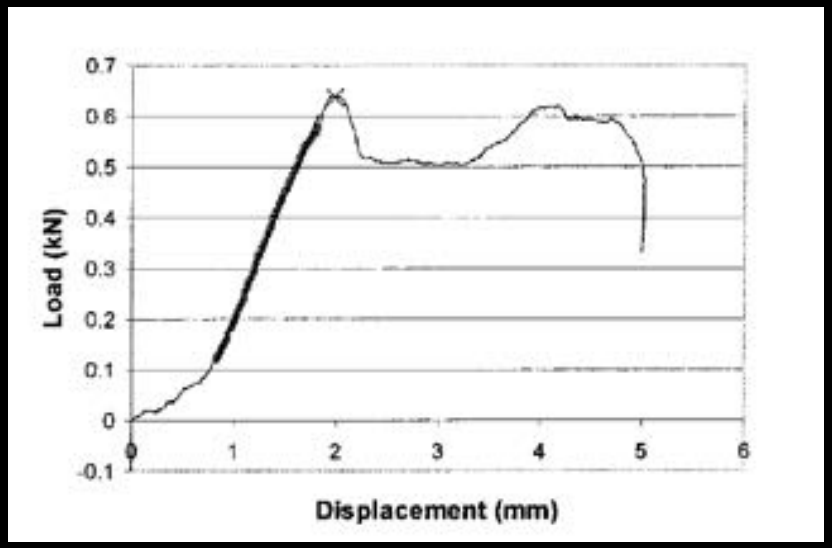
Ligament	Spinal Level	Gender	Mean Failure Force ± SD (N)
Anterior longitudinal ligament	C3–C4	M	494.0 ± 359.2
		F	294.4 ± 194.0
	C5–C6	M	326.2 ± 115.6
		F	284.8 ± 169.6
	C7–T1	M	355.1 ± 242.0
		F	673.5 ± 104.4
Posterior longitudinal ligament	C3–C4	M	462.9 ± 356.8
		F	87.0 ± [illegible]
	C5–C6	M	15.3 ± [illegible]
		F	58.4 ± [illegible]
	C7–T1	M	415.3 ± 90.4
		F	431.4 ± 191.8
Ligamentum flavum	C3–C4	M	315.8 ± 97.9
		F	134.0 ± 21.4
	C5–C6	M	269.7 ± 143.0
		F	136.2 ± 45.0
	C7–T1	M	177.4 ± 137.0
		F	303.6 ± 98.2

3500-4500 N



Bass et al 2007

Cervical Vertebra Body Failure Load



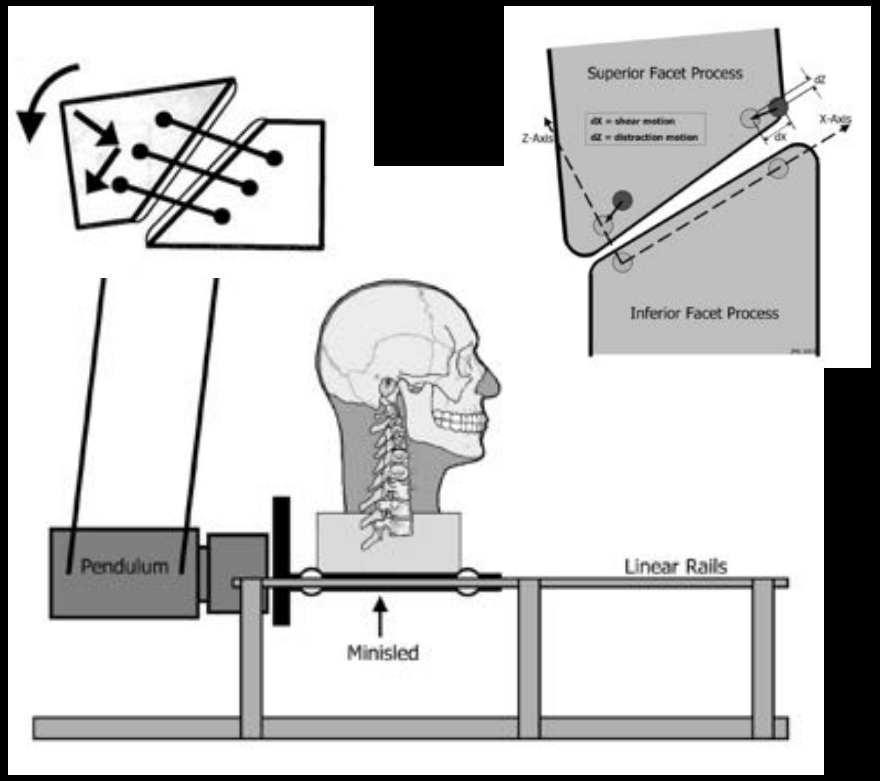
- 550 - 754 N

Truumees et al 2003

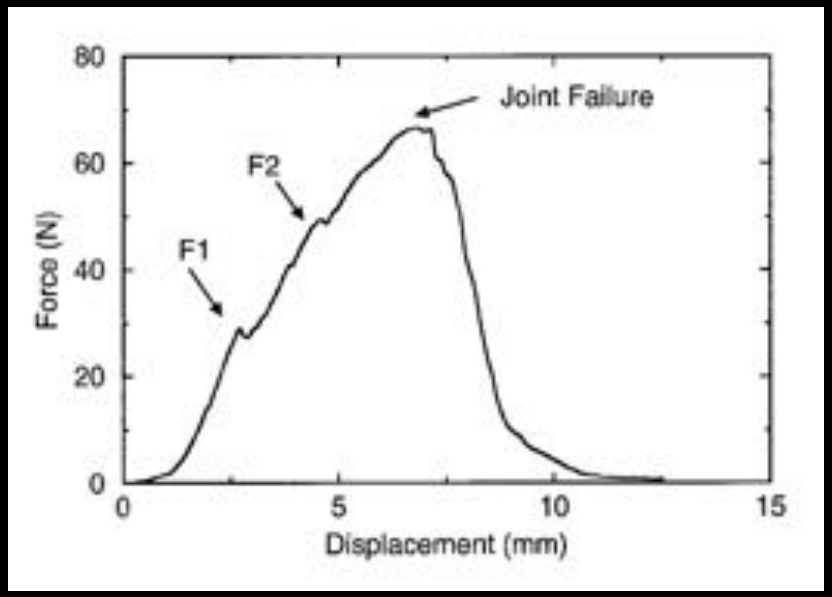
Morroney et 1988

Facet Joint Whiplash Kinematics

- Capsular strain 40% at -8Gx
  - Stemper, Yonganatan, Pintar 2004
  - Pearson et al 2004



Facet Capsule Failure Load



- 95-115 N C3–C4
- 75-85 N C5–C6

Myklebust et al (1988)

Winkelstein et al (1999)

Effect of Head Posture

- Axial pre-torque of the head and neck increases facet capsular strains (check six)

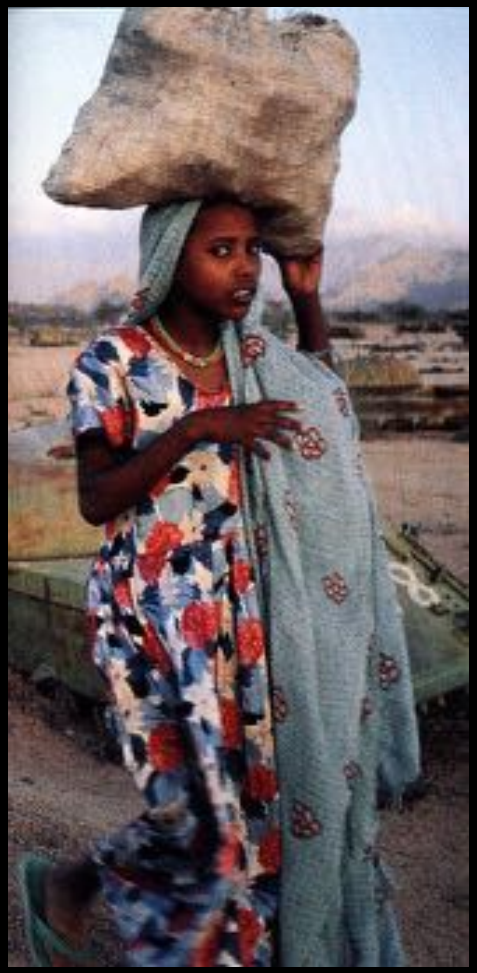
Need For in Vitro Model

- Simulate High G loads
- Measure stress and strain
- Identify weak links and dangerous postures
- Study the effects of personal equipment
- Study the effects of pathology and surgery
- Record events during cervical kinematics under preload
- Validate finite element models

In Vivo Cervical Preload

- Head Weight: 34-47 N
- Helmet and mask: 20 N

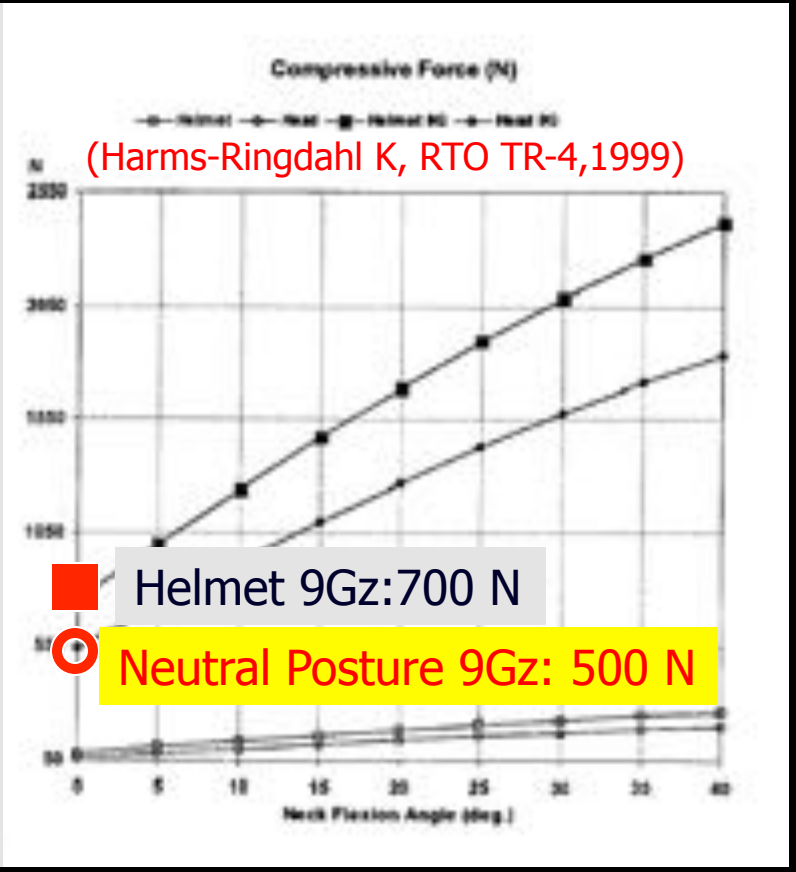
- Muscle preload: 53-1175 N
  - Moroney 1988
  - Hattori et al 1981



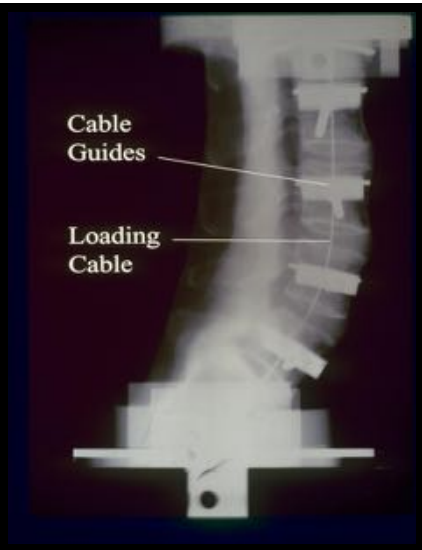
Calculated Cervical Preload

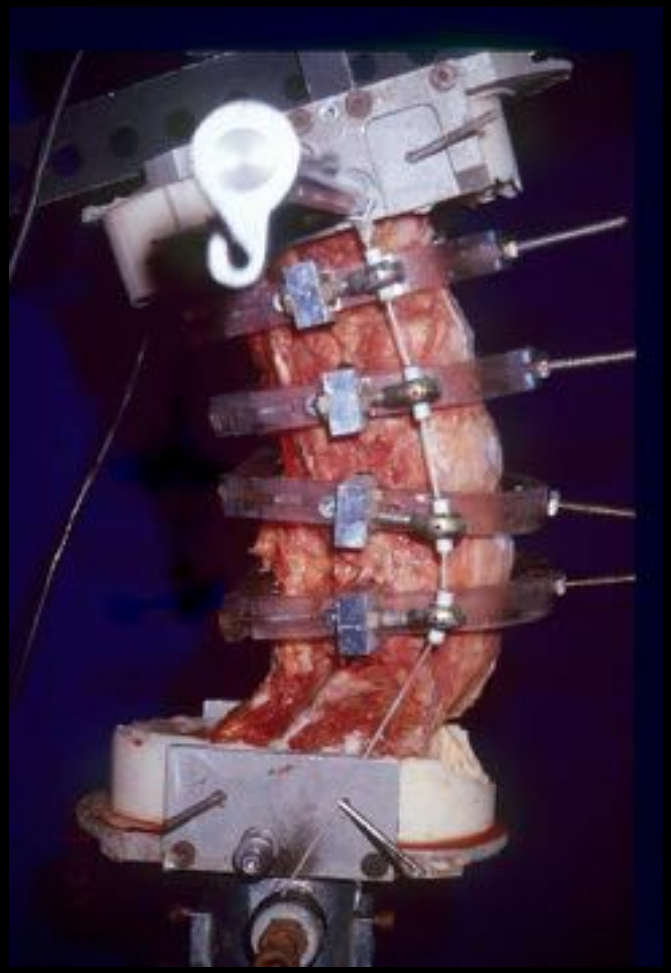
- Head weight and posture
  - Increased weight: Increased loads
  - Neck flexion: Increased Loads
- 9Gz Loads
  - Neutral Posture: 550 N
  - Neutral Posture Helmet : 750 N

(Harms-Ringdahl K, RTO TR-4,1999)



Follower Load Lumbar Model



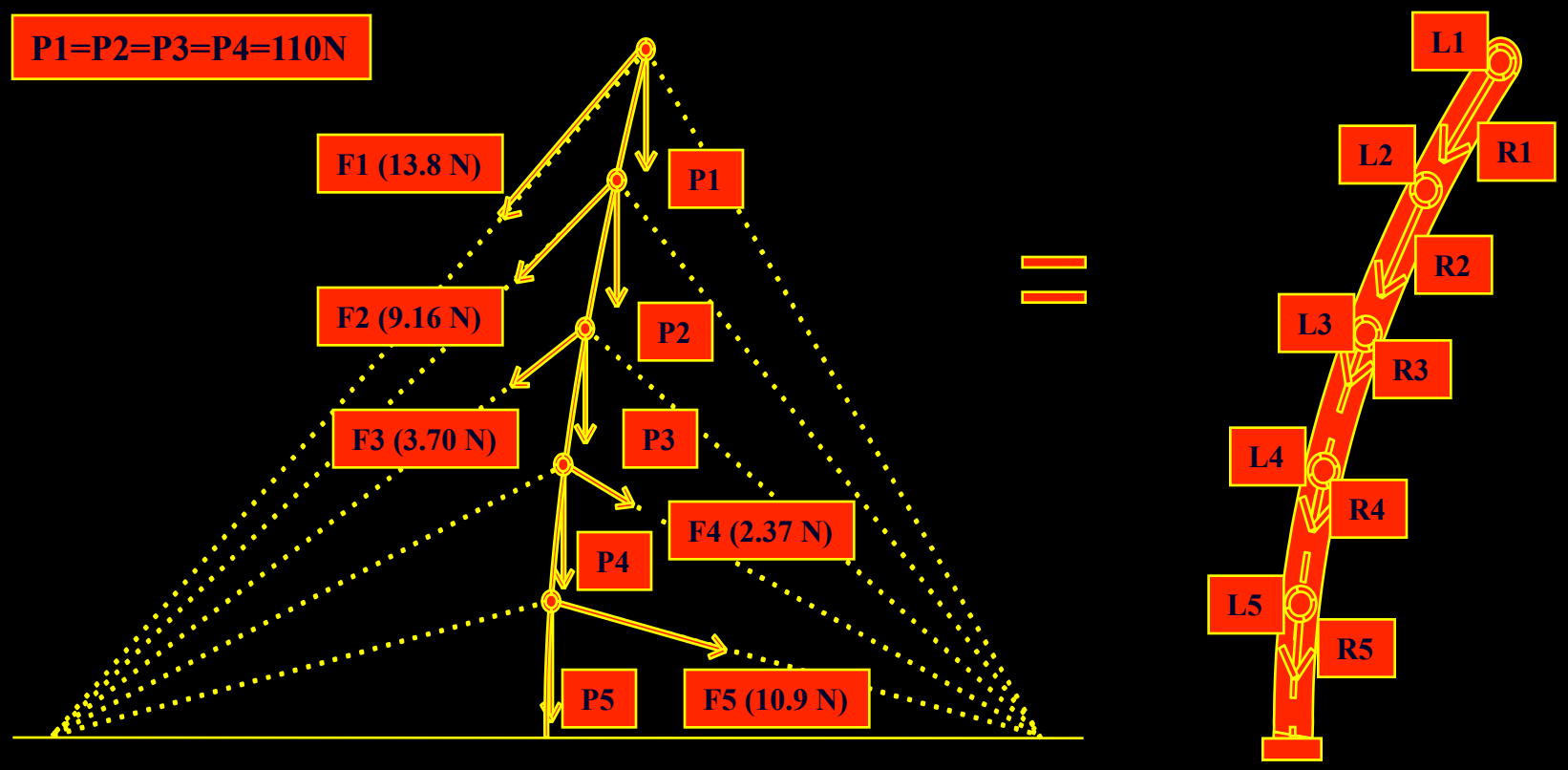


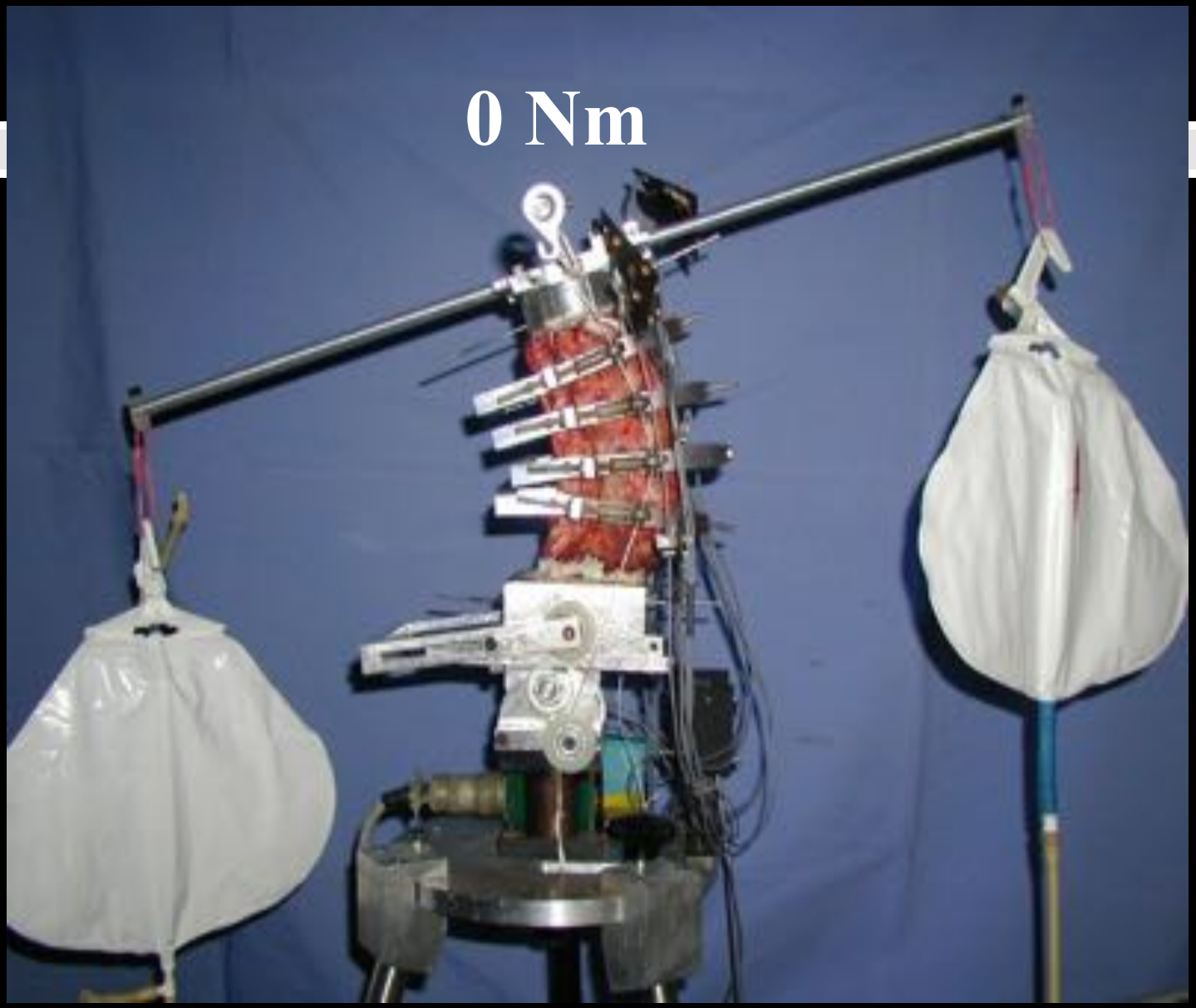
- Physiologic preload
- No buckling
- Near normal ROM

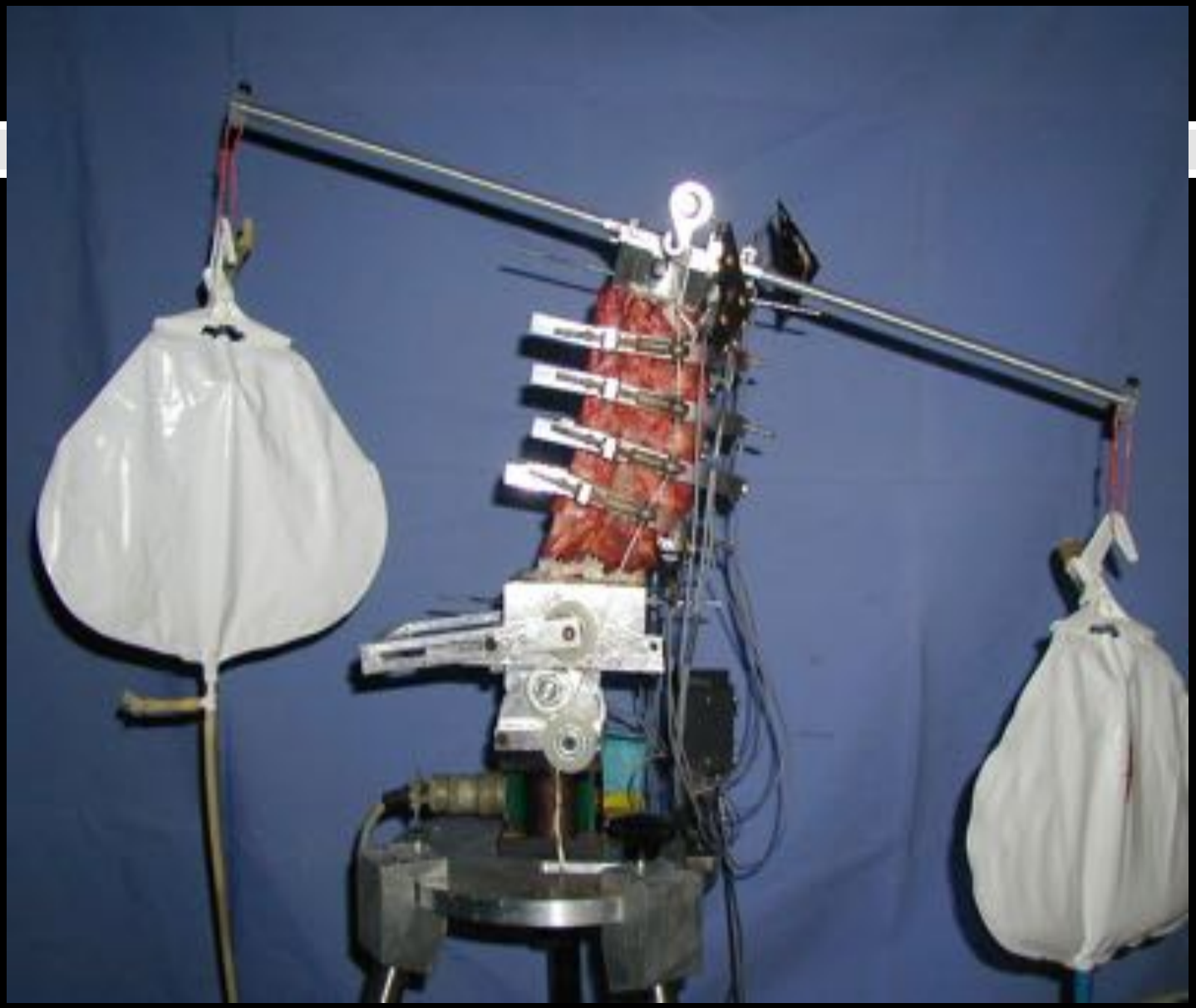
(Partwardhan et al: Spine 1999, Spine 2000)

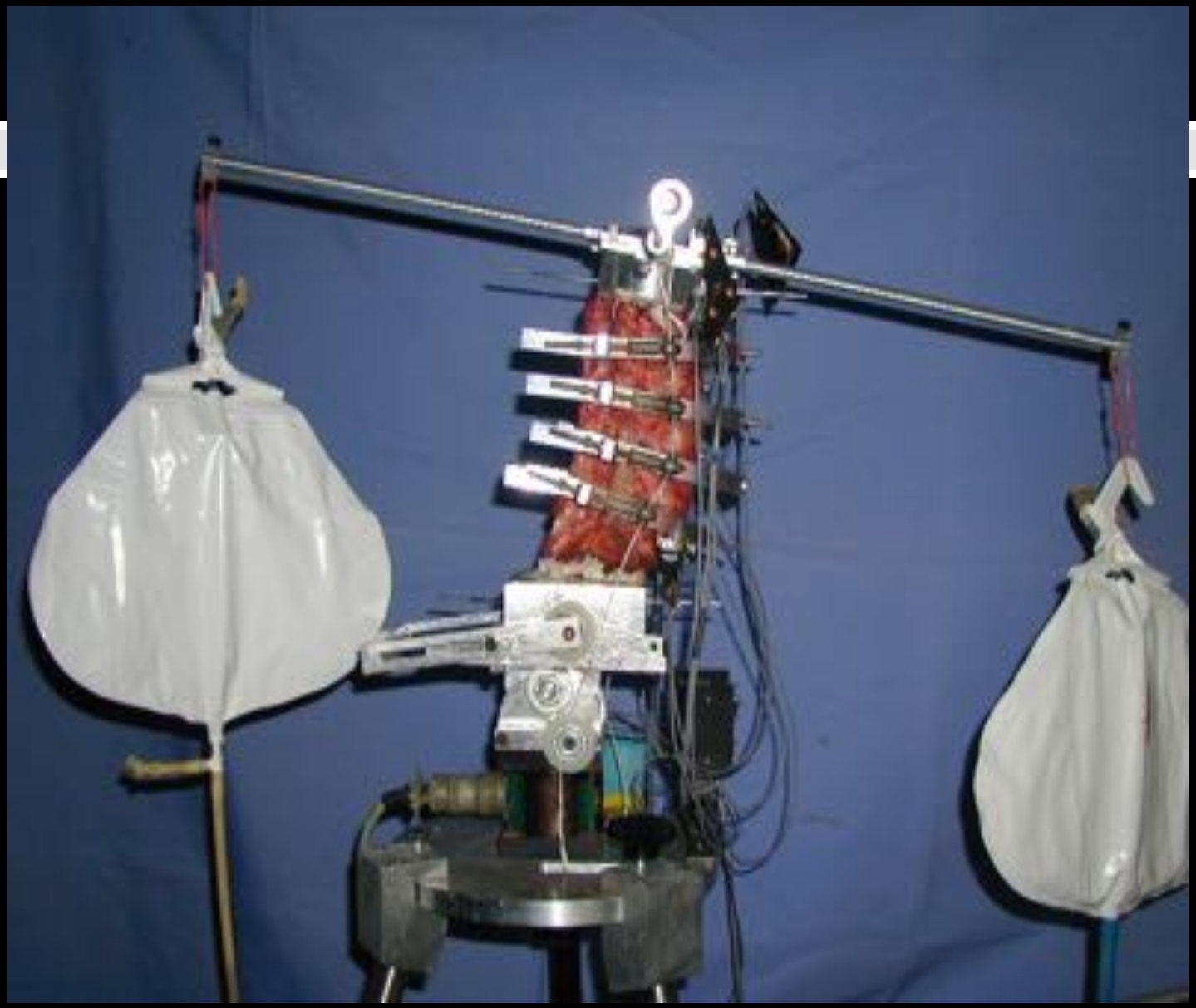
Muscle Co-Activation Vectors

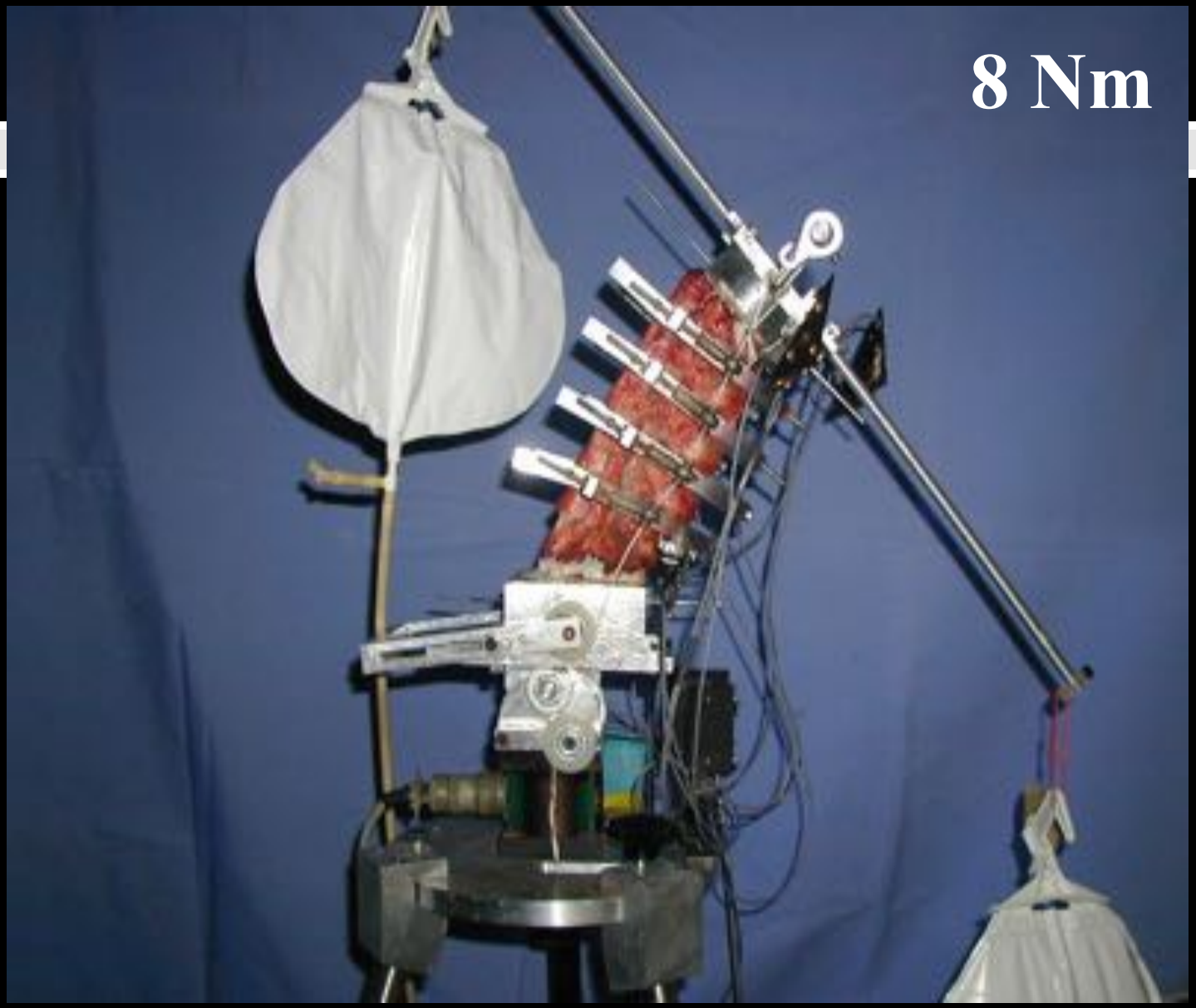
Patardhan, et al: J. Biomechanical Engineering, June 2001)



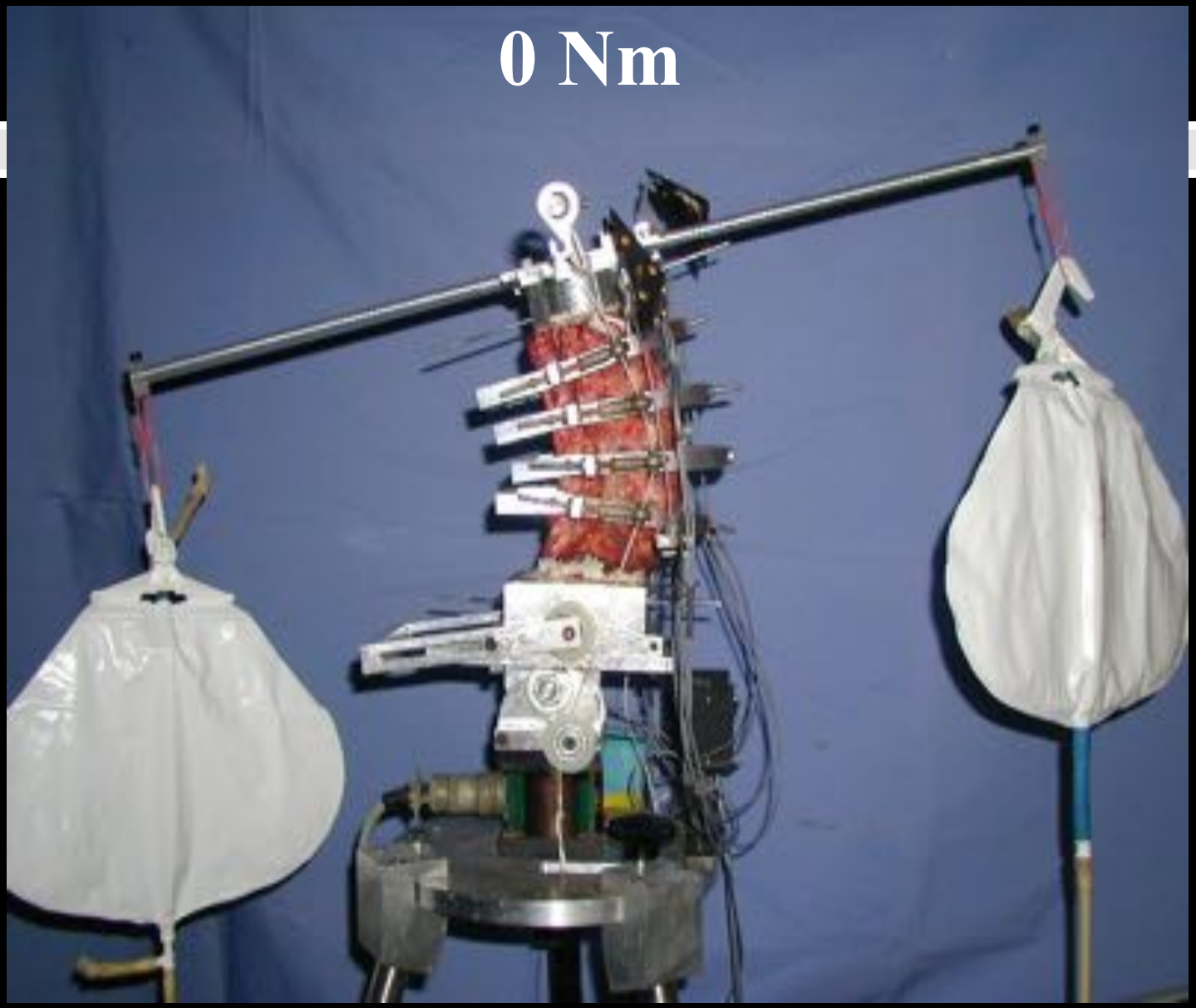

0 Nm

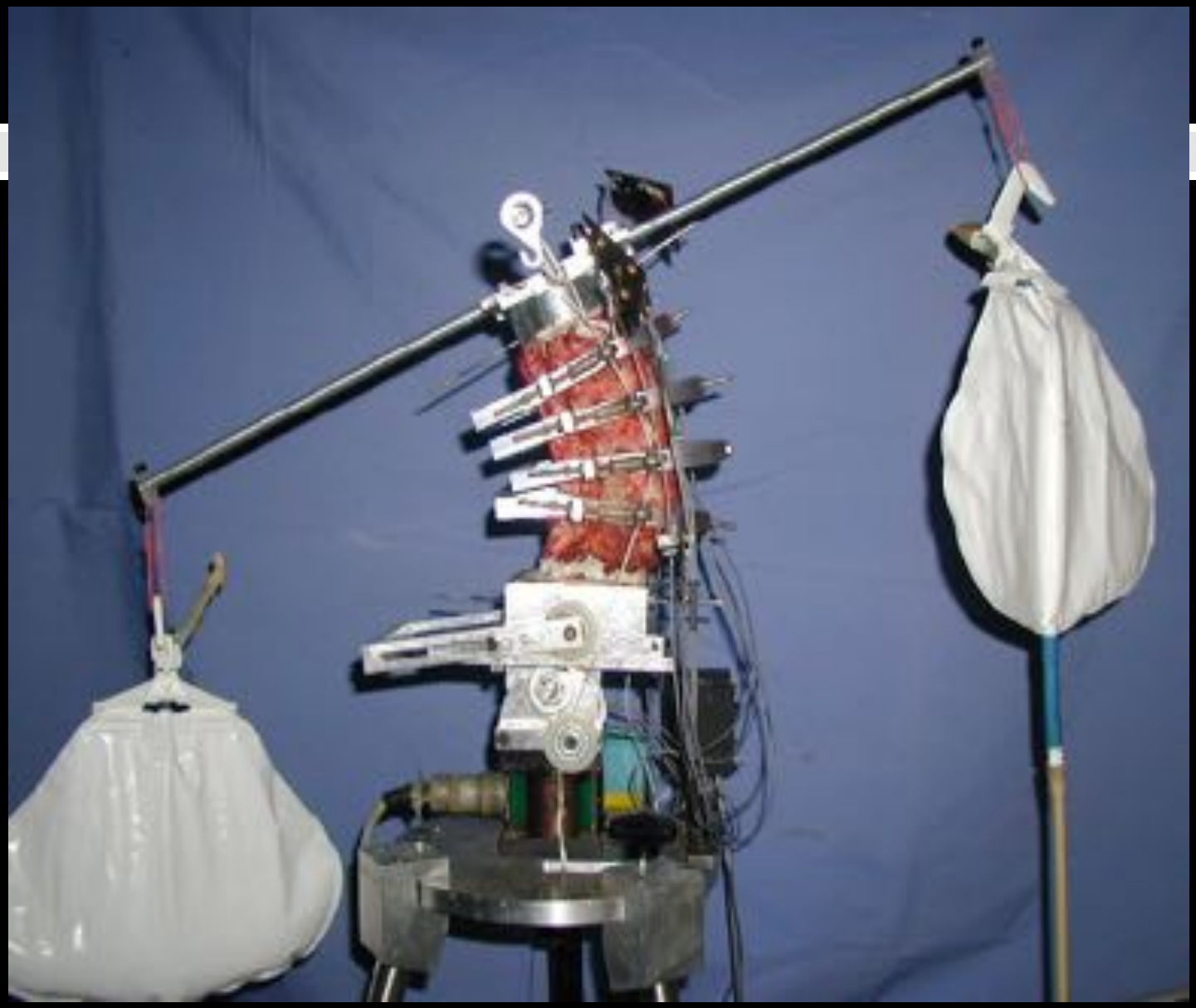


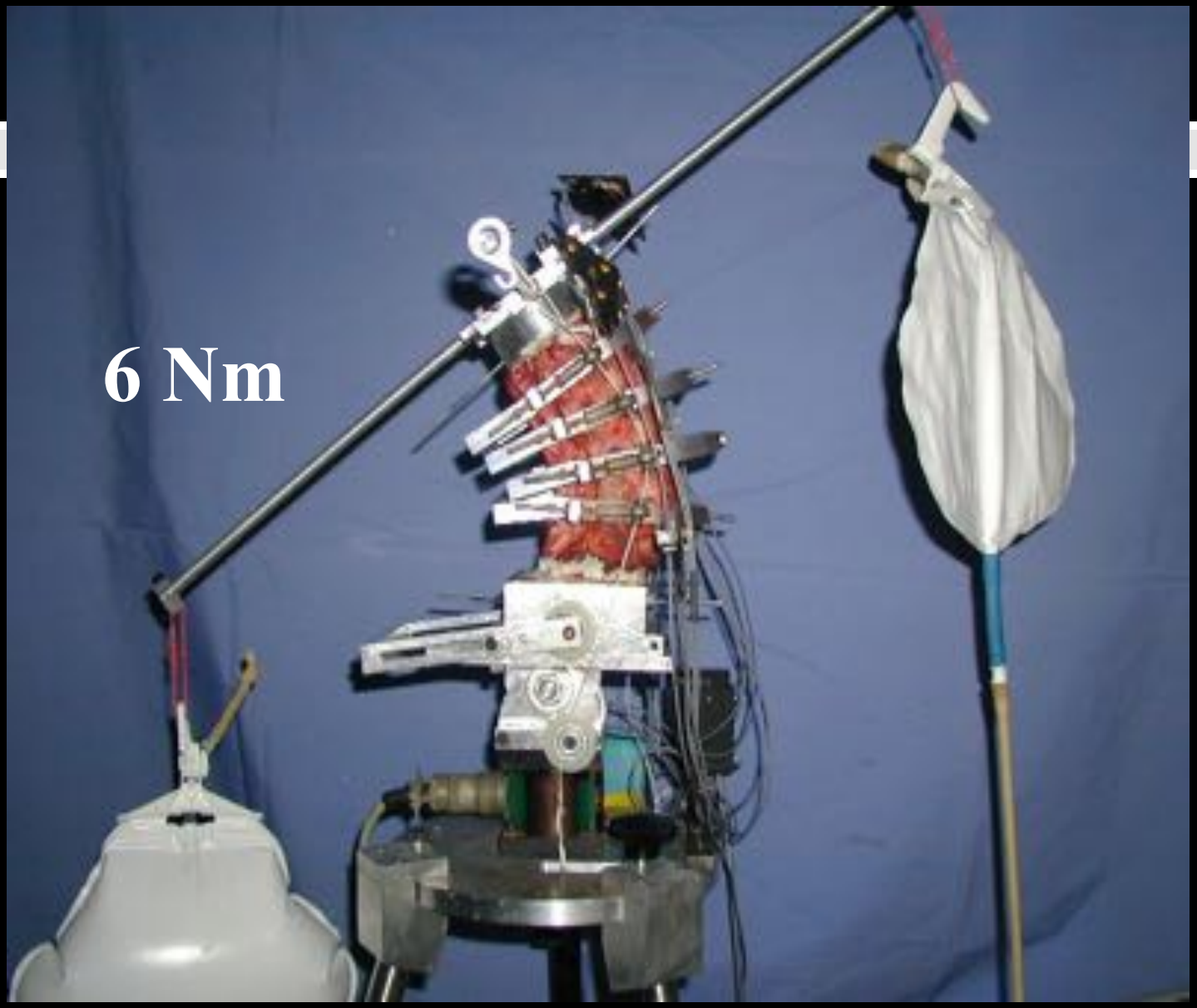


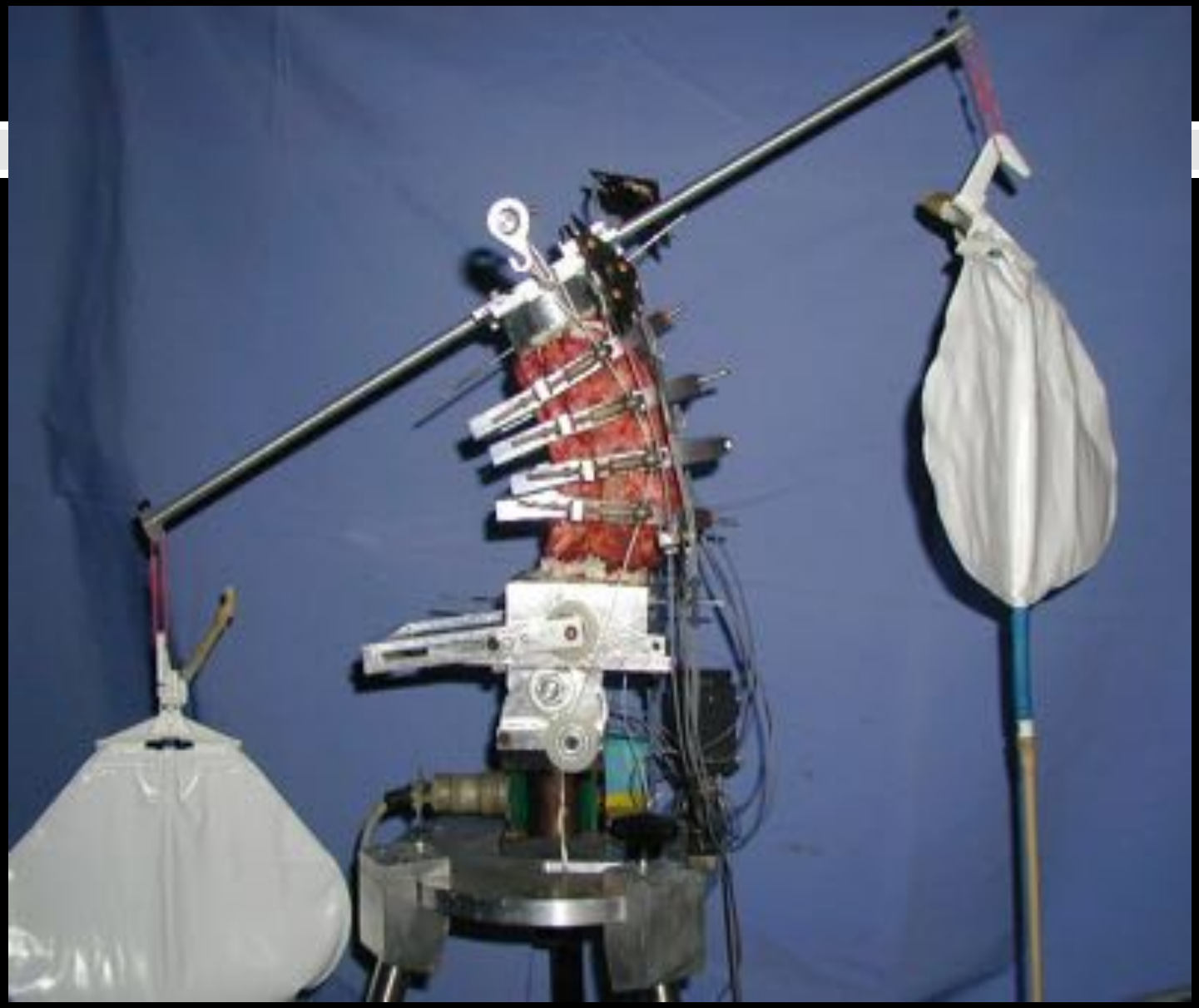

8 Nm

0 Nm

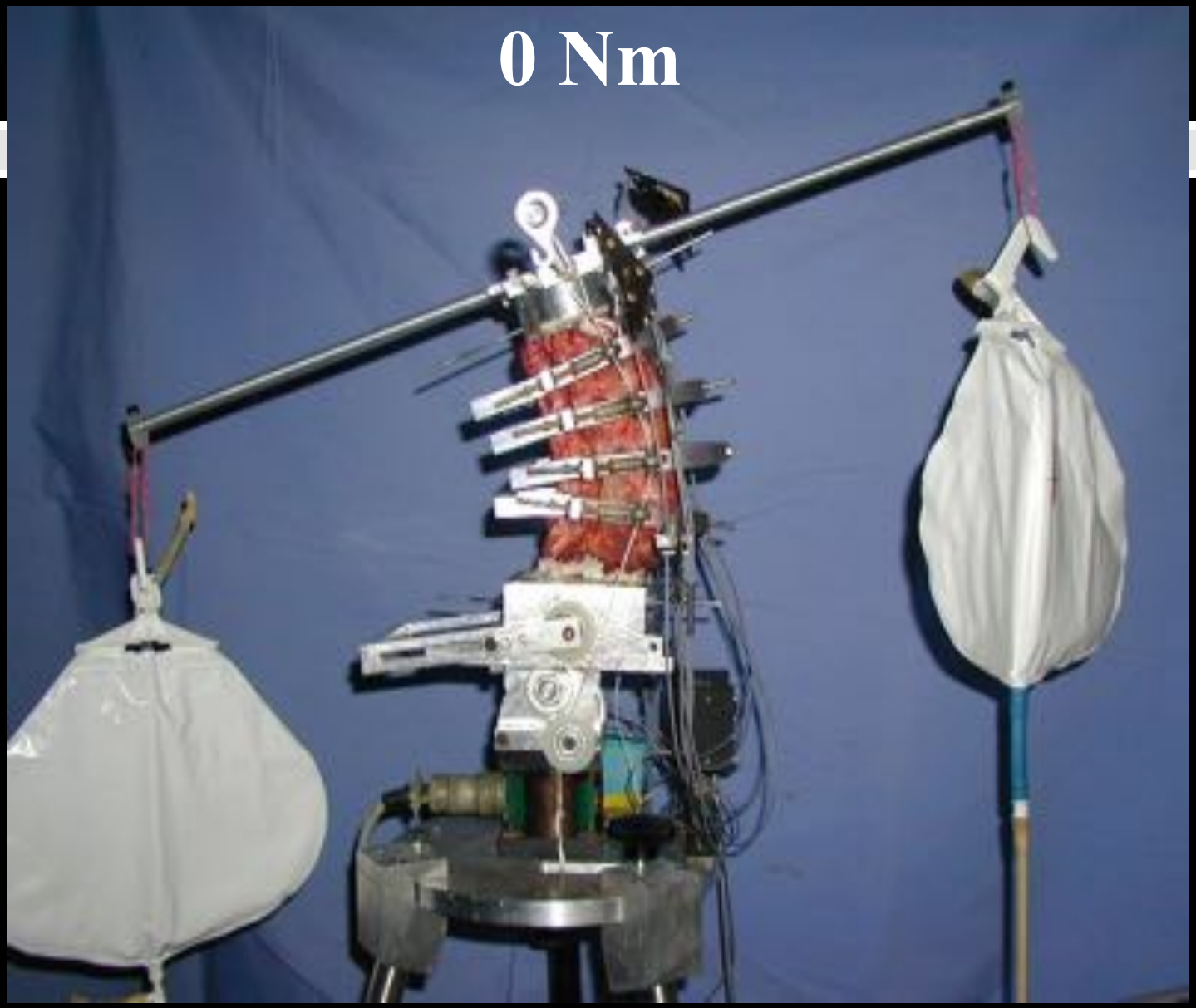





6 Nm

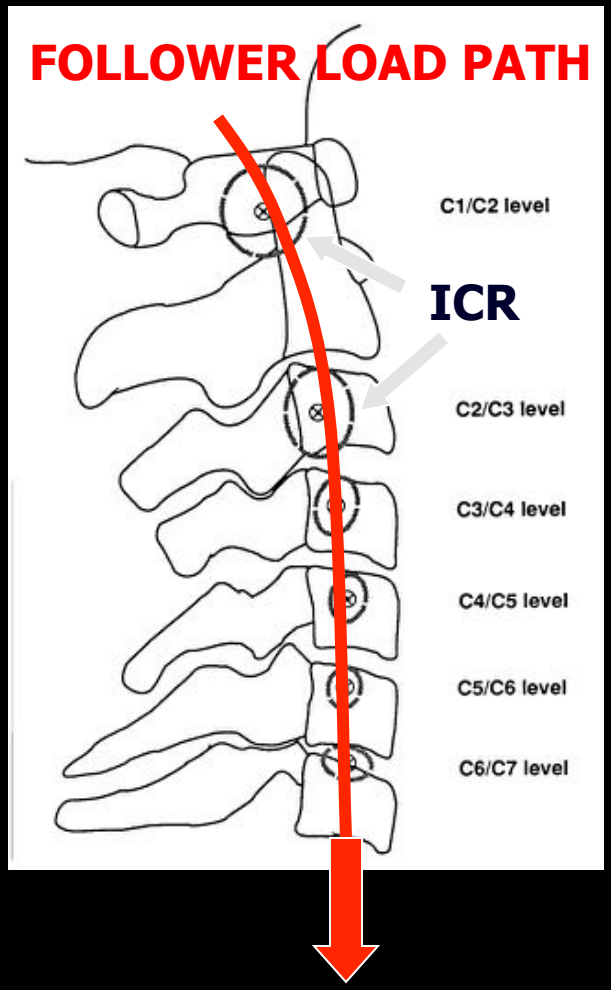


0 Nm



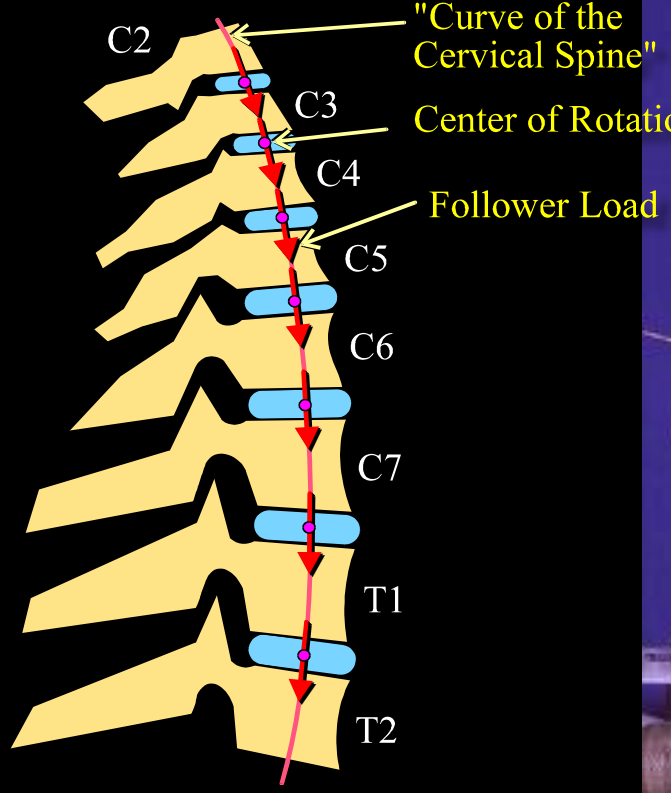
The Cervical Follower Load

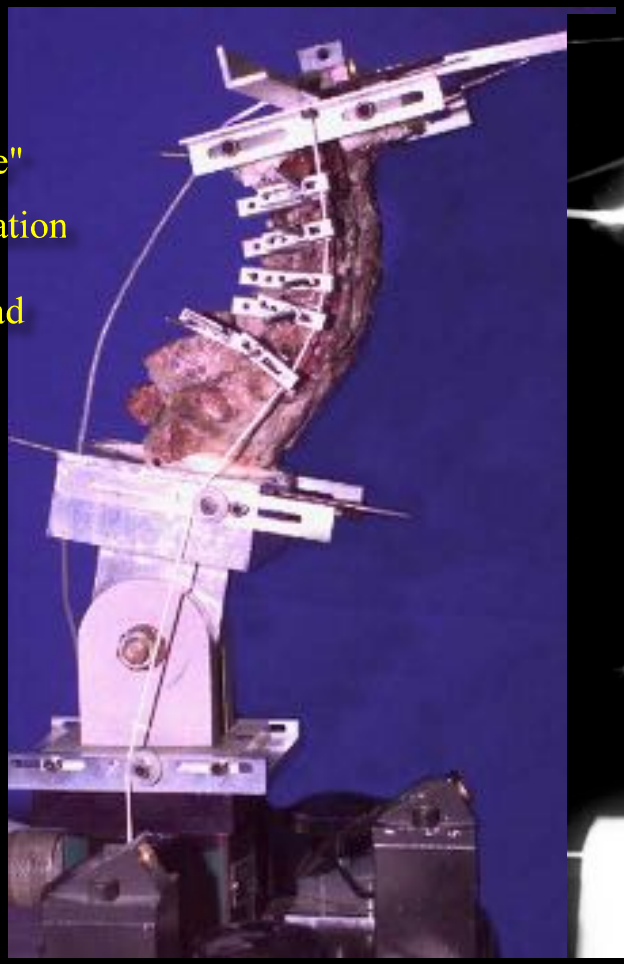
- A preload applied along the Instantaneous Centers of Rotation (ICR) will not produce artifact rotation or shear
- Kinematic studies possible
  - Introduced by Patwardhan et al Spine 2000
  - Studied also by Panjabi and colleages Spine 2002



Cervical Follower Preload

(Patwardhan et al: Spine 2000)





Experiment Hypothesis

1. Cadaveric cervical spines can sustain +9Gz load without deformation

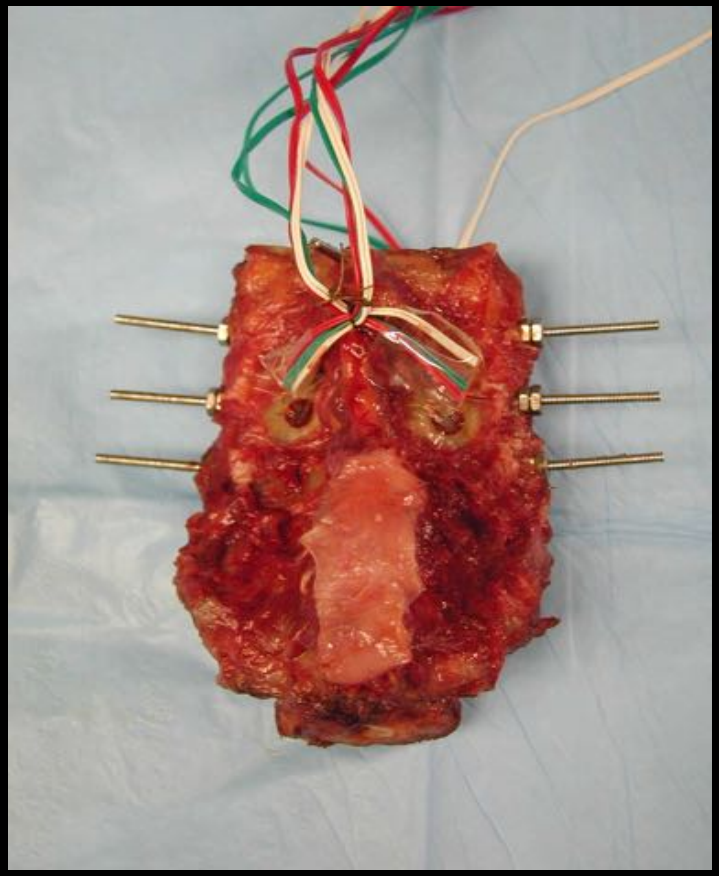
2. Facet failure strain is greater than +9Gz strain

Experiment Material

- 13 human cervical spines
- C3 to T1
- Mean age 52 years (23-74)
- X-ray screening

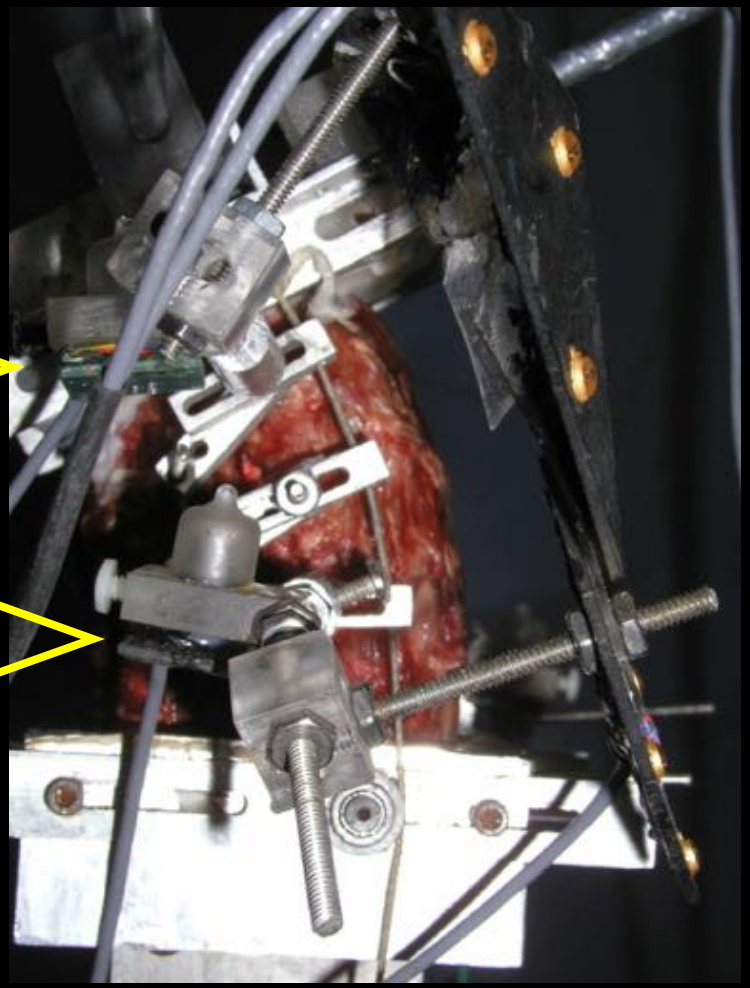
Specimen Preparation

- Bone screws into lateral masses
- Follower load path
  (Patwardhan et al Spine 2000)
- Strain gauges
  - 3 element rosettes
  - Body and each facet (3)



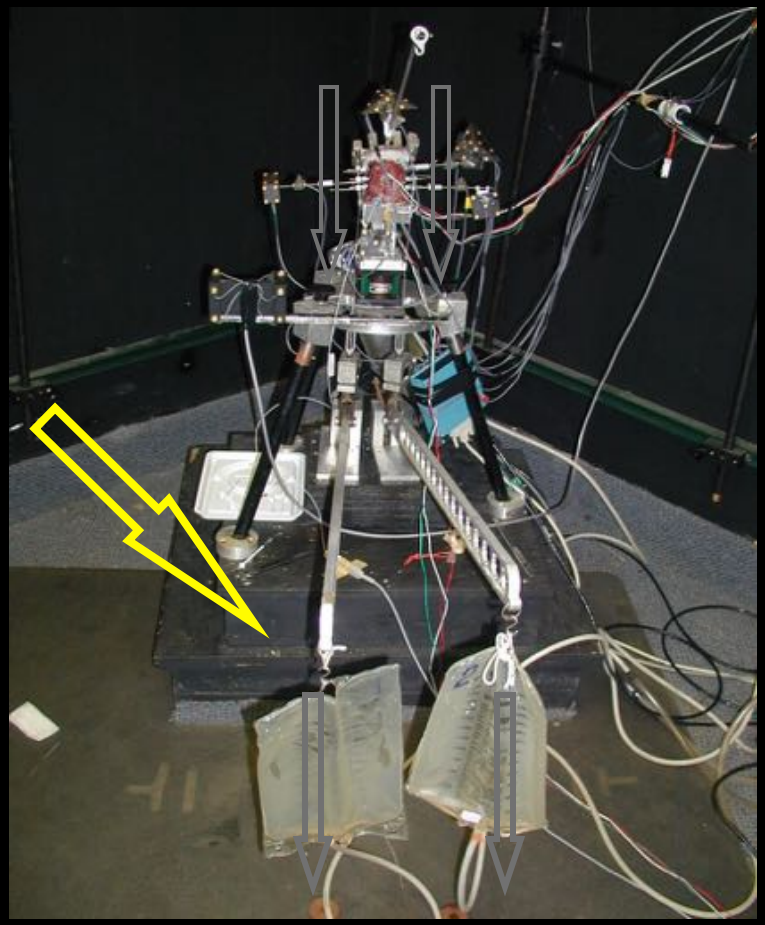
Follower Load Path Optimization

- Pulleys were adjusted so that at 200 N load no artifact motion was produced
- Optimization confirmed with angle sensors

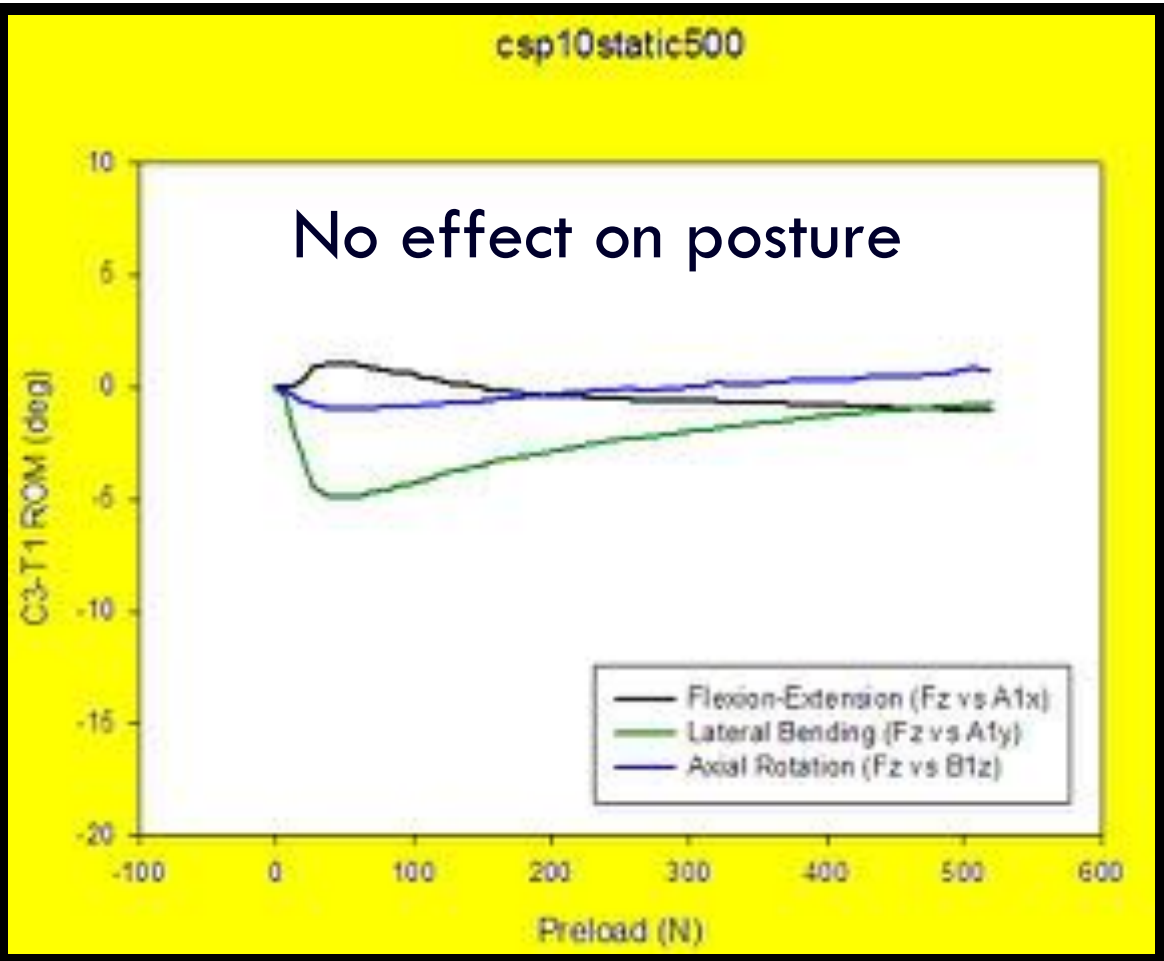


Neutral Posture Model

- Bilateral simultaneous loading through arms and lateral cables.

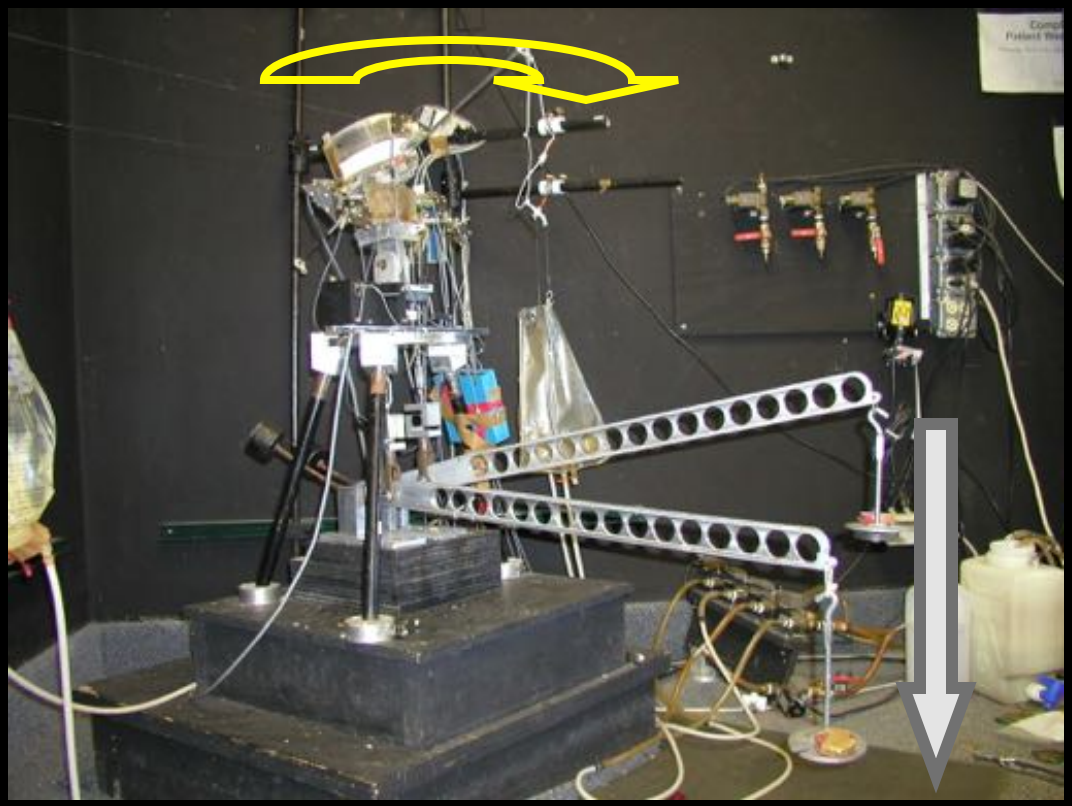


Static 6.5 +Gz (500 N) Results

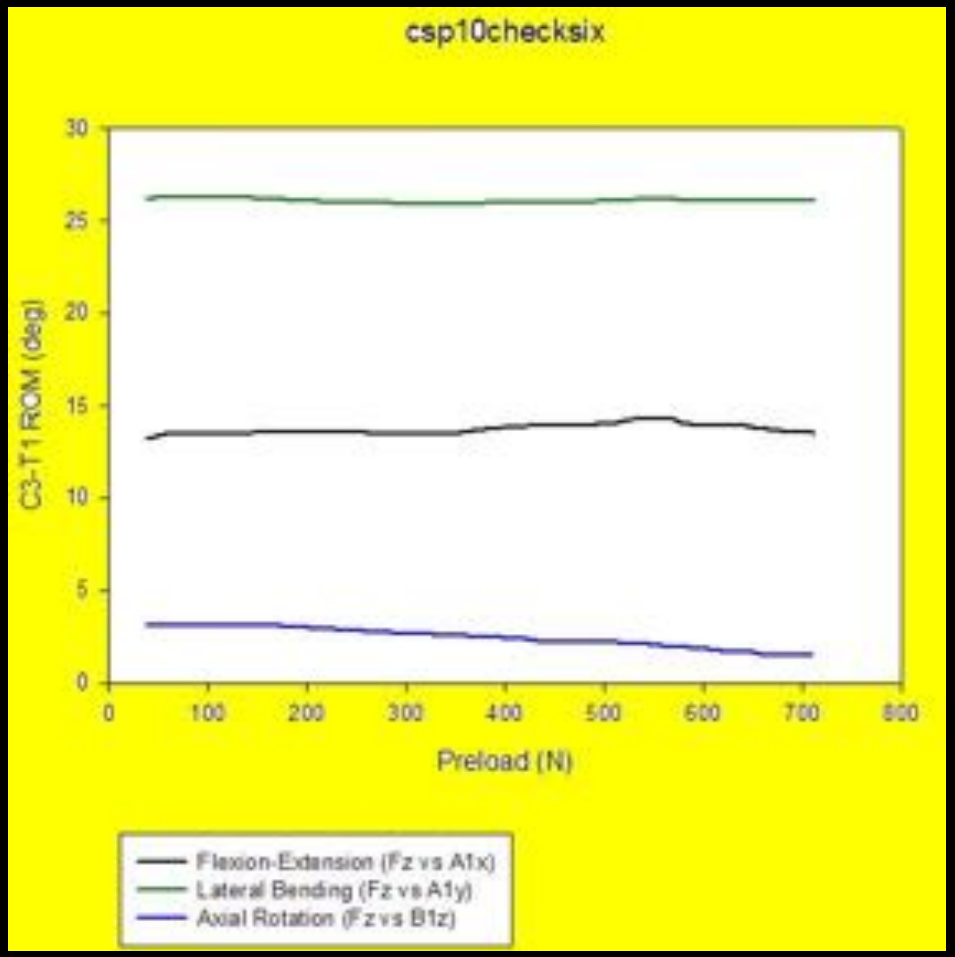


Check Six Model

- Maximum rotation to one side
- Load through arms



Check Six Model at+9Gz (700 N)



Hypothesis 1

1. Cadaveric cervical spines can sustain +9Gz load without deformation
   1. In neutral
   2. In check six

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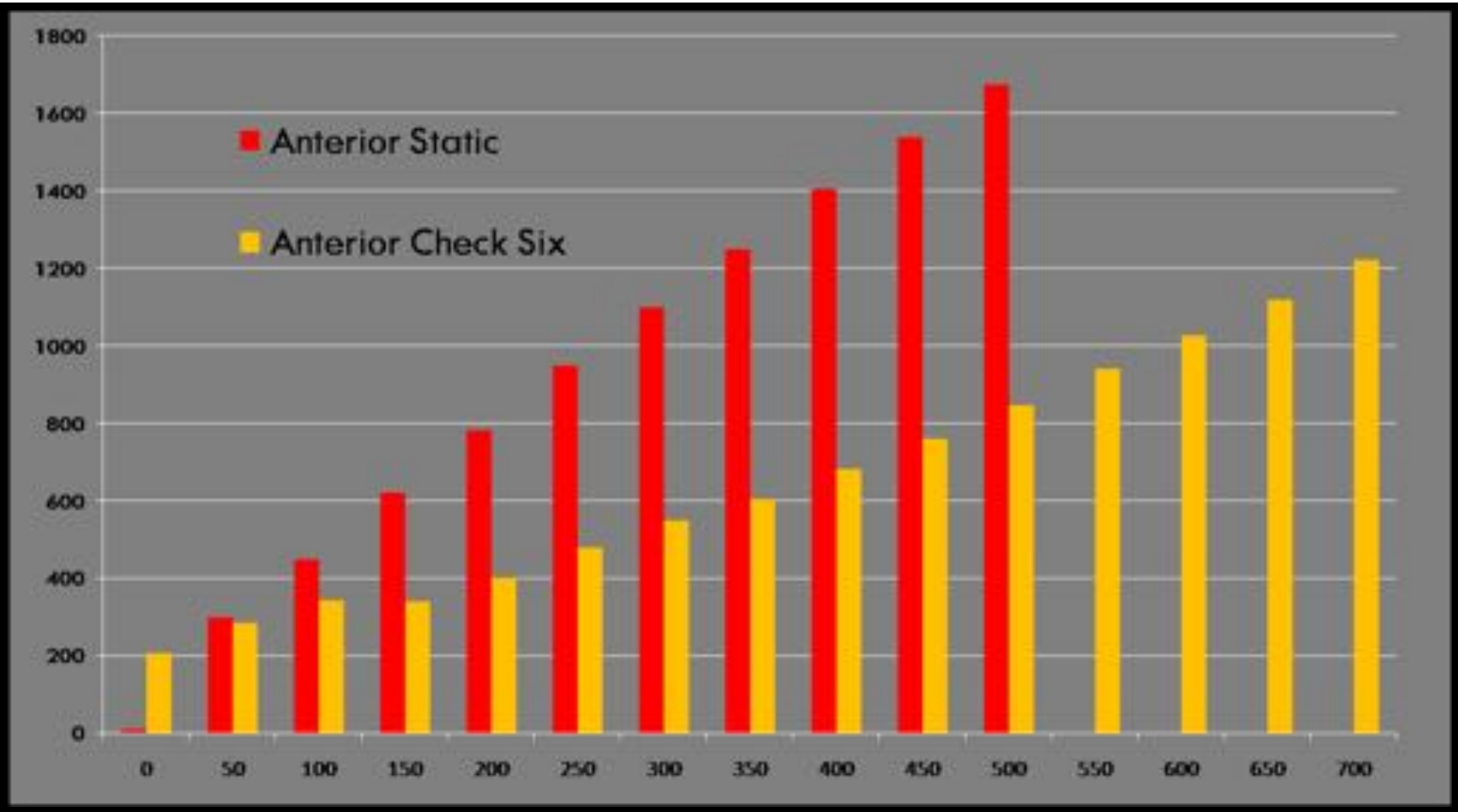
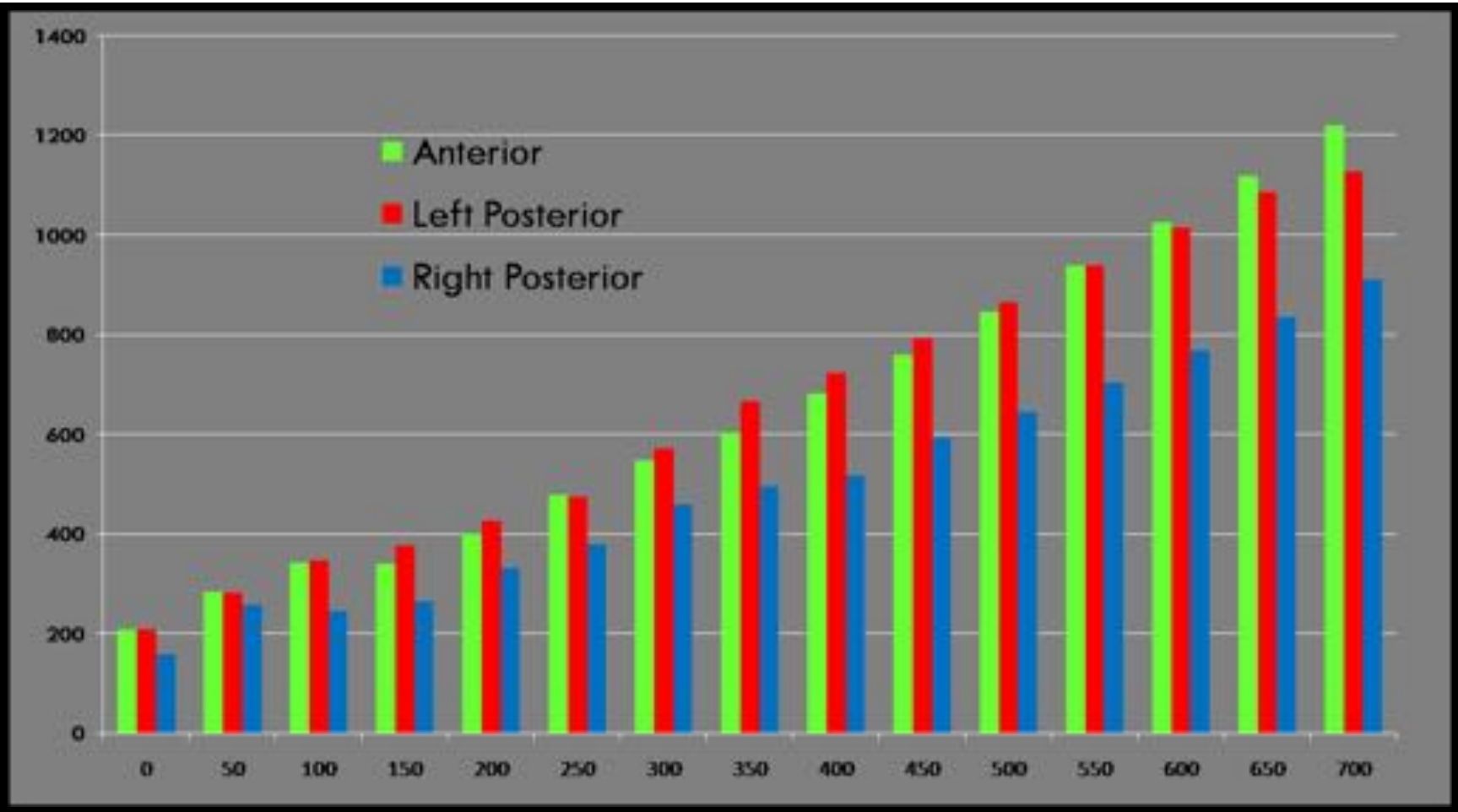
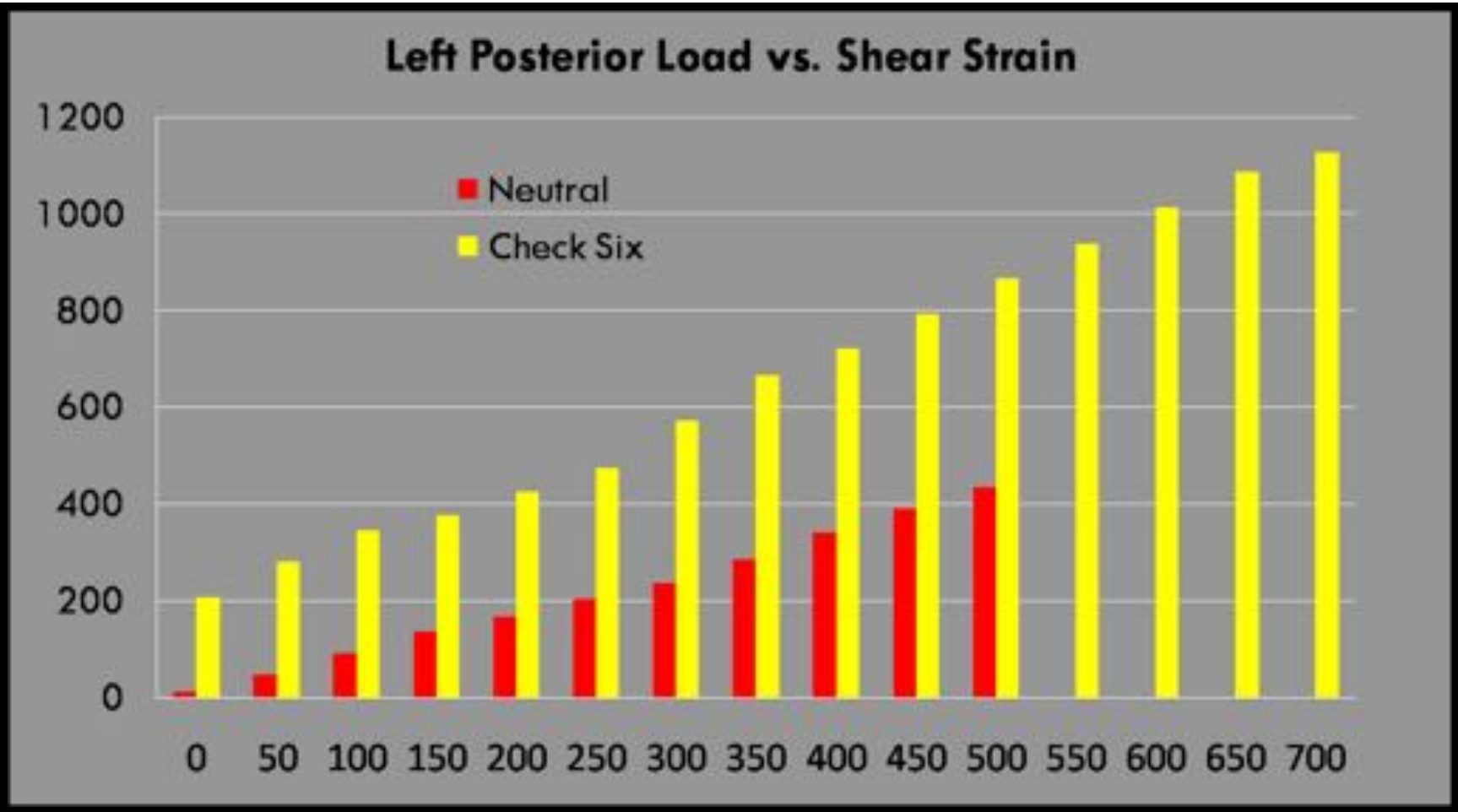
Results: Body Strains Static vs Check Six



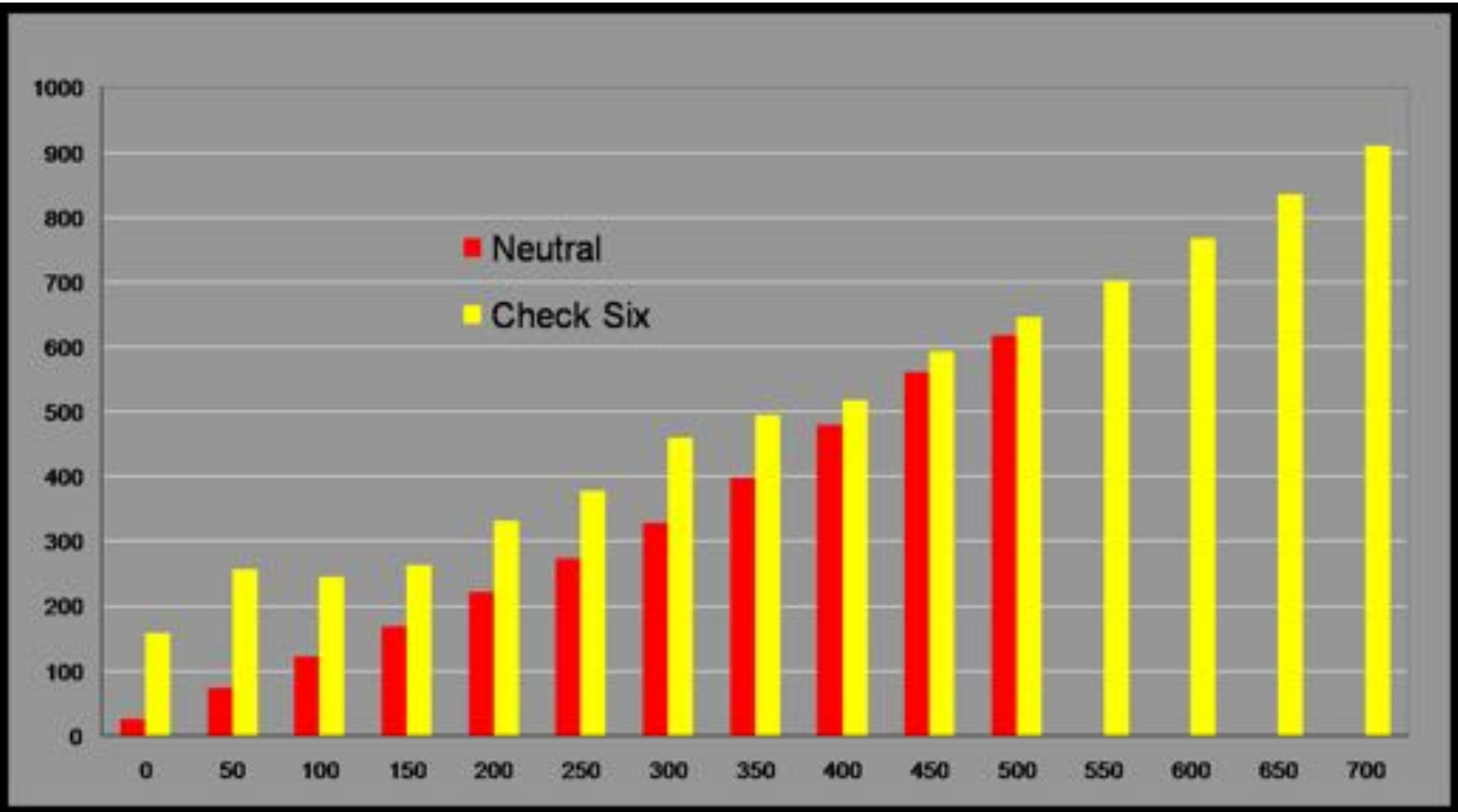
Results: Strains in Left Check Six



Left Facet Strain in Left Check Six



Right Facet Strain in Left Check Six



Hypothesis 2 and 3

Strain in the loaded facet is greater in check six compared to the neutral posture

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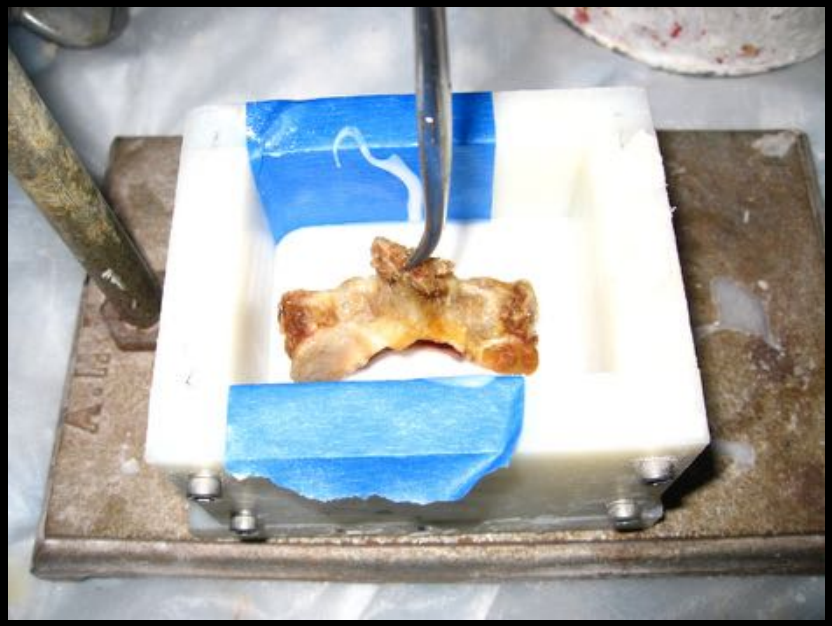
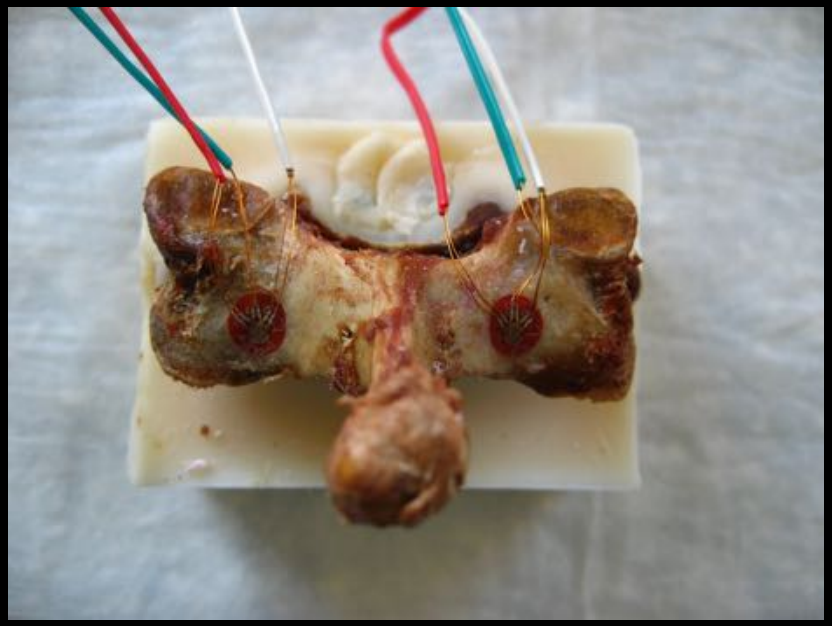
Facet Failure Tests

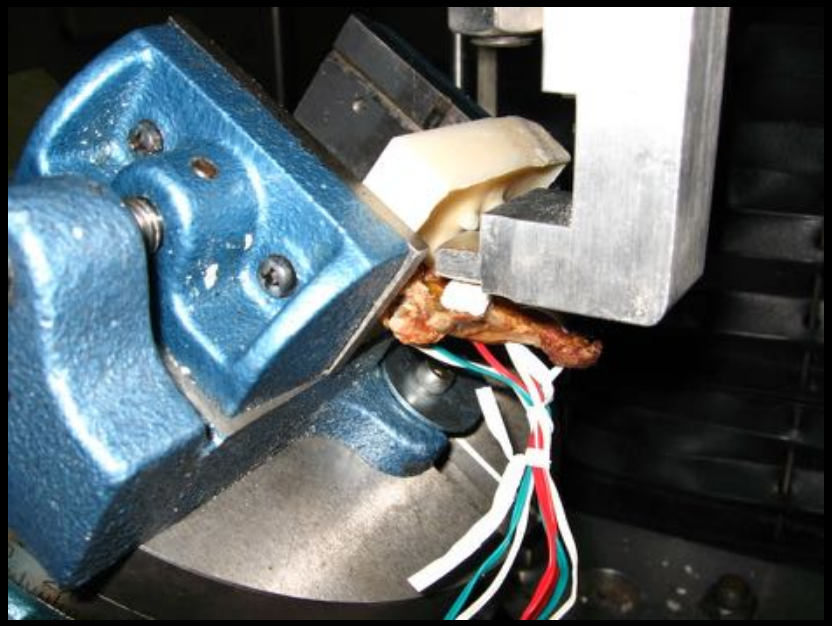
C5 Dissected Free and Potted

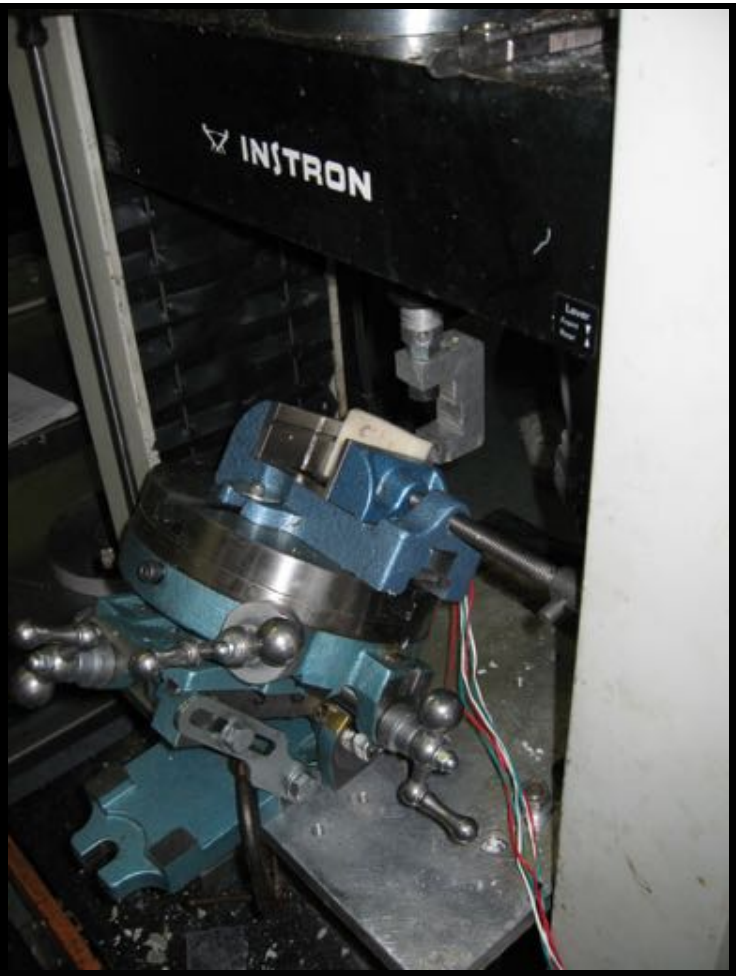


Instrumented with Strain Gauges

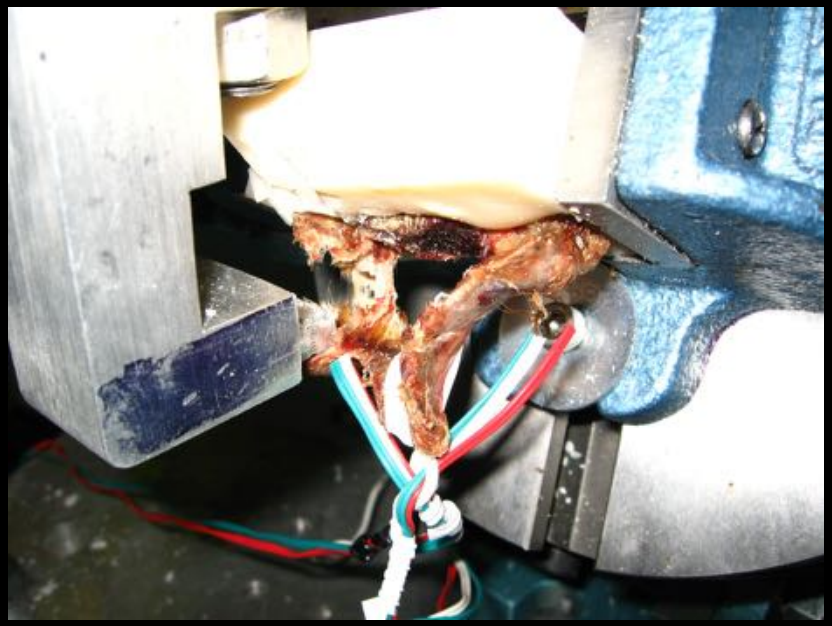


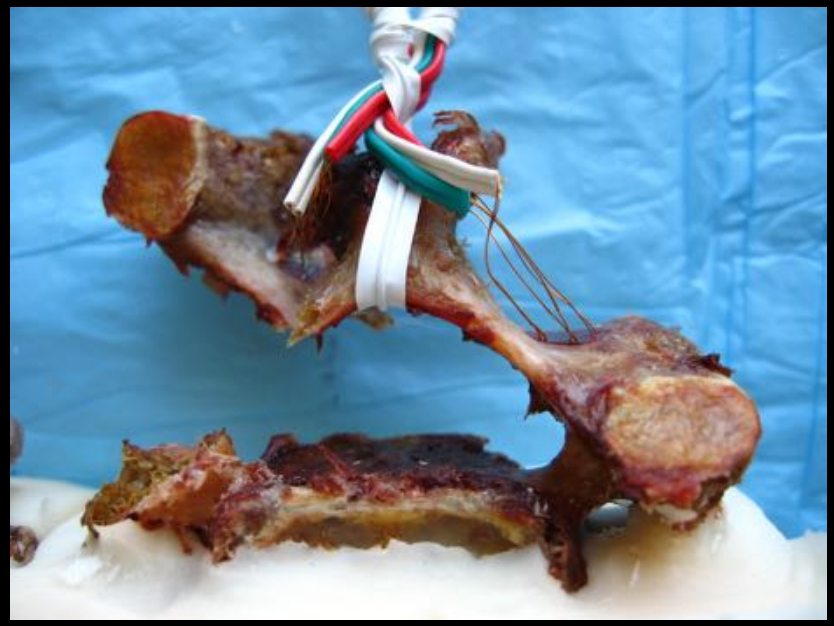
One Facet Pressed to Failure





Failure Mode





Average Failure Strains

- Failure Stain Facet 5879 Me
- Max Aver. Stain Check Six 1150 Me

Hypothesis 4

- Facet failure strain is greater than strain experienced in +9Gz loading

PROVED

Conclusions 1 Clinical

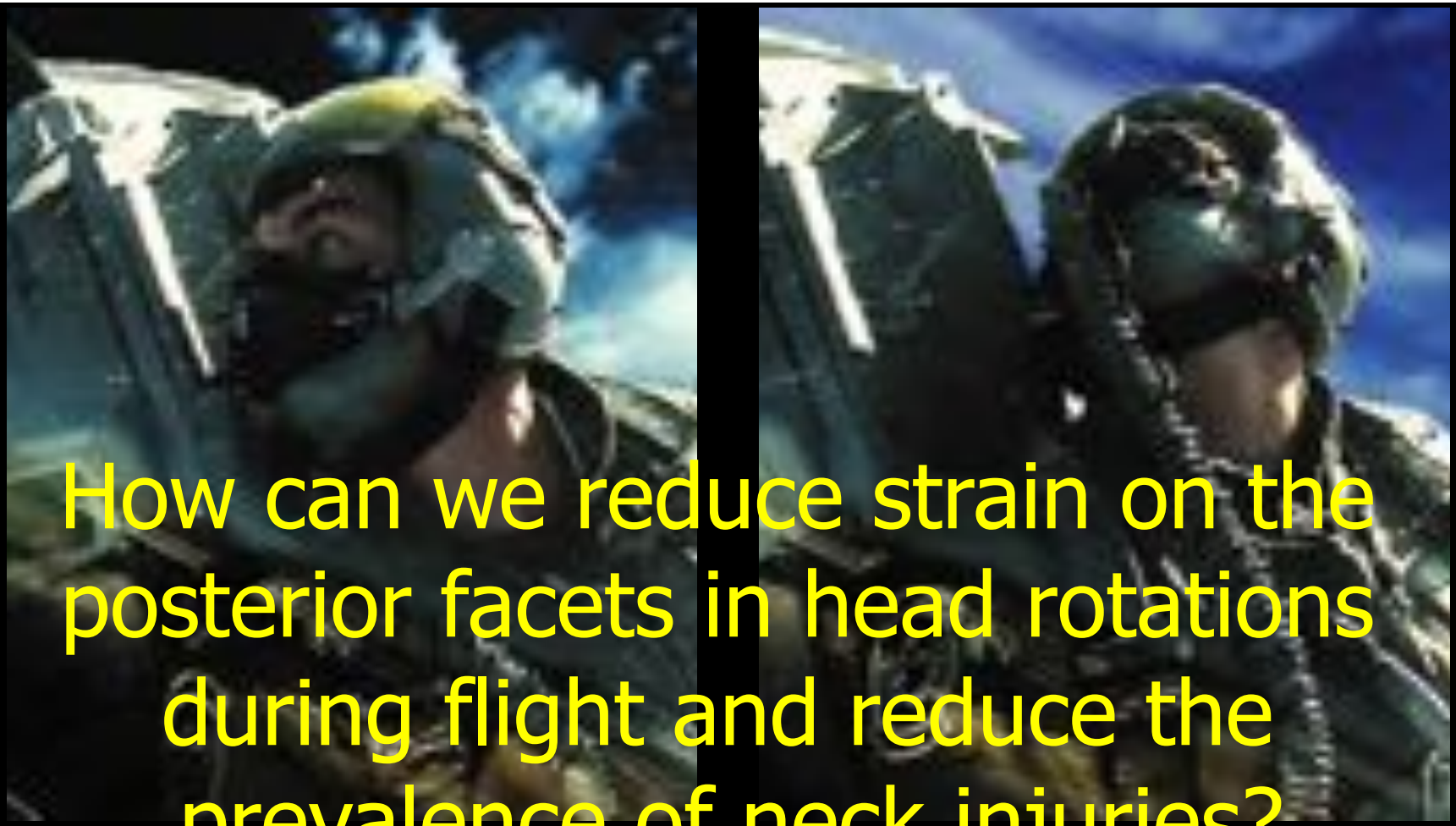
- Neck injuries real problem for fighter pilots
- Prevalence between 12-80%
- Major risk factors age >35 and high G aircraft
- Facet joint and muscle sprains common pathologies
- Many similarities to Whiplash Injuries
- Spine fractures and disk injuries rare
- Long term consequences unknown (no literature)
- Neck Disability Index not applicable to pilots

Conclusions 2 Biomechanics

- The Follower Load Model can be used successfully to replicate the effects of G load on lower cervical spine specimens

- Facet Strains at +9Gz
  - Helmet (700 N) Check Six 1/5 of Failure Value
  - No helmet (500 N) Check Six 1/7 of Failure Value
  - No helmet (500 N) Neutral 1/14 of Failure Value

Conclusion 3: Check Six is the Problem



How can we reduce strain on the posterior facets in head rotations during flight and reduce the prevalence of neck injuries?

Protection Against Neck Injuries

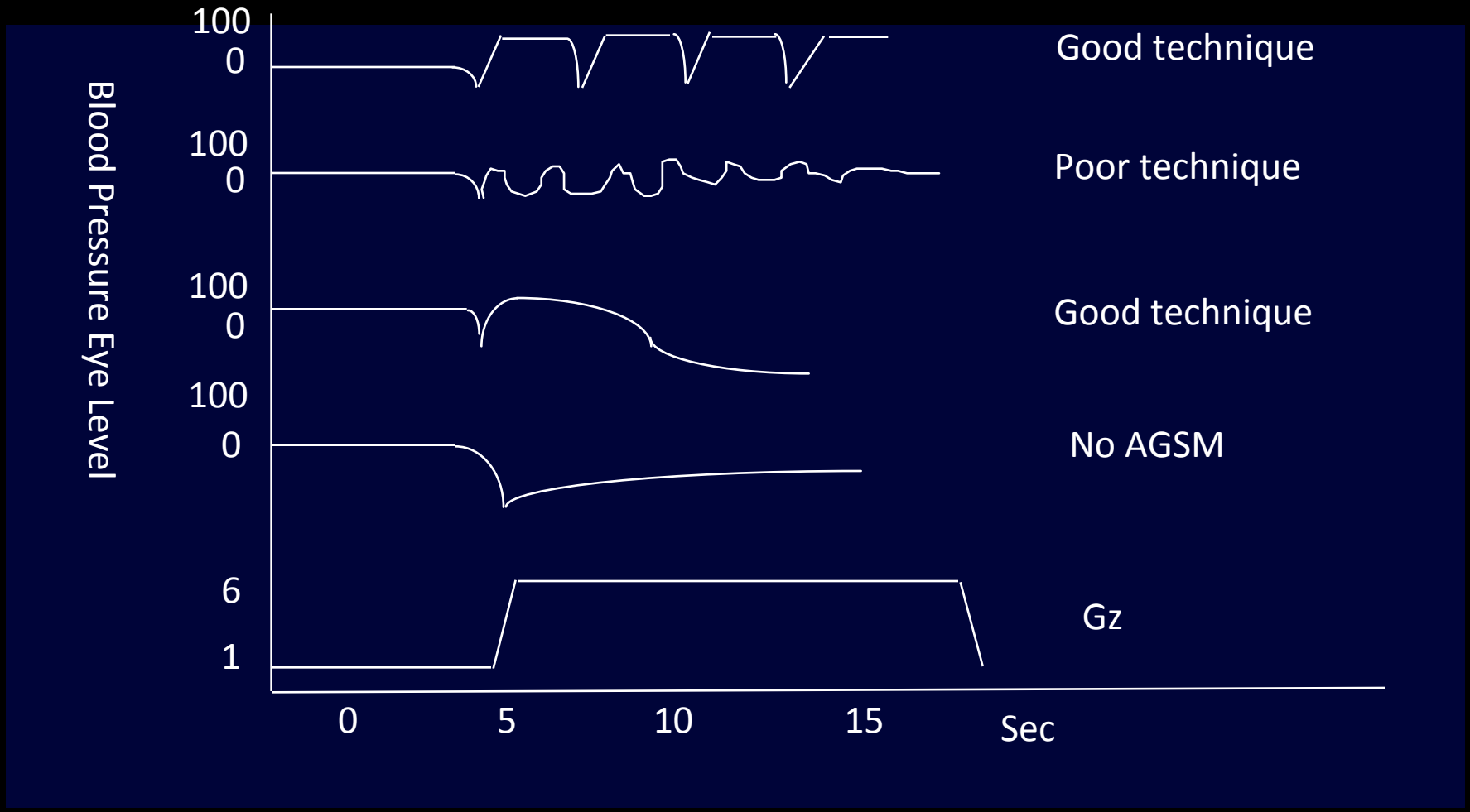
- Physical fitness programs
- Cockpit strategies
  - No head turn
  - Head positioning
- Biomechanical Modifications
  - Seat headrest
  - Seat inclination
  - Harness design
  - Assistive devices

NOT PRACTICAL

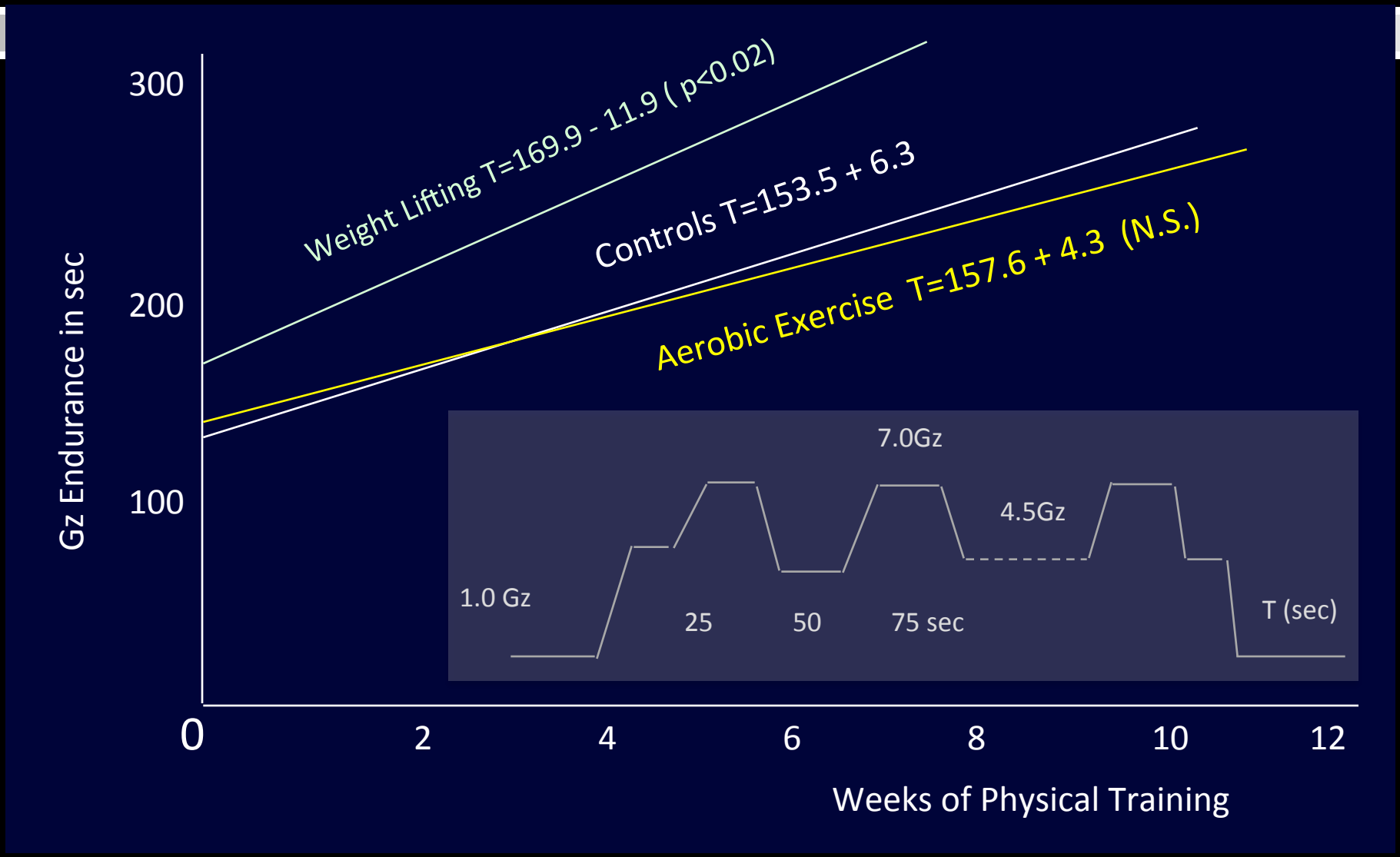
Physical Fitness Programs

- Result of fatal accidents investigations where fatique and loss of consciousness in flight from G- load was documented and exercising advised
- F-16/F-15/F-18

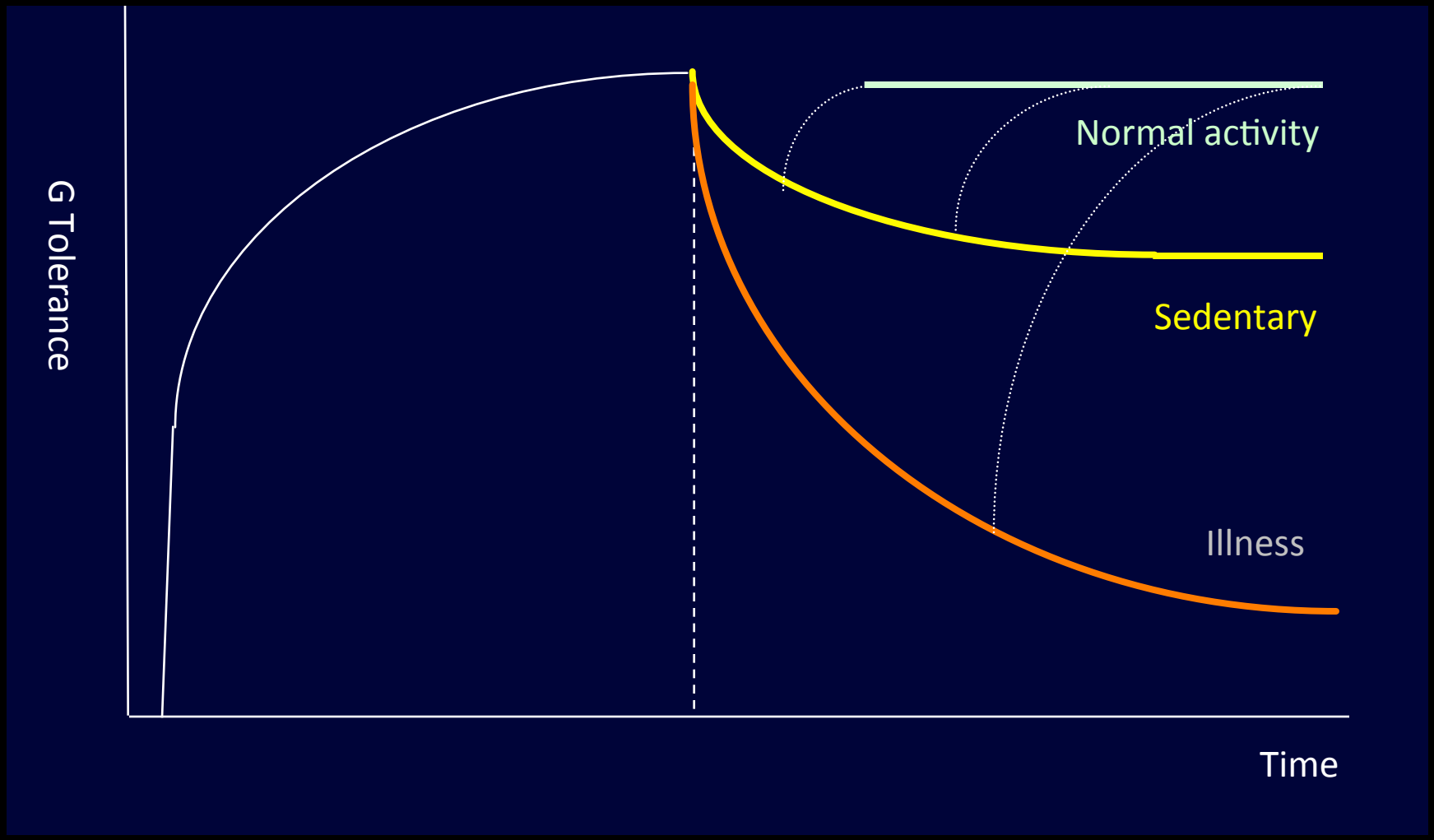
AGSM Quality and Blood Pressure



Effect of Training on Gz Tolerance

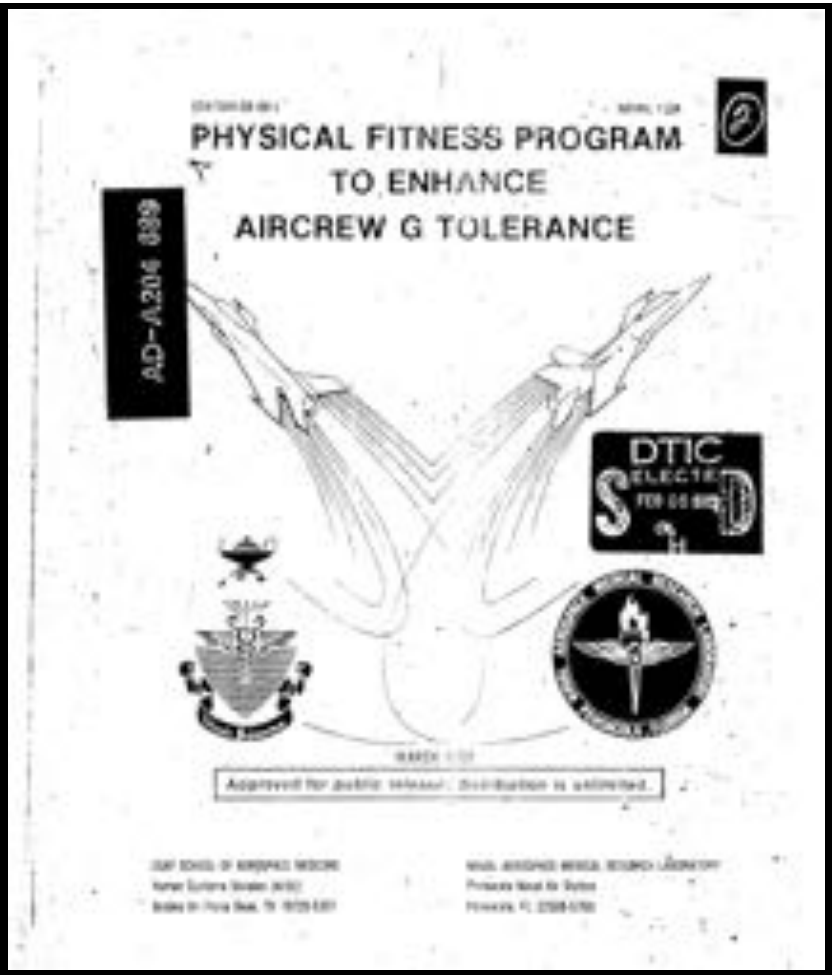


Effect of Illness on G Tolerance



Physical Fitness and G Tolerance

- 1988 USAF/US Navy Physical Fitness Program
- 1991 Implemented in Greece


PHYSICAL FITNESS PROGRAM
TO ENHANCE
AIRCREW G TOLERANCE

AD-A204 889

DTIC
ELECTE
S D

Physical Fitness Programs

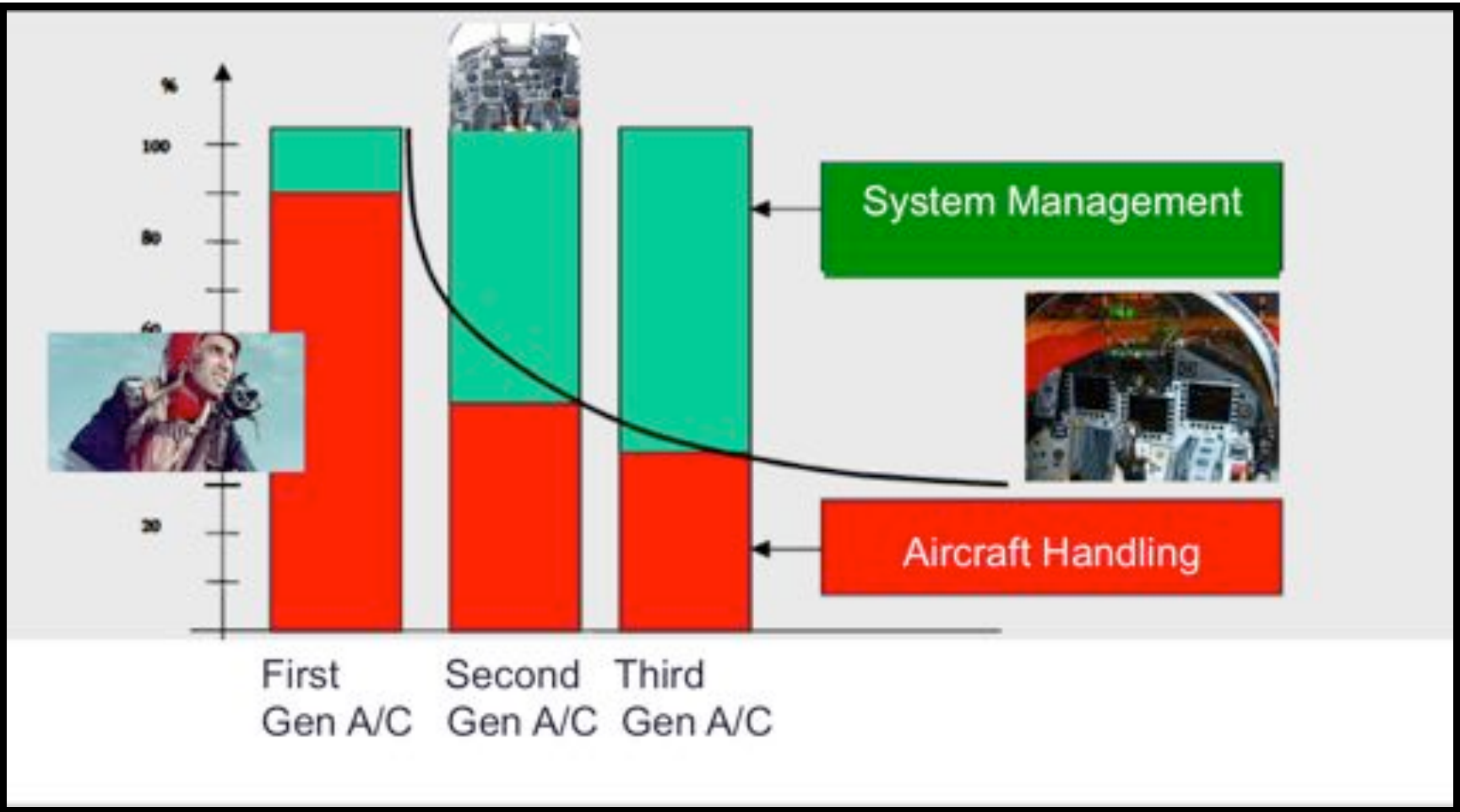
- Emphasis on Anti - G - Straining Maneuver: AGSM
  - Muscle strength
  - Lower leg
  - Chest wall
  - Abdominals
- Neck exercises a byproduct

Pilot Fitness in Greece

Each Fighting Wing

- Gym
- Personal trainer
- Participation

Initially Very Accepted But Then..



Pilot Neck Pain Greek Experience

- Anonymous questionnaire
- Neck Disability Index
- Fighter and trainers
- Total of 485 responses

Results: Low G Aircraft

- A-7E **6%**

- T-2E **5%**

Results: Low G Aircraft

- T-6A **1%**

- Instructors **57%!**

Results: High G Aircraft

- F-16 C/D **27%**

- F-4E **26%**

Results: High G Aircraft

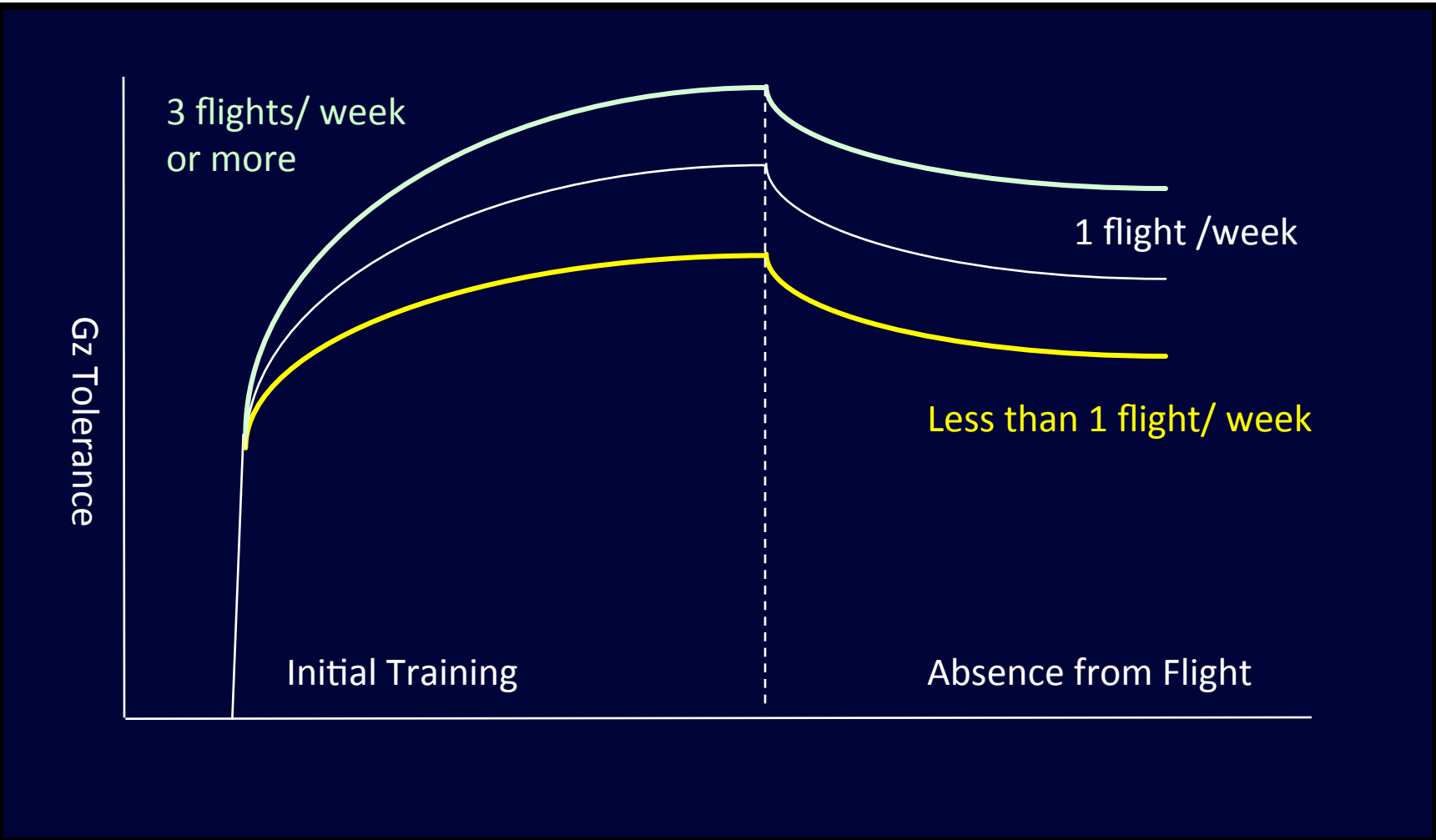
- RF-4 **21%**

- M-2000 **12%**

Greek Study Results

- Age: 31-35
- Flight time: 800-1300
- Gs: >4Gz
- Position: Check six , Flexion , Rotation
- Mission: BFM, ACM
- 50% lower prevalence than that reported in literature
  - Better fitness
  - Gradual flight training?

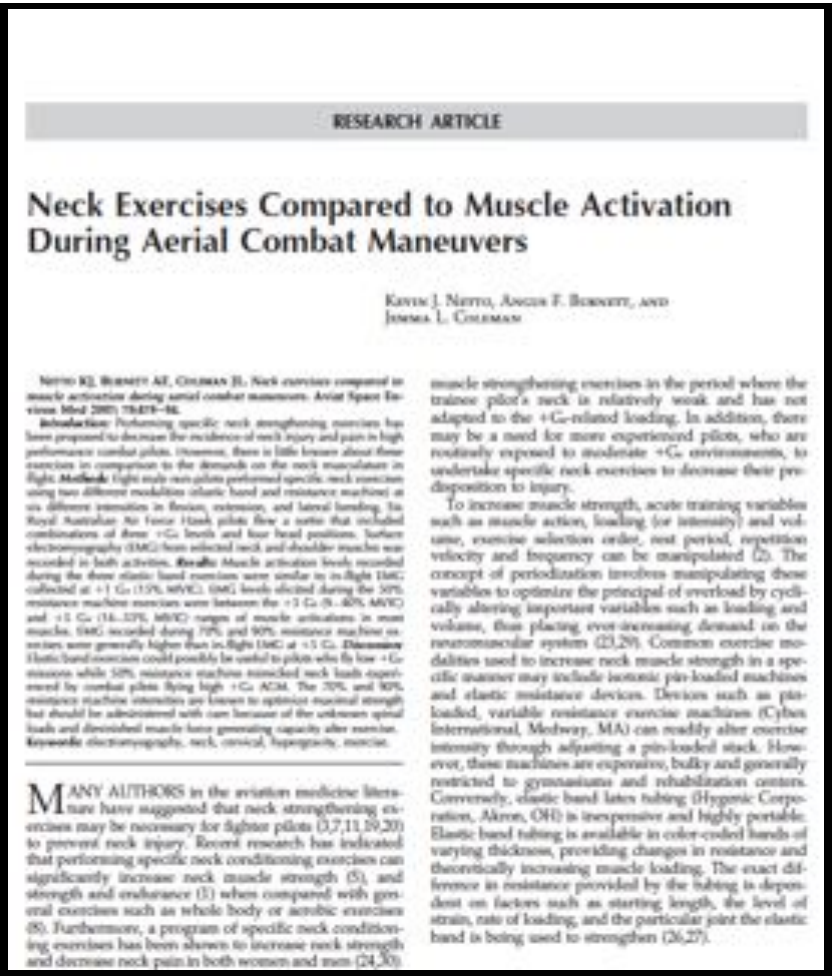
Effect of Flight on Gz Tolerance



Specific neck training methods

- Very few data
- General strength training vs neck only = no difference in neck injury rates (1-3 years)
- Machine better than elastic bands for neck injury reduction

Specific Neck Exercises for Pilots



RESEARCH ARTICLE

Neck Exercises Compared to Muscle Activation During Aerial Combat Maneuvers

Kevin J. Netto, Angus F. Burnett, and Jemma L. Coleman

Netto KJ, Burnett AF, Coleman JL. *Neck exercises compared to muscle activation during aerial combat maneuvers.* Aviat Space Environ Med 2007; 78:879–86.

Introduction: Performing specific neck strengthening exercises has been proposed to decrease the incidence of neck injury and pain in high performance combat pilots. However, there is little known about these exercises in comparison to the demands on the neck musculature in flight. **Methods:** Eight male non-pilots performed specific neck exercises using two different modalities (elastic band and resistance machine) at six different intensities in flexion, extension, and lateral bending. Six Royal Australian Air Force Hawk pilots flew a sortie that included combinations of three +Gz levels and four head positions. Surface electromyography (EMG) from selected neck and shoulder muscles was recorded in both activities. **Results:** Muscle activation levels recorded during the three elastic band exercises were similar to in-flight EMG collected at +1 Gz (15% MVIC). EMG levels elicited during the 50% resistance machine exercises were between the +3 Gz (9–40% MVIC) and +5 Gz (16–53% MVIC) ranges of muscle activations in most muscles. EMG recorded during 70% and 90% resistance machine exercises were generally higher than in-flight EMG at +5 Gz. **Discussion:** Elastic band exercises could possibly be useful to pilots who fly low +Gz missions while 50% resistance machine mimicked neck loads experienced by combat pilots flying high +Gz ACM. The 70% and 90% resistance machine intensities are known to optimize maximal strength but should be administered with care because of the unknown spinal loads and diminished muscle force generating capacity after exercise.

Keywords: electromyography, neck, cervical, hypergravity, exercise.

MANY AUTHORS in the aviation medicine literature have suggested that neck strengthening exercises may be necessary for fighter pilots (3,7,11,19,20) to prevent neck injury. Recent research has indicated that performing specific neck conditioning exercises can significantly increase neck muscle strength (5), and strength and endurance (1) when compared with general exercises such as whole body or aerobic exercises (8). Furthermore, a program of specific neck conditioning exercises has been shown to increase neck strength and decrease neck pain in both women and men (24,30) muscle strengthening exercises in the period where the trainee pilot's neck is relatively weak and has not adapted to the +Gz-related loading. In addition, there may be a need for more experienced pilots, who are routinely exposed to moderate +Gz environments, to undertake specific neck exercises to decrease their predisposition to injury.

To increase muscle strength, acute training variables such as muscle action, loading (or intensity) and volume, exercise selection order, rest period, repetition velocity and frequency can be manipulated (2). The concept of periodization involves manipulating these variables to optimize the principal of overload by cyclically altering important variables such as loading and volume, thus placing ever-increasing demand on the neuromuscular system (23,29). Common exercise modalities used to increase neck muscle strength in a specific manner may include isotonic pin-loaded machines and elastic resistance devices. Devices such as pin-loaded, variable resistance exercise machines (Cybex International, Medway, MA) can readily alter exercise intensity through adjusting a pin-loaded stack. However, these machines are expensive, bulky and generally restricted to gymnasiums and rehabilitation centers. Conversely, elastic band latex tubing (Hygenic Corporation, Akron, OH) is inexpensive and highly portable. Elastic band tubing is available in color-coded bands of varying thickness, providing changes in resistance and theoretically increasing muscle loading. The exact difference in resistance provided by the tubing is dependent on factors such as starting length, the level of strain, rate of loading, and the particular joint the elastic band is being used to strengthen (26,27).

- 8 non-pilots vs
- 6 pilots flying
- Surface EMG
- Elastic band/Resistance

- 3 Gz levels
  - Elastic band =1Gz
  - 50% resistance =3-5Gz
  - 70% resistance > 5 Gz

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Specific Neck Exercises for Pilots

- Elastic band useful for low Gz
- 70 - 90% resistance optimum strength
- Unknown overload effects

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Muscle Strength Training

- Frequency of muscle endurance training the only determinant of acute in flight neck pain
- 24 weeks of neck exercises reduces neck pain in Danish pilots

New Areas of Research

Aerotrim

Trampoline

Conclusions

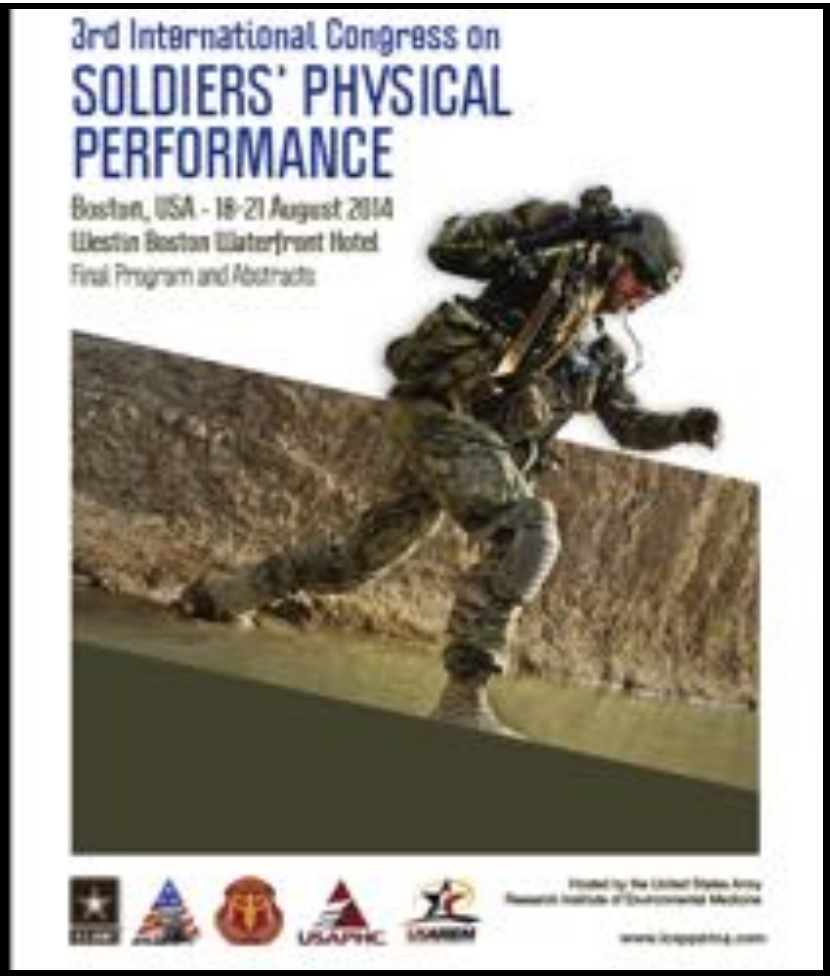
- Very few data on pilot neck injuries prevention strategies
- Neck muscle specific strength exercises useful but evidence lacking

A Good Fitness Program

- Efficacy: vs time cost
- Palatability
  - expensive apparatus
  - too complicated
  - simply not 'fun.'
- Exercises specificity
- Target population
  - Fighter pilot
  - Helicopter
  - Transport

Areas for Further Research

- Aerobic training amd neck muscle injuries
- Neck specific programs
- AGSM performance
  - Respiratory effort
  - Strength training




Thank you for staying in formation!