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

Vertebra

Facets

C1-C2

C5-C6

Vertebra
Cervical Spine Anatomy

- Vertebra Body
- Disk
- Spinal Cord
In-Flight Spine Injuries

- 1948 (Shaw)
- 1964 (Mayers)
- 1970 AGARD Report AR-140
In-flight Neck Injuries

- 1982 AGARD: Pathophysiology and pathology of spinal injuries
- 1999 RTO-TR-4 NATO
In-flight Disk Ruptures

- 1990 Clark (ASEM)
- 1994 Hamalainen (ASEM)
- 1996 Newman (ASEM)
In-flight Neck Fractures

- 1988 Andersen (ASEM)
- 1989 Schall (ASEM)
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
Epidemiology of Neck Pain

- 90% F-15

- 75% - 85% F/A-18
Epidemiology of Neck Pain

- 35-50% F-16
- 3% EF-2000
Clinical Studies

- Kinematic Studies
- Radiographic changes
- MRI studies
### Table 3-1: Occurrence of Inter-vertebral Disk Degeneration in Pilots and Non-flying Controls (37).

| Disk | All Disk Changes (%)<sup>1</sup> | Mild Disk Changes (%)<sup>2</sup> | Moderate Disk Changes (%)<sup>3</sup> | P <
|------|-------------------------------|---------------------------------|---------------------------------|---
|      | Pilots | Controls | Pilots | Controls | Pilots | Controls |      |
| C<sub>2-3</sub> | 25      | 18       | 0       | 5        | 15     | 14       | n.s. |
| C<sub>3-4</sub> | 88      | 64       | 0       | 7        | 88     | 36       | 0.01 |
| C<sub>4-5</sub> | 67      | 50       | 29      | 32       | 29 (38)<sup>4</sup> | 18       | n.s. |
| C<sub>5-6</sub> | 79      | 86       | 8       | 36       | 67     | 50       | n.s. |
| C<sub>6-7</sub> | 72      | 68       | 13      | 9        | 58 (64) | 45 (59) | n.s. |
| Mean | 68      | 57       | 10      | 22       | 53     | 33       |      |

<sup>1</sup> include mild, moderate, and severe;  
<sup>2</sup> include mild;  
<sup>3</sup> include moderate;  
<sup>4</sup> in parenthesis includes severe.

Hamalainen, O., Vanharanta, H., Kuusela, T.
<table>
<thead>
<tr>
<th>Groups</th>
<th>CAP</th>
<th>%</th>
<th>HPAP</th>
<th>%</th>
</tr>
</thead>
<tbody>
<tr>
<td>N¹</td>
<td>24</td>
<td></td>
<td>24</td>
<td></td>
</tr>
<tr>
<td>Age (yrs)</td>
<td>31.4</td>
<td></td>
<td>32.5</td>
<td></td>
</tr>
<tr>
<td>Flying Time (hrs)</td>
<td>1272</td>
<td></td>
<td>1642</td>
<td></td>
</tr>
<tr>
<td>Signal Intensity²</td>
<td>0</td>
<td>0</td>
<td>12.5</td>
<td>12.5</td>
</tr>
<tr>
<td>Osteophytes</td>
<td>2</td>
<td>12.5</td>
<td>2</td>
<td>12.5</td>
</tr>
<tr>
<td>Disk Height</td>
<td>8</td>
<td>33.3</td>
<td>6</td>
<td>20</td>
</tr>
<tr>
<td>Disk protrusion</td>
<td>9</td>
<td>41.3</td>
<td>12</td>
<td>50</td>
</tr>
<tr>
<td>Deformities³</td>
<td>1</td>
<td>4.2</td>
<td>1</td>
<td>4.2</td>
</tr>
</tbody>
</table>

¹ Number of subjects per group; ² vertebrae; ³ Disk; ⁴ Spinal column; ⁵ Bold indicate values > in HPA.
Reliability of Imaging Studies

- Not reliable in predicting neck pain
Reliability of Clinical Examinations

- Cervical flexor endurance good predictor
<table>
<thead>
<tr>
<th>G Level</th>
<th>Low</th>
<th>Medium</th>
<th>High</th>
</tr>
</thead>
<tbody>
<tr>
<td>AIRCRAFT TYPE</td>
<td>F-1</td>
<td>A7, A-4, F-4, F-5</td>
<td>F-15</td>
</tr>
<tr>
<td>Vanderbeek (1988)</td>
<td></td>
<td>30.7%</td>
<td>51.2%</td>
</tr>
<tr>
<td>Knudson et al (1988)</td>
<td></td>
<td>30-50%</td>
<td></td>
</tr>
<tr>
<td>Newman (1997)</td>
<td></td>
<td></td>
<td>82%</td>
</tr>
<tr>
<td>Kikukawa (1994)</td>
<td></td>
<td>14.8%</td>
<td>30%</td>
</tr>
<tr>
<td>Hamalainen et al (1997)</td>
<td></td>
<td>38%</td>
<td></td>
</tr>
</tbody>
</table>
Lower MVC in extensor muscles in fighter pilots with neck pain.
Where does the pain come from?

- Disk
- Ligaments
- Muscle
- Bone
- Facet
Biomechanical Studies

- Mostly impact studies
- Few acceleration studies
  - In vivo
  - In vitro

In flight EMG: MVC %
Fatigue after static loading
Anthropometric data
Centrifuge studies
Finite element studies
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

Bass et al. 2007

<table>
<thead>
<tr>
<th>Ligament</th>
<th>Spinal Level</th>
<th>Gender</th>
<th>Mean Failure Force ± SD (N)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Anterior longitudinal ligament</td>
<td>C3–C4</td>
<td>M</td>
<td>494.0 ± 358.2</td>
</tr>
<tr>
<td></td>
<td>C5–C6</td>
<td>F</td>
<td>294.4 ± 194.0</td>
</tr>
<tr>
<td></td>
<td>C7–T1</td>
<td>M</td>
<td>326.2 ± 115.6</td>
</tr>
<tr>
<td></td>
<td></td>
<td>F</td>
<td>284.8 ± 169.6</td>
</tr>
<tr>
<td></td>
<td></td>
<td>M</td>
<td>355.1 ± 242.0</td>
</tr>
<tr>
<td></td>
<td></td>
<td>F</td>
<td>673.5 ± 104.4</td>
</tr>
<tr>
<td>Posterior longitudinal ligament</td>
<td>C3–C4</td>
<td>M</td>
<td>462.9 ± 368.8</td>
</tr>
<tr>
<td></td>
<td>C5–C6</td>
<td>F</td>
<td>47.0 ± 191.4</td>
</tr>
<tr>
<td></td>
<td>C7–T1</td>
<td>F</td>
<td>58.4 ± 191.8</td>
</tr>
<tr>
<td></td>
<td></td>
<td>M</td>
<td>415.3 ± 90.4</td>
</tr>
<tr>
<td></td>
<td></td>
<td>F</td>
<td>431.4 ± 191.5</td>
</tr>
<tr>
<td>Ligamentum flavum</td>
<td>C3–C4</td>
<td>M</td>
<td>315.8 ± 97.9</td>
</tr>
<tr>
<td></td>
<td>C5–C6</td>
<td>F</td>
<td>134.0 ± 21.4</td>
</tr>
<tr>
<td></td>
<td>C7–T1</td>
<td>F</td>
<td>269.7 ± 143.0</td>
</tr>
<tr>
<td></td>
<td></td>
<td>M</td>
<td>136.2 ± 45.0</td>
</tr>
<tr>
<td></td>
<td></td>
<td>F</td>
<td>177.4 ± 137.0</td>
</tr>
<tr>
<td></td>
<td></td>
<td>M</td>
<td>303.6 ± 98.2</td>
</tr>
</tbody>
</table>

3500–4500 N
Cervical Vertebra Body Failure Load

550 - 754 N
- Capsular strain
  40% at -8Gx
Facet Capsule Failure Load

- F1: 38-40 N, C3–C4
- F2: 45-50 N, C5–C6

Myklebust et al (1988)
Effect of Head Posture

- Axial pre-torque of the head and neck increases facet capsular strains
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

Muscle Co-Activation Vectors

P1 = P2 = P3 = P4 = 110N

F1 (13.8 N)
F2 (9.16 N)
F3 (3.70 N)
F4 (2.37 N)
F5 (10.9 N)
0 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.

FOLLOWER LOAD PATH

ICR

C1/C2 level
C2/C3 level
C3/C4 level
C4/C5 level
C5/C6 level
C6/C7 level
Cervical Follower Preload

(Patwardhan et al: Spine 2000)
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 from 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

No effect on posture
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.
2. In neutral.
3. In check six.
Results: Body Strains Static vs Check Six
Results: Strains in Left Check Six
Left Facet Strain in Left Check Six

Left Posterior Load vs. Shear Strain

- Neutral
- Check Six
Hypothesis 2 and 3

Strain in the loaded facet is greater in check six compared to the neutral posture!!
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
Hypothesis 4

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

PROVED
Conclusions 1 Clinical

- real problem
- 12-80%
- age >35 high G
- Facet joint and muscle sprains
- Long term consequences unknown
- Neck Disability Index not applicable
The Follower Load Model can be used successfully to replicate the effects of G load on lower cervical spine specimens.

- **Facet Strains at +9Gz**
  - 1/5 of Failure Value
  - 1/7 of Failure Value
  - 1/14 of Failure Value
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
- Biomechanical Modifications

NOT PRACTICAL
Physical Fitness Programs

Result of fatal accidents in investigations where fatigue and loss of consciousness in flight due to G-load was documented and exercising advised for F-16/F-15/F-18.
AGSM Quality and Blood Pressure

![Graph showing blood pressure measurements for different techniques and AGSM conditions.](image_url)
Effect of Training on Gz Tolerance

- **Controls**: T = 153.5 ± 6.3
- **Aerobic Exercise**: T = 157.6 ± 4.3 (N.S.)
- **Weight Lifting**: T = 169.9 ± 11.9 (p<0.02)

Gz Endurance in sec

Weeks of Physical Training
Effect of Illness on G Tolerance
Physical Fitness and G Tolerance
Physical Fitness Programs

Emphasis on Anti-G-Straining Maneuver: AGSM

- Muscle strength
- Lower leg
- Chest wall
- Abdominals
- Neck exercises as a byproduct
Each Fighting Wing
- Gym
- Personal trainer
- Participation
Initially Very Accepted But Then..
Pilot Neck Pain Greek Experience
Results: Low G Aircraft

6%

5%
Results: Low G Aircraft

1%

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

- 3 flights/week or more
- 1 flight/week
- Less than 1 flight/week
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

8 non-pilots vs 6 pilots flying
Specific Neck Exercises for Pilots

Elastic band useful for low Gz.
70–90% resistance optimum strength.

Unknown overload effects.
Muscle Strength Training

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 Cost

Palatability

Exercises specificity

Target population

Fighter pilot

Helicopter pilot

Transport
Areas for Further Research

Aerobic training and neck muscle injuries

Neck-specific programs

AGSM performance

Respiratory effort

Strength training
Thank you for staying in formation!