BARCZYK BIOMECHANICS INSTITUTE

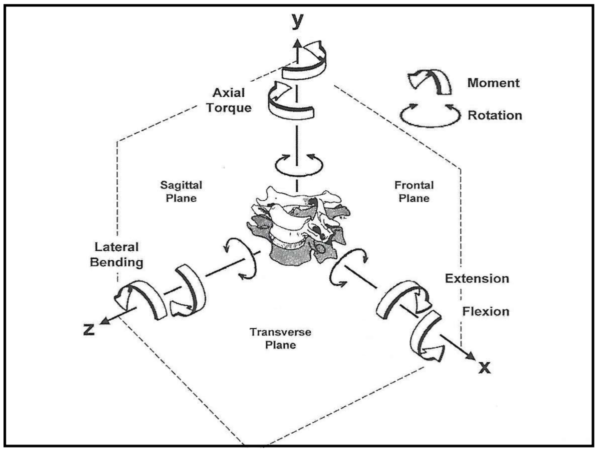
HUMAN INJURY MECHANISMS and THRESHOLDS

PRESENTED BY: DAVID J. BARCZYK, D.C.

Dr. David J Barczyk
337-255-7102
drb@bcgclinics.com

Injury Mechanisms

- Accelerations
  - shear
  - torque
- Compression
- Blunt Force Trauma
  - contusions
  - fractures
- Lacerations



Vehicle Stiffness

- Properties of vehicles…
  - U.S. NCAP and foreign equivalents
    - Stiffness of vehicles has increased to improve crashworthiness in higher speed tests
  - Stiffer seat backs
  - Very little concern for MPDC crashworthiness
  - No FMVSS for MPDC protection
  - No injury criteria for MPDC protection

30 MPH Frontal

- Myths, junk science, and pseudo experts
  -- property damage is related to the risk for (and severity of) injury. It says:
    - Crashes without property damage are safe
    - Injury risk and injury severity are directly proportional to crash damage
    - More property damage equals greater injury
  - The facts: this relationship does not exist and is without a scientific basis
    At low speeds, crashes can be highly elastic, resulting in proportionately greater energy transfer

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- Researchers have compared crash damage to injury risk
  - Results: in the lower speed range, there is often an inverse relationship between property damage and injury potential (13-16)
  - Walz and Muser (17): "The greater the vehicular damage, the less the biomechanical loading (and the inverse)"
- Outcome studies have also failed to correlate crash damage and injury severity (18-21)
  - Radanov et al. (22) reported finding no differences in outcome between crash severity assessment groups

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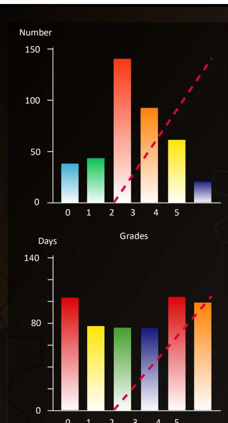
Hijioka A, Narusawa K: Risk factors for long-term treatment of whiplash injury in Japan: analysis of 400 cases. *Arch Orthop Surg* 121:490-493, 2001 (ref 26).



Correlation of property damage with injury

Correlation of property damage with treatment duration

Grade 0	No damage
Grade 1	Slight damage
Grade 2	Damage to bumper
Grade 3	1/3 of car damaged
Grade 4	1/2 of car damaged
Grade 5	Total destruction

Sir Isaac Newton

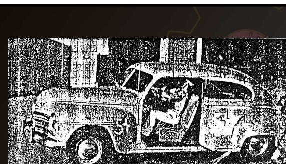
Newton's 3 Laws

- First law states that a body will remain at rest or in uniform motion unless it is acted upon by an outside force.
- This is commonly referred to the law of inertia.
- Inertia- the tendency of an object to resist changes in its state of motion.

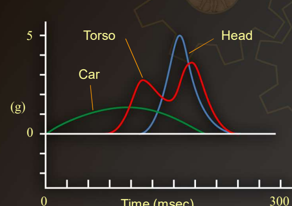
Accelerations

- 1st: Vehicle
- 2nd: Torso
- 3rd: Head and Cervical Spine

This illustrates Newton's 1st law.



First human test subject



Newton’s 3 Laws

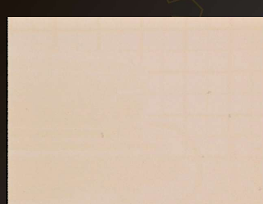
- In the second law, Newton defines what the change in motion from his first law would be. The law states that if the net force acting on a body is not zero, the body will be accelerated in the direction of the net force. The magnitude of the acceleration will directly proportional to the net force and inversely proportional to the mass of the body.

F=MA

Newton’s 3 Laws

- Newton’s third law states that whenever a body exerts a force upon another body, the other body exerts a force of equal magnitude, in the opposite direction, on the first body.
- This is commonly termed “ for every action there is an equal and opposite reaction.

- Newton’s laws provide the scientific foundation for acceleration injuries.



With the exception of a small dent in the Honda’s trunk lid and a broken plastic retaining clip on the front, these are all no-damage crashes.

5.4, 9.3, and 9.9 mph (V_c) rear impacts

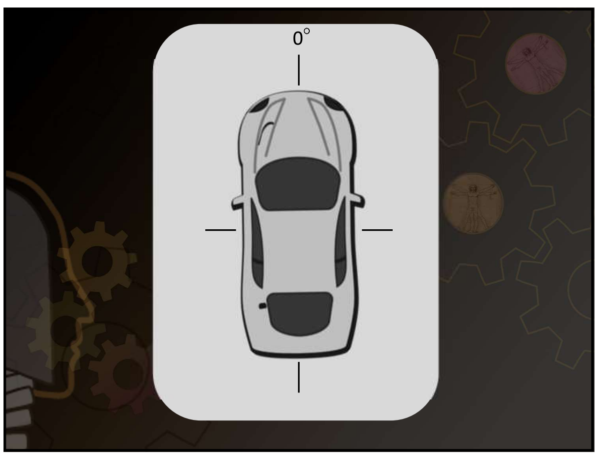
3.7, 6.6, and 7.2 mph rear impacts

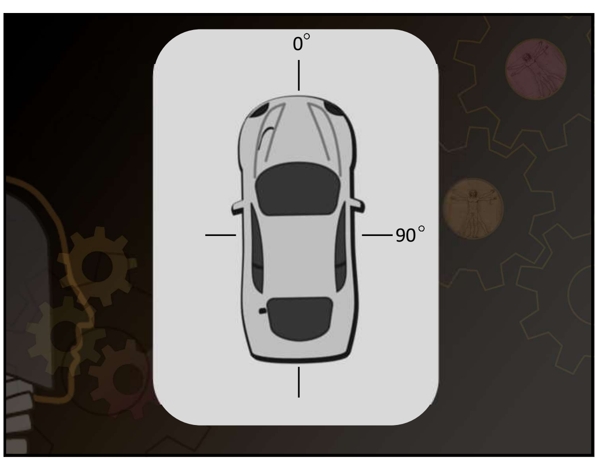
3.0, 4.8, 7.5, 7.8, 8.3, and 8.6 mph rear impacts

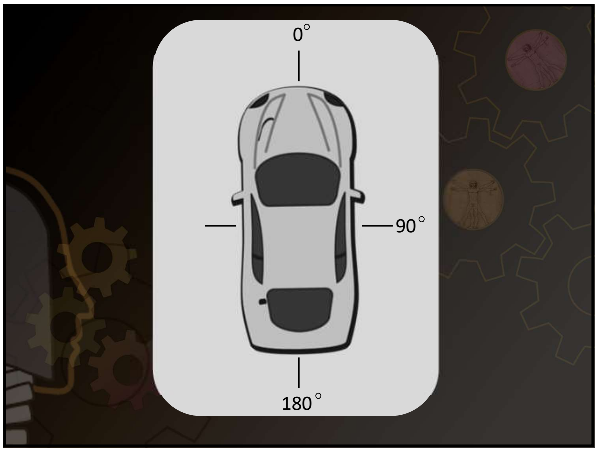
4.1, 7.0, and 7.2 mph frontal impacts

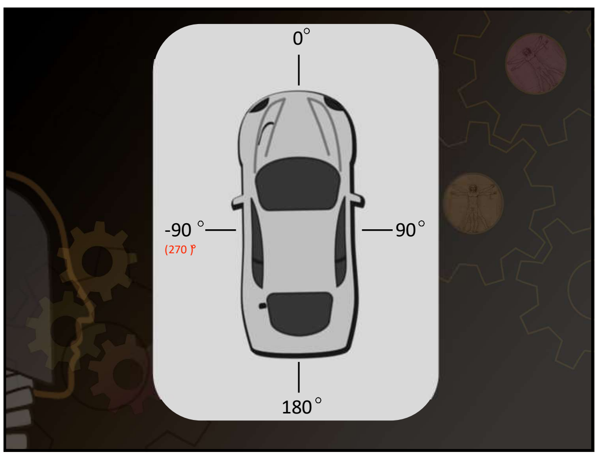
Plastic Crashes, Elastic Crashes and Ride Down.

PDOF and Occupant Kinematics


0°

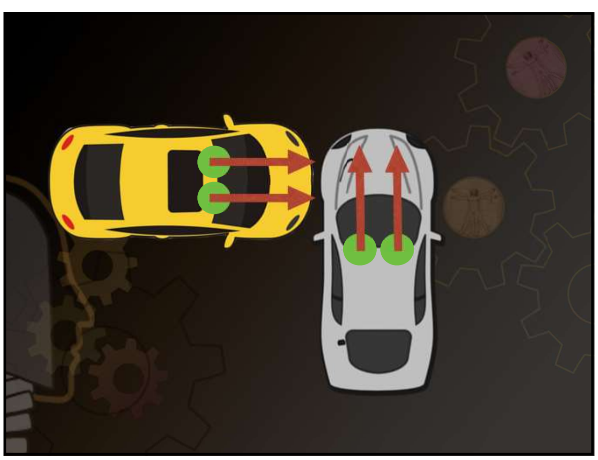

0°
90°

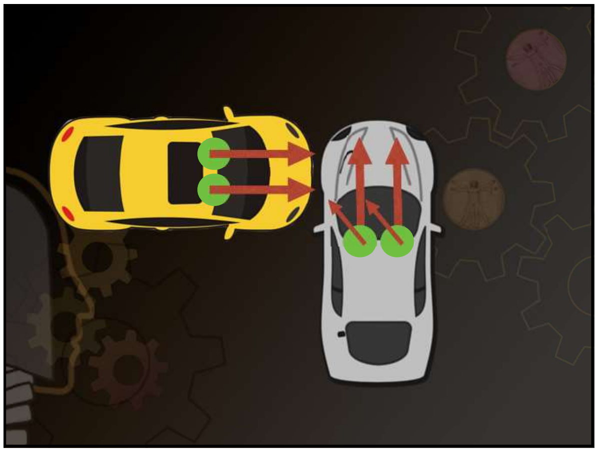


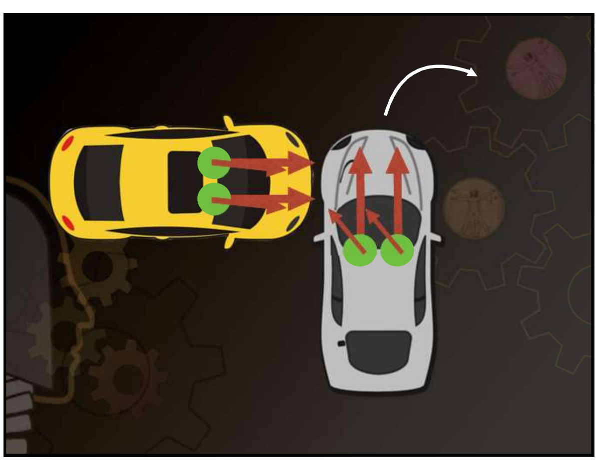


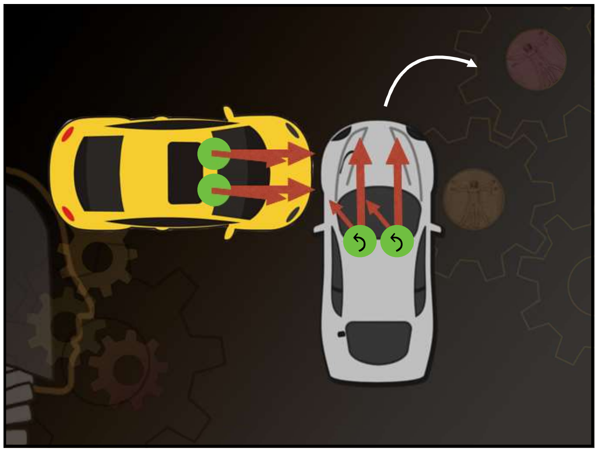
Occupant motion is parallel and opposite the principle direction of force.


Broad Side
Impact









Biomechanics

- More definitions
  - *Impact velocity*
  - *Closing velocity* (V_c) (or differential velocity)
  - *Change in velocity* (delta V)
  - Generally, 10 mph delta V is considered a LOSRIC
  - Above 12-15 mph delta V, spinal cord injuries can occur

Ford Tempo after 17 mph delta V crash

Acceleration is time dependent

- Why impacts at lower speeds can be significant
  - The factor which injures the occupant is the kinetic energy of the crash converted to occupant motion (kinematics)
  - Delta V is often considered independent of crash pulse
  - But it is acceleration that results in injured tissues
    - Acceleration is time dependent

$$a = \frac{\Delta v}{\Delta t}$$

Acceleration is time dependent

When the duration of a crash is long, acceleration will be low (with delta V held constant)

$$a = \frac{\Delta v}{\Delta t}$$

When the duration of a crash is brief, acceleration will be high (with delta V held constant)

$$a = \frac{\Delta v}{\Delta t}$$

Crash test s99-15

Subject: RH
Vc: 36.9 mph
delta V: 17.1 mph
Head acceleration: 10.3 g
Impact vector: frontal w/airbag

High speed, long duration, crash (36.9 mph and 17.1 mph delta V). Major property damage. Head acceleration was 10.3 g.

Crash test s00-2

Subject: JH
Vc: 7.8 mph
delta V: 5.8 mph
Head acceleration: 12.7 g
Impact vector: rear

Compare to low speed, brief duration, zero damage crash. Closing speed was 7.8 mph (21%). Delta V was 5.8 mph (34%). Head acceleration was 12.7 g (123%). Obviously, property damage doesn't tell the whole story.

Bumper contact (light flash)

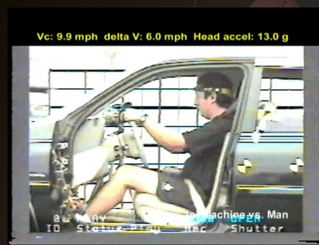
Seat strikes occupant

Flattening of spinal curves; axial compression and ramping

Head lag phase (retraction); high shear, axial tension

Head/neck extension phase; high bending moments

Forward (reentry) phase; head acceleration peaks, shear reverses



From Spine Research Institute of San Diego, 1999. Subject sustained mild CAD injury

Lighter subjects experience greater acceleration than heavier subjects

Have less interaction with seat back and head restraint

Forward (reentry) phase is more violent, with greater bending moments

Indicates a differential risk for injury (43,44); consistent with clinical and epidemiological literature (23,45-49)

From Spine Research Institute of San Diego, 1999.

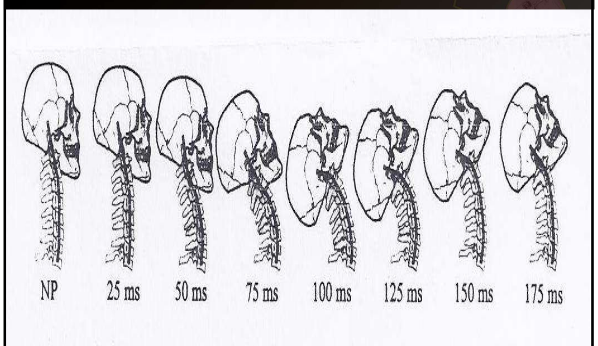
Stiffness Matters

- Bumper
- Frame
- Tire and wheel
- Tow Packages

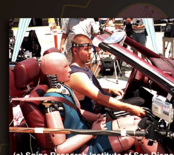
Whiplash Produces an S-Shaped Curvature of the Neck With Hyperextension at Lower Levels

JN Grauer, MM Panjabi, J Cholewicki, J Nibu, J Dvorak

- Study Design: “A bench-top trauma sled was used to apply four intensities of whiplash trauma to human cadaveric cervical spine specimens
- Measure intervertebral rotations using high-speed cinematography…
- The trauma classes were 2.5g, 4.5g, 6.5g, and 8.5g. Significance was defined at P < 0.01…



Risk Assessment



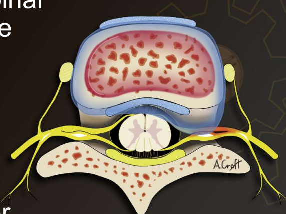
- Important vehicle factors
  - Relative sizes of crash partners
  - Impact vector
  - Contact points
  - Property damage
  - Head restraint geometry
  - Seat; type and any resulting damage
  - Use of restraint systems; air bag deployment

Risk Assessment

- Important occupant factors
  - Sex
  - Age
  - Stature
  - Medical history
  - Position in vehicle
  - Awareness/preparedness for crash

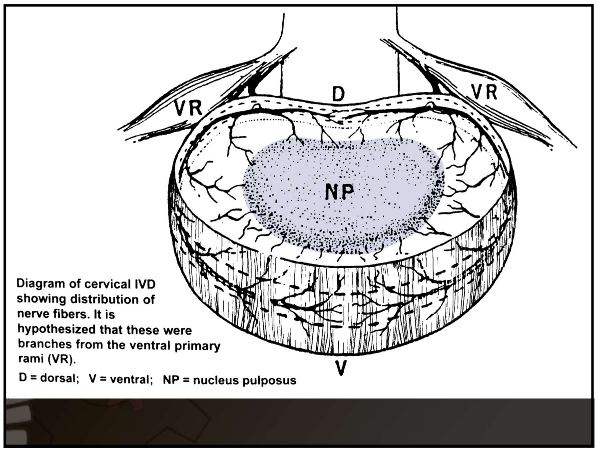
The soft tissue injury

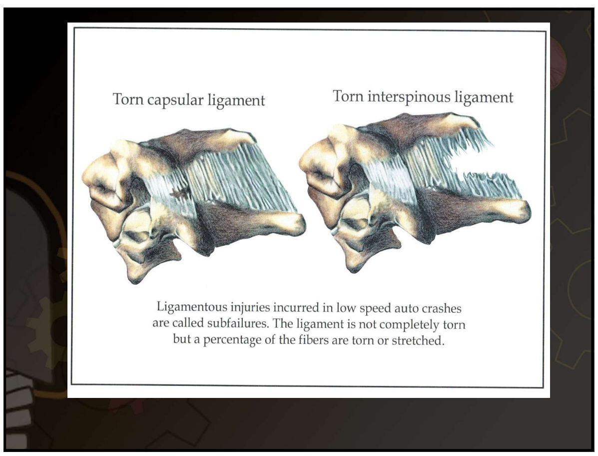
- It is chiefly the spinal structures that are injured
  - Disc
  - Ligament
  - Facet joints
  - End plates
- Muscles, however, are where we often feel the pain

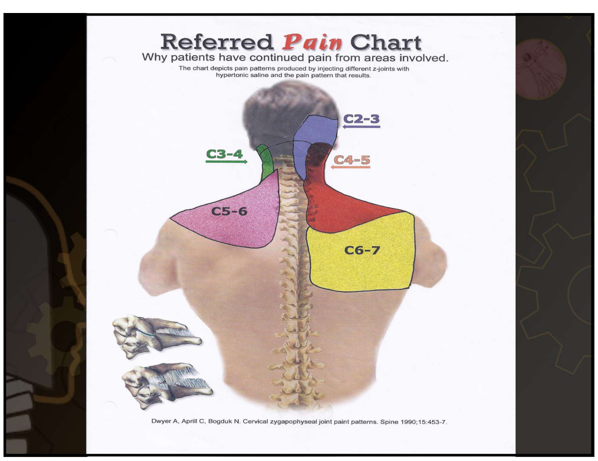


Healing Properties of Tissues

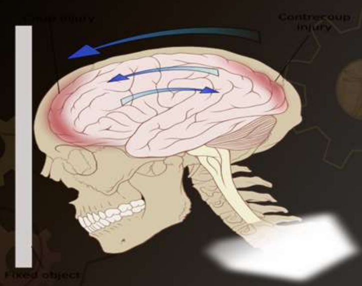
- It's about the blood supply
- Bone
- Muscle
- Ligament


VR
D
VR
NP
V
Diagram of cervical IVD showing distribution of nerve fibers. It is hypothesized that these were branches from the ventral primary rami (VR).
D = dorsal; V = ventral; NP = nucleus pulposus


Torn capsular ligament
Torn interspinous ligament
Ligamentous injuries incurred in low speed auto crashes are called subfailures. The ligament is not completely torn but a percentage of the fibers are torn or stretched.


Referred Pain Chart
Why patients have continued pain from areas involved.
The chart depicts pain patterns produced by injecting different z-joints with hypertonic saline and the pain pattern that results.
C2-3
C3-4
C4-5
C5-6
C6-7
Dwyer A, Aprill C, Bogduk N. Cervical zygapophyseal joint paint patterns. Spine 1990;15:453-7.

TBI- Coup/Contrecoup



Whiplash Injury Determination With Conventional Spine Imaging and Cryomicrotomy

N Yoganandan, J F Cusick, F A Pintar, R D Rao

Objective: To replicate soft tissue injuries resulting from single input of whiplash acceleration to whole human cadavers simulating vehicular rear impacts, and to assess the ability of different modes of imaging to visualize soft tissue cervical lesions.

- **Methods:** Four intact entire human cadavers underwent single whiplash acceleration (3.3g or 4.5g) loading by use of a whole-body sled…
- **Results:** Cryomicrotome sections identified stretch and tear of the ligamentum flavum, anulus disruption, anterior longitudinal ligament rupture, and zygopophysial joint compromise with tear of the capsular ligaments.

- Posterior column abnormalities consisted primarily of zygopophysial joint diastasis, attributed to the localized extension of the lower spine during the initial whiplash acceleration…
- The study has clearly shown that structural alterations occur to the head-neck complex as a result of whiplash injury.
- These alterations do not completely lend themselves to identification by routine spine radiographs and computed tomography.

Mechanical Evidence of Cervical Facet Capsule Injury During Whiplash: A Cadaveric Study Using Combined Shear, Compression, and Extension Loading

GP Siegmund, BS Myers, MB Davis, HF Bohnet, BA Winkelstein

- Study Design: A comparison of cervical facet capsule strain fields in cadaveric motion segments exposed to whiplash-like loads and failure loads.

- The applied forces and moments did not exceed those that might be expected under whiplash loading at a speed change of 8 km/h.
- Findings suggest that capsular ligament fibers experienced sub-catastrophic failures under the whiplash-like loading of the flexibility test.

- Suggests that markedly different clinical outcomes might occur in different individuals under otherwise similar loading conditions…
- The risk of facet capsular ligament injury may be related more to individual differences in subcatastrophic failure thresholds than to the magnitude of the loads to which an individual is exposed.

- "Today I will do what others won't, so tomorrow I can accomplish what others can't."
  Jerry Rice

- physiologic extension limits were exceeded at th intervertebral levels of C6-C7 and C7-T1 for all c the trauma classes…
- …Even though the head extension is less at 75 milliseconds, it is accompanied by flexion in the upper levels. This flexion must be compensated by additional extension in the lower levels. …hyper-extension in the lower levels at 75 milliseconds, but not at the maximum head extension…

- The reaction time to brace the spine is approximately 200 milliseconds. This is longer than the time to peak trauma that was observed in the present study, which was less than 125 ms."

Whiplash injuries and the potential for mechanical instability

MM Panjabi, K Nibu, J Cholewicki

The purpose of the study was to quantify the mechanical changes that occur in the cervical spine specimen as a result of experimental whiplash trauma.

- There is a consensus that most whiplash patients suffer soft-tissue injuries….
- Patients with more severe injuries shows signs of clinical instability, …determined using accepted instability criteria…
- In patients with milder soft tissue injuries, these injuries may go undetected …, as they are not completely identified by the presently available imaging methods…

Sub failure tissue injuries explain the decreased function and pain associated with trauma.

Table 1 Averages (SDs) of ranges of motion (ROM) in degrees as measured in *n* specimens by the flexibility test: **A** flexion, **B** extension, and **C** total (flexion plus extension)

A Flexion ROM

	n	C0-C1	C1-C2	C2-C3	C3-C4	C4-C5	C5-C6	C6-C7
Intact	8	7.2 (2.5)	12.3 (2.0)	3.7 (1.2)	4.0 (2.4)	4.8 (3.1)	5.5 (2.9)	4.2 (2.6)
2.5 g	8	7.9 (3.0)	11.3 (2.1)	3.7 (0.7)	4.2 (1.8)	5.1 (2.7)	5.4 (1.3)	5.2 (5.0)
4.5 g	5	7.4 (1.4)	13.1 (1.7)	3.6 (0.8)	4.1 (1.6)	4.4 (1.9)	7.9 (2.0)	4.1 (0.7)
6.5 g	5	6.7 (1.0)	11.2 (2.1)	4.0 (0.7)	3.0 (2.4)	5.5 (2.1)	5.9 (2.7)	5.8 (1.3)
8.5 g	5	6.9 (1.2)	13.1 (1.5)	4.1 (1.5)	4.6 (1.3)	5.2 (2.3)	8.6 (2.5)	6.5 (1.8)
10.5 g	2	6.9 (2.4)	17.1# (1.5)	3.0 (0.7)	3.0 (0.0)	4.4 (1.8)	6.4 (1.3)	4.7 (2.2)

B Extension ROM

	n	C0-C1	C1-C2	C2-C3	C3-C4	C4-C5	C5-C6	C6-C7
Intact	8	20.2 (4.6)	12.1 (6.5)	3.2 (0.9)	4.2 (2.7)	4.9 (1.8)	4.8 (3.1)	3.8 (2.3)
2.5 g	8	20.8 (4.0)	12.7 (6.4)	3.3 (0.9)	3.8 (3.2)	5.0 (2.5)	5.3 (2.9)	4.3 (2.8)
4.5 g	5	23.3 (3.6)	12.9 (2.8)	3.6 (1.0)	5.8 (3.8)	5.4 (3.6)	9.6* (1.4)	4.4 (1.5)
6.5 g	5	23.4 (2.1)	10.8 (3.1)	3.6 (0.7)	3.5 (2.2)	4.6 (1.9)	10.2* (4.2)	7.9 (4.2)
8.5 g	5	21.4 (2.9)	10.4 (4.8)	3.7 (1.0)	3.7 (0.9)	6.1 (2.2)	11.5* (4.4)	6.6 (2.5)
10.5 g	2	20.0 (0.5)	14.2 (2.6)	3.4 (1.9)	2.6 (0.5)	3.9 (2.5)	13.6* (1.7)	5.2 (3.2)

C Total (Flexion plus Extension) ROM

	n	C0-C1	C1-C2	C2-C3	C3-C4	C4-C5	C5-C6	C6-C7
Intact	8	27.4 (3.7)	24.4 (5.6)	6.8 (1.4)	8.2 (4.7)	9.8 (4.0)	10.4 (5.2)	8.0 (4.3)
2.5 g	8	28.7 (4.5)	24.0 (5.9)	7.0 (1.4)	8.0 (4.6)	10.1 (3.9)	10.7 (3.9)	9.5 (7.4)
4.5 g	5	30.7 (4.9)	25.9 (4.3)	7.3 (1.8)	9.9 (5.4)	9.8 (5.0)	17.4* (1.7)	6.4 (4.6)
6.5 g	5	30.1 (2.8)	22.0 (4.4)	7.5 (1.0)	6.2 (4.2)	10.2 (3.3)	16.8* (6.2)	13.7 (5.4)
8.5 g	5	28.3 (4.0)	23.7 (6.3)	7.8 (2.3)	7.6 (2.7)	11.2 (4.2)	20.1* (6.7)	13.1 (4.2)
10.5 g	2	26.9 (2.8)	31.3 (1.1)	6.3 (2.6)	5.5 (0.5)	8.3 (4.3)	20.0* (3.0)	9.9 (5.3)

* $P < 0.05$; # $P < 0.1$ (with respect to intact values)

- Complete disruptions of the various anatomic elements in severe whiplash trauma is sometimes identified at the time of surgery…
- A significantly larger number of victims are subjected to less severe whiplash.
- Incomplete soft tissue injuries, which are not readily visualized even by MRI…
- long-term symptoms, may be explained on the basis of incomplete soft tissue injuries that may not easily heal.

- Sub failure injuries, soft tissues are not completely torn, but become stretched beyond their elastic limit…
- The reaction time for an unwarned victim to develop sufficient muscle force to brace the spine is approximately 200ms…This is more than twice as long as the time to the peak whiplash trauma, i.e., when there is maximum risk for injury…

Assessment of Accident Injuries: Comparison of Radiographic, MR Imaging, Anatomic, and Pathologic Findings

A Stabler, J Eck, R Penning, SP Milz, R Bartl, D Resnick, M Reiser

- **Purpose:** To assess the ability of postmortem radiography and magnetic resonance (MR) imaging to depict occult cervical spine injuries as compared with anatomic and pathologic findings…
- **Results:** Eight of the 10 specimens had 28 posttraumatic lesions: three fractures , 10 facet joint capsule lesions with bleeding, five soft-tissue and ligament lesions, eight disk lesions, and two spinal cord lesions.

- "Only 11 of the 28 lesions were detected on the MR images during the initial blinded reading session
- Seventeen of the 28 lesions were detected on MR images after direct correlation with the lesions confirmed at pathologic examination.