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Rear Impact Efforts at VRTC

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Previous efforts at VRTC

- Mallory & Stammen, 2006
  - – BioRID II, RID3D, Hybrid III, THOR-NT
  - – FMVSS 202 (18 kph) and FMVSS 301 (30 kph)
  - – Handling, durability, static seat interaction
  - – Injury criteria compatibility
  - – Dynamic sensitivity to seat design
    - 1999 Ford Taurus (“poor” performance)
    - 2001 Ford Taurus (“good” performance)

Rear Impact Biofidelity

- Biofidelity of Rear Impact Dummies
  - Production seats
    - Not repeatable
    - Can't be instrumented
    - Realistic test environment
  - Custom-built experimental seats
    - Repeatable
    - Can be instrumented
    - Fixed non-rotating seatback (rigid or padded)

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Objectives & Tasks

- Evaluate biofidelity of available RIDs (BioRID II, RID3D)
  - Choose biofidelity test condition(s)
  - Develop experimental seat for rear impact sled testing
  - Conduct sled tests
    - PMHS (Post-Mortem Human Subjects)
    - Dummies (BioRID II, RID3D, Hybrid III)
  - Assess biofidelity of dummies

VRTC

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- Investigate the mechanism of injury
  - Develop and validate 3-D cervical spine kinematic instrumentation
  - Identify injurious kinematics (if possible)

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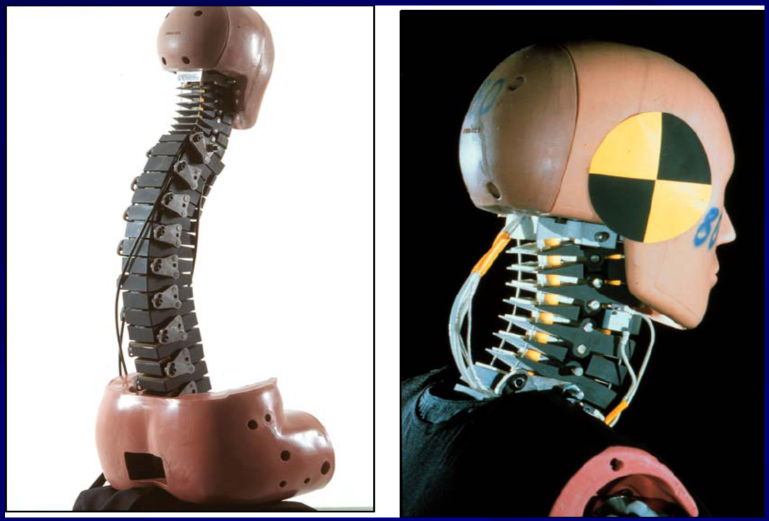
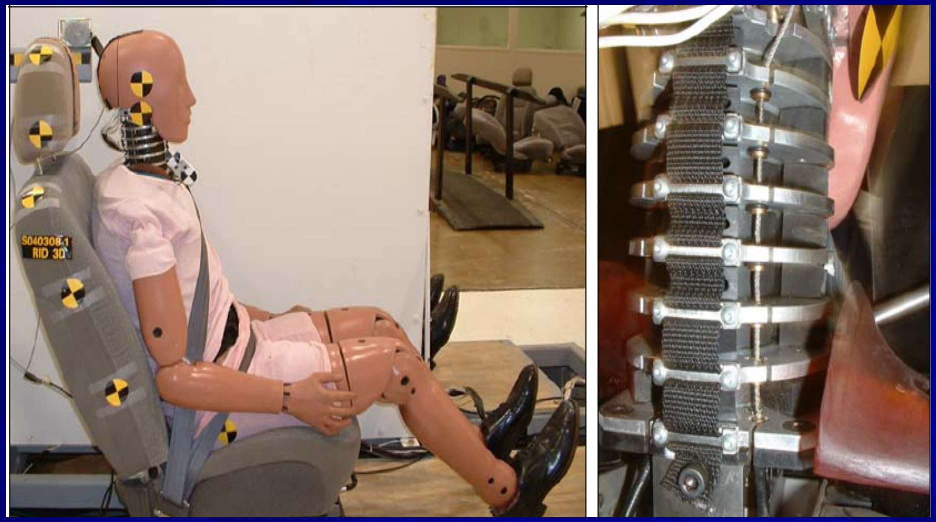
  - Assess biofidelity of dummies
- Investigate the mechanism of injury
  - Develop and validate 3-D cervical spine kinematic instrumentation
  - Identify injurious kinematics (if possible)
- Determine most biofidelic dummy and relevant injury criterion

Rear Impact Dummies



<BioRID II>

- Fully articulated spine
  - C1-C7, T1-T12, L1-L5
- Vertebrae pinned at each joint
  - Allows intervertebral rotation
- 2-D Sagittal plane motion only



<RID3D>

- Custom neck designed for biofidelic rear impact performance
- Thor Thorax, ES2 Lumbar spine
- Can handle higher severity test conditions and off-axis (3D) loading

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  - Develop and validate 3-D cervical spine kinematic instrumentation
  - Identify injurious kinematics (if possible)
- Choose appropriate dummy & injury criterion
  - Assess efficacy of various ICs (if possible)

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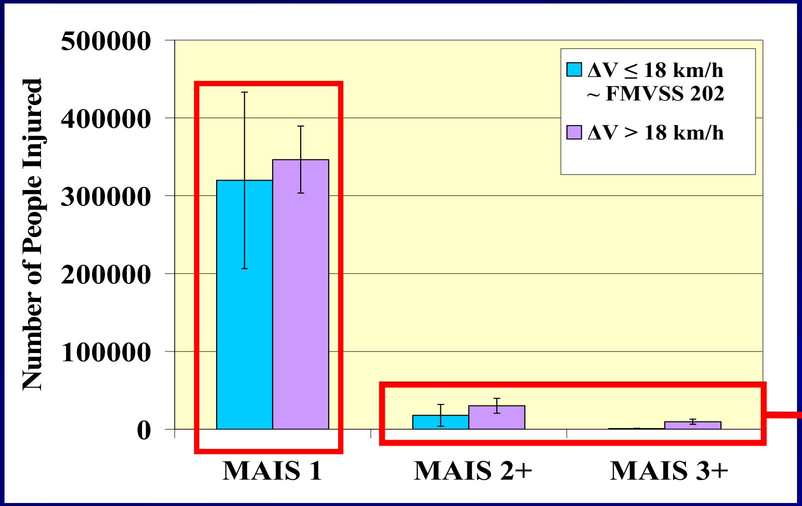
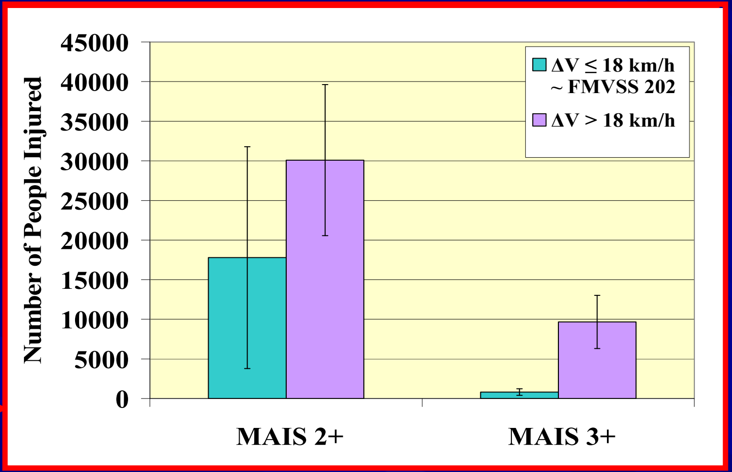
Choose Biofidelity Test Condition

- NASS/CDS Analysis
  - AIS 1 injuries → ΔV > 18 kph ~ ΔV ≤ 18 kph
  - AIS 2 and 3+ injuries → ΔV > 18 kph >> ΔV ≤ 18 kph





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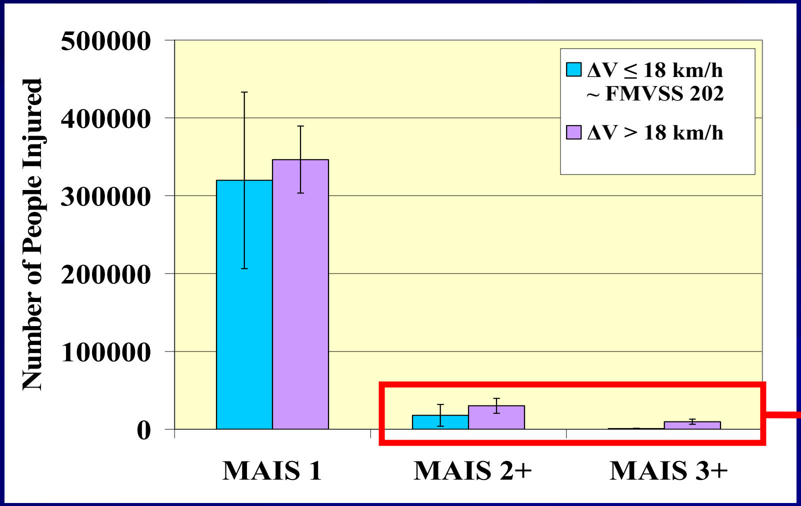

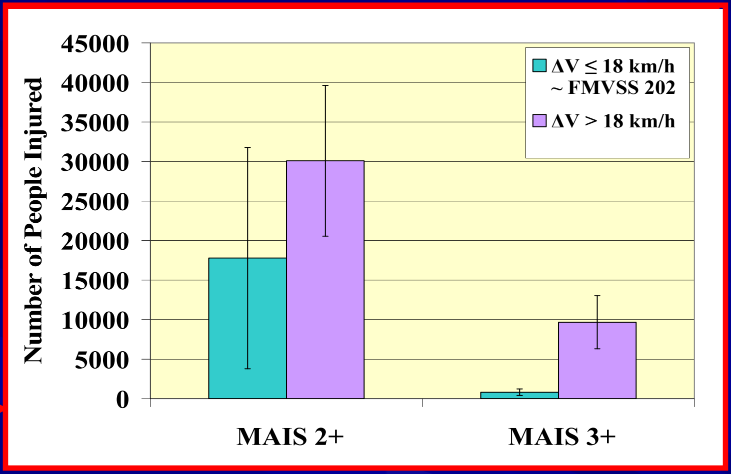

- Moderate-speed test condition (24 kph, 10.5 g)
- Low-speed test condition (FMVSS 202 → 16 kph, 8.5 g)

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Development of Experimental Seat

- Design goals for experimental seat:
  - Able to match the ‘yielding’ seat back motion of a typical OEM seat
  - Capable of measuring/evaluating external biofidelity
    - 6 load cells in seat back
    - 4 load cells in seat pan
    - 4 load cells in head restraint
  - Durable and Reusable
    - Withstand multiple tests without degradation in response
  - Repeatable & Reproducible
    - Two seats side-by-side

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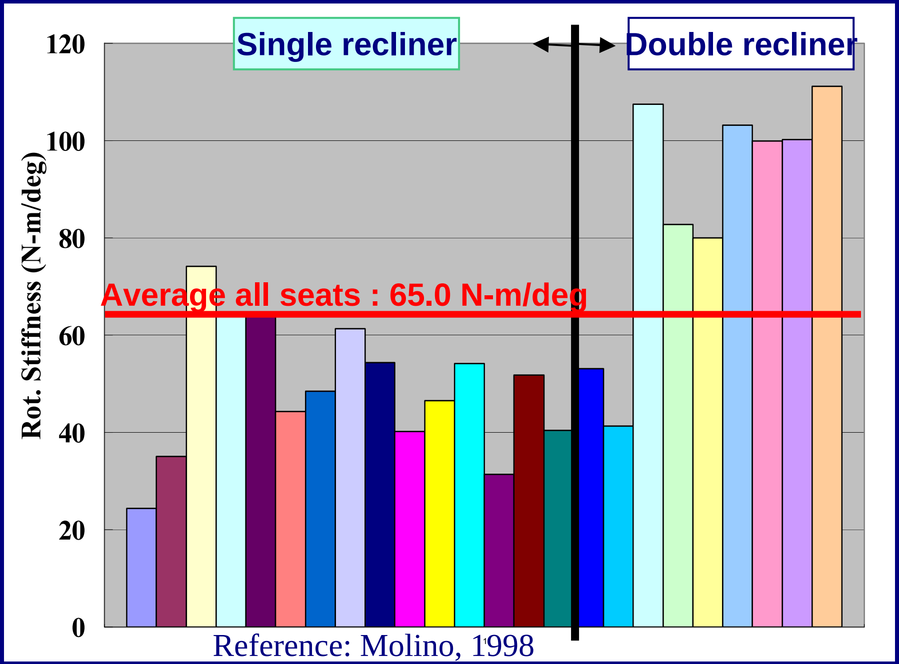
Development of Experimental Seat

- Average static rotational stiffness of OEM seats is 65 N-m/deg (Molino, 1998)

- **Static Rotational Stiffness of OEM seats**



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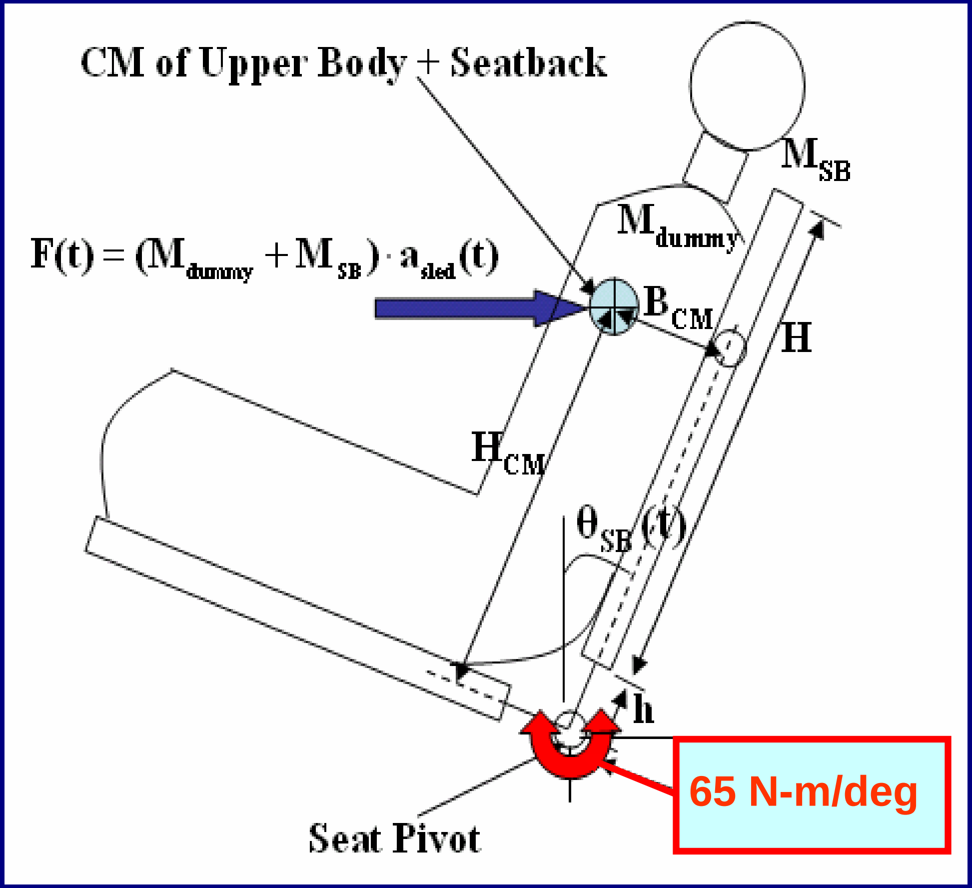
Development of Experimental Seat

- Average static rotational stiffness of OEM seats is 65 N-m/deg (Molino, 1998)
- A model was created to simulate a 50th percentile male dummy seated in a common seat geometry
- A rotational stiffness of 65 N-m/deg was applied at the pivot



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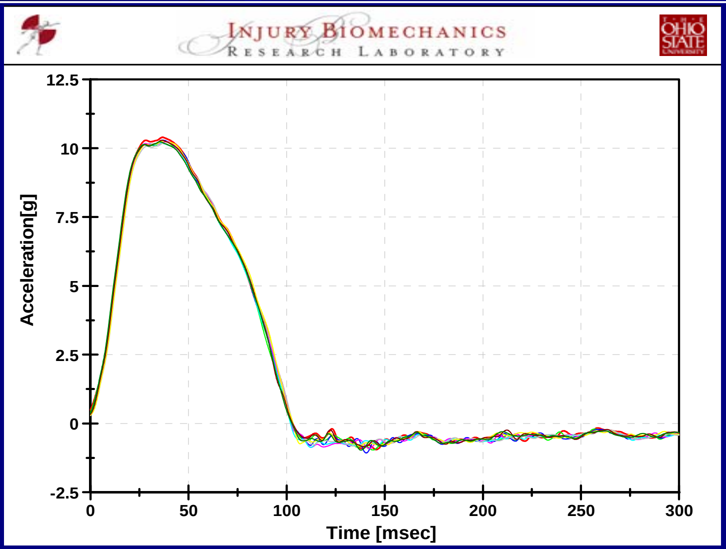
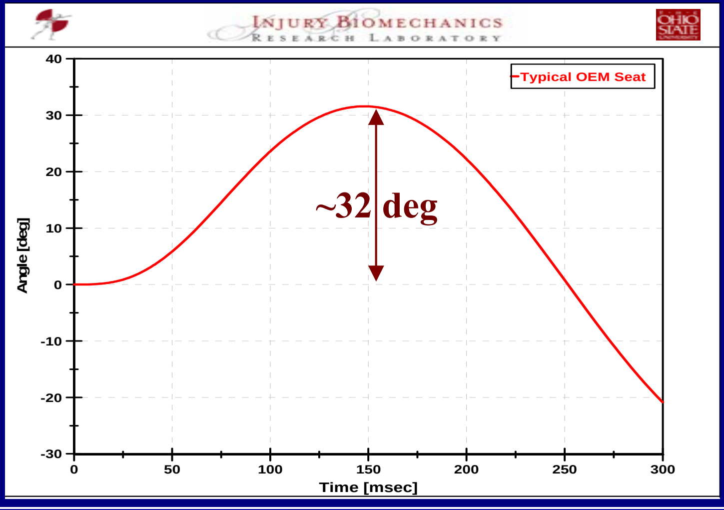
- A moderate pulse of 10.5 g / 24 kph was applied and the resulting seat back angle vs. time was calculated





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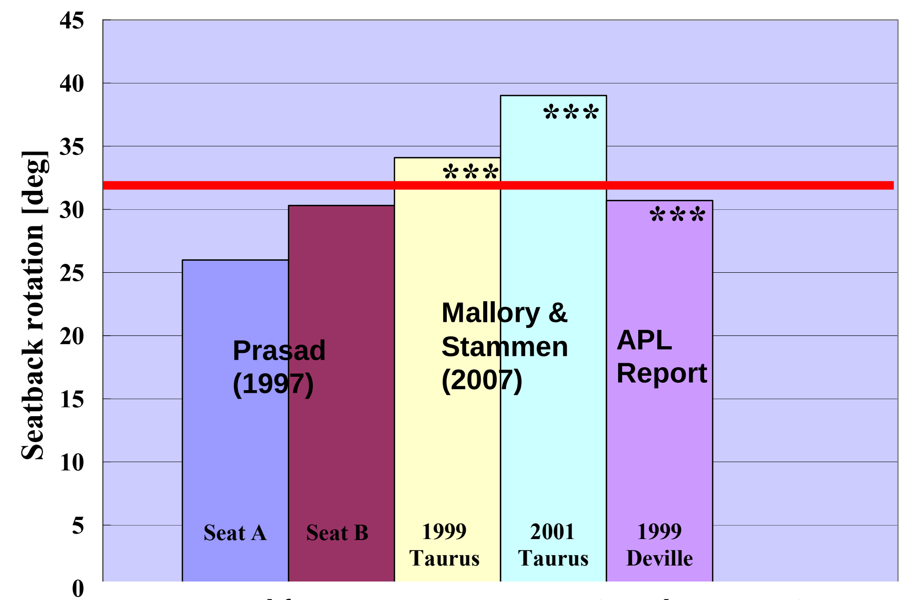
- A model was created to simulate a 50th percentile male dummy seated in a common seat geometry
- A rotational stiffness of 65 N-m/deg was applied at the pivot
- A moderate pulse of 10.5 g / 24 kph was applied and the resulting seat back angle vs. time was calculated
- The peak angle was ~ 32 degrees which is consistent with previous studies

Previous Studies: Seatback Rotations at 24 kph

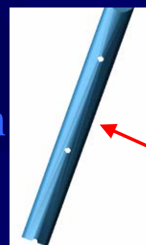


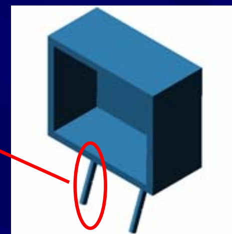
*** Estimated from response in FMVSS 202 and FMVSS 301 tests

Development of Experimental Seat

Head restraint

Diameter :17 mm





Mass : 5.5 kg

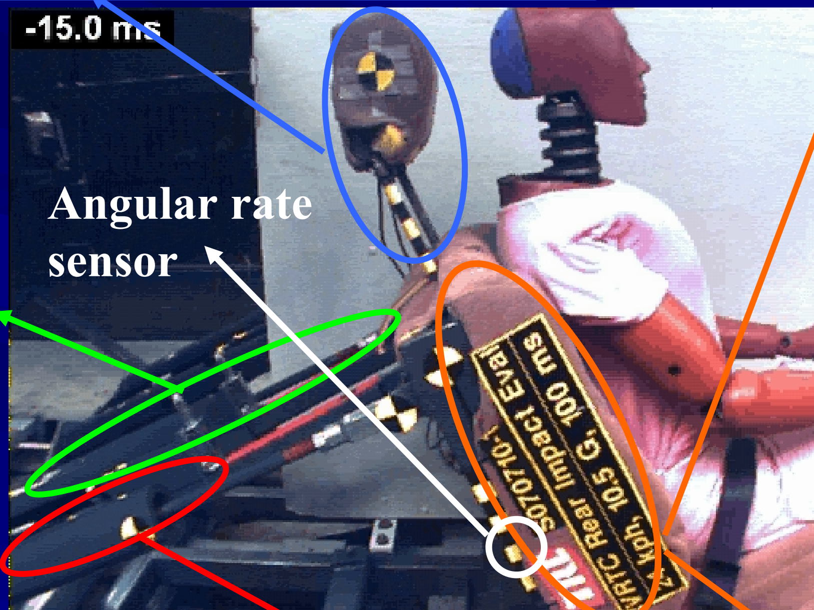
Seat

-Mass: 30 kg

-Padding/cushions/seat cover of 1999 Toyota Camry seat

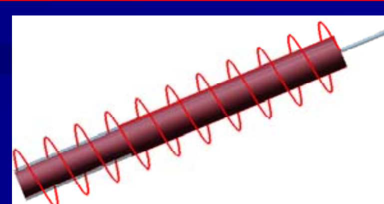
Damper

One-way damper (×2)

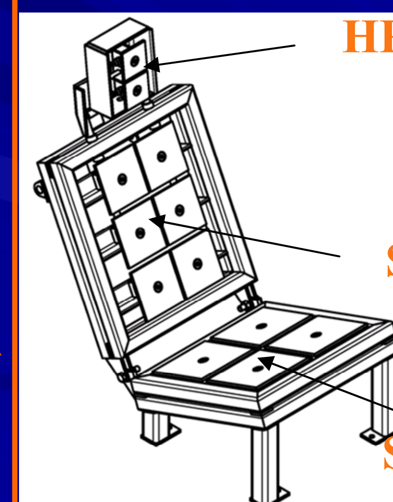


Spring

Stiffness:
13500 N/m (×2)

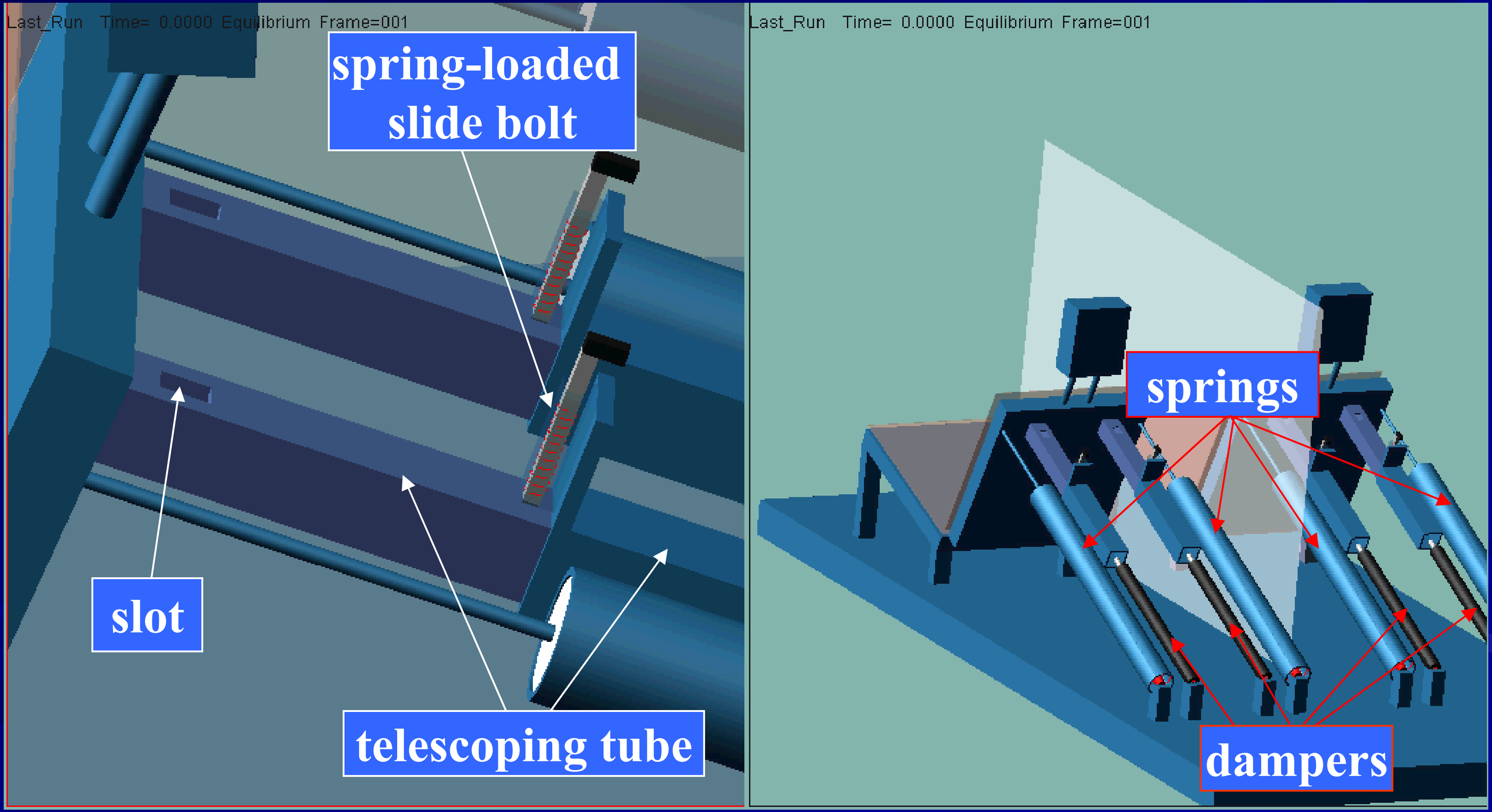


Seat instrumentation



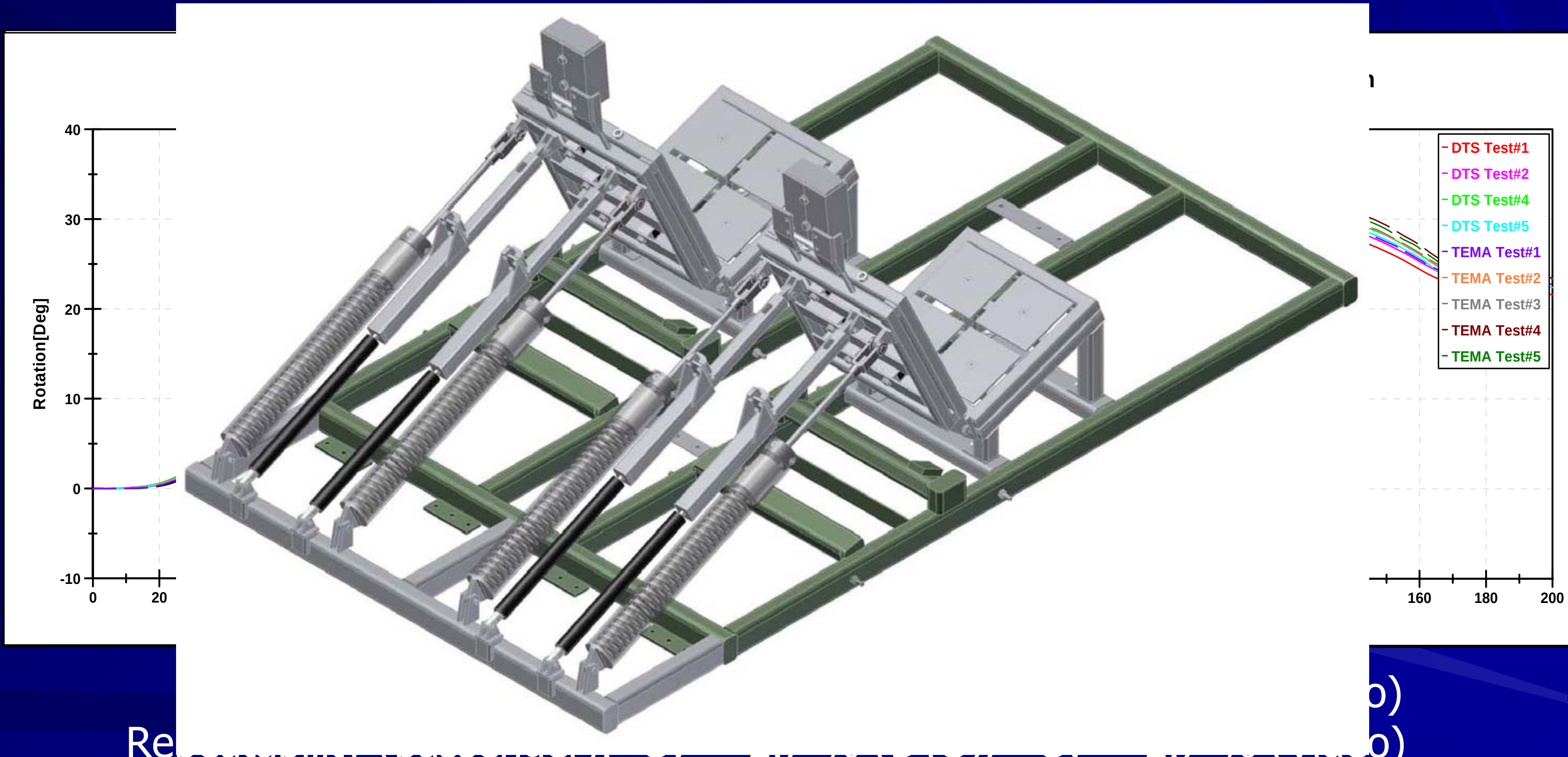
Development of Experimental Seat

- Implement telescoping tube with spring-loaded slide bolt so damper only contributes in rebound:



Development of Experimental Seat

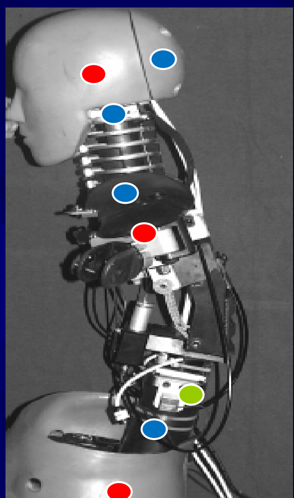
- R&R → Steel Ballast:



Reproducibility: CV = 3.0 % (DTS); CV = 3.0 % (Video)

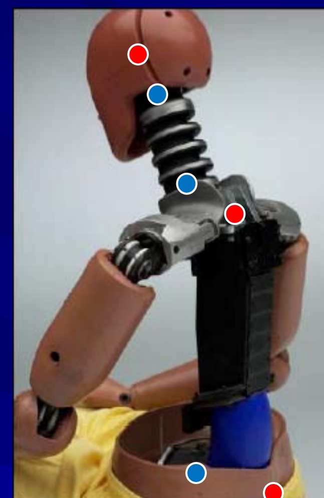
Biofidelity measurements

- Dummies versus PMHS:



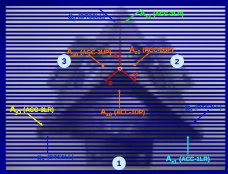
<RID3D>

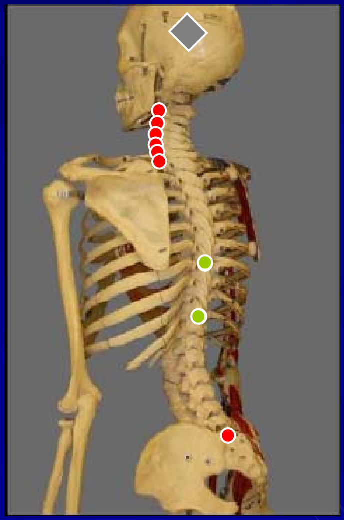
<BioRID II>



<Hybrid III>

- ● Accelerometers (x, z)
- ● Accelerometers (x, z) & angular rate sensor (y)
- ● Load cell
- ◆ Aluminum tetrahedron
  - 9au
  - 3aω
  - 6aω





<PMHS>

● ●	RID 3D	BioRID II	Hybrid III	PMHS
Head	Two Acc (x, z) One ARS (y)	Two Acc (x, z) One ARS (y)	Two Acc (x, z) One ARS (y)	6aω
T1	Two Acc (x, z) One ARS (y)	Two Acc (x, z) One ARS (y)	Two Acc (x, z) One ARS (y)	Two Acc (x, z) One ARS (y)
T8	None	Two Acc (x, z)	None	Two Acc (x, z)
T12	Two Acc (x, z)	None	None	Two Acc (x, z)
L1	None	Two Acc (x, z)	None	
Pelvis	Two Acc (x, z) One ARS (y)	Two Acc (x, z) One ARS (y)	Two Acc (x, z) One ARS (y)	Two Acc (x, z) One ARS (y)

●	RID 3D	BioRID II	Hybrid III	PMHS
Skull Cap	Fx, Fz	Fx, Fz	None	None
Upper neck	Fx, Fz, My	Fx, Fz, My	Fx, Fz, My	None
Lower neck	Fx, Fz, My	Fx, Fz, My	Fx, Fz, My	None
Lumbar	Fx, Fz, My	Fx, Fz, My	Fx, Fz, My	None
Muscle Substitute (front)	None	Fx	None	None
Muscle Substitute (rear)	None	Fx	None	None

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Develop Cervical Spine Instrumentation

- No consensus
  - Injury mechanism / relevant injury criteria
- Proposed injury sites vary
  - Facet joints, capsular ligaments, intervertebral discs
- Agreement as to how injuries occur
  - Relative rotation and displacement between adjacent vertebrae exceeding the physiological range of motion (ROM)
- Measure detailed intervertebral kinematics

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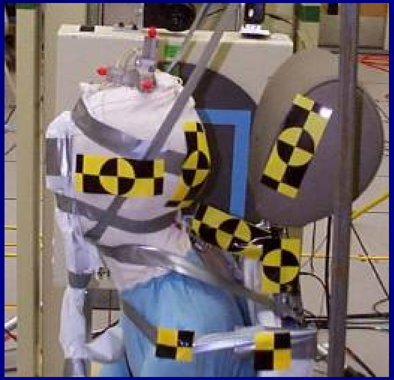
Background: Intervertebral Kinematics

- High speed x-ray imaging system (Ono et al, 1997; Deng et al, 2000)
  - Minimally invasive
  - Detailed anatomic view of kinematics
  - Fully intact PMHS / Volunteers
  - Limited field of view, Low sampling rate
    - Low-speed tests and/or rigid non-yielding seatback


(Deng et al., 2000)

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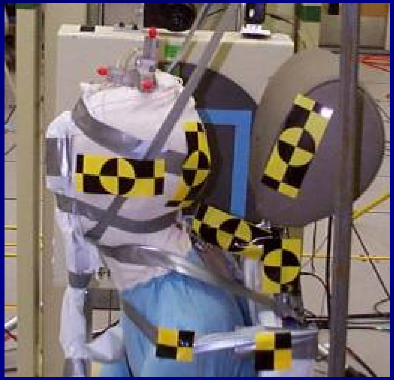

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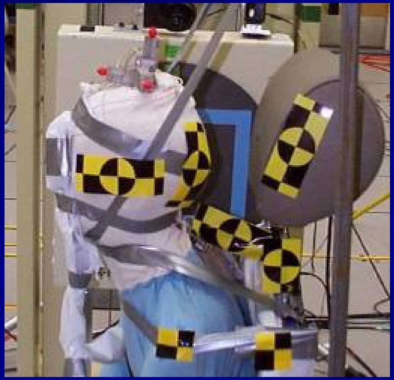

(Deng et al., 2000)

- Isolated Cervical Spine Specimens (mini-sled)

  (Panjabi et al., 1998; Stemper et al., 2003; Tencer et al., 2004; Panjabi et al., 2005)
  - Detailed anatomic view of kinematics
  - Does not limit severity of test conditions
  - Muscle/skin – not intact
  - No ramping / SB interaction
  - No T1 rotation

(Tencer et al., 2004)

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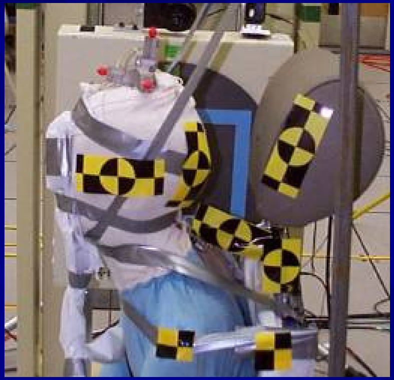

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Background: Intervertebral Kinematics

- Cervical kinematics using accels and ARS
  - High sample rate
  - Does not limit severity of test conditions
  - Full body PMHS in any seating environment
  - Hard to install instrumentation
    - Spinous process: interaction of instrumentation with SB / HR
- Bertholon et al (2000)
  - Two accels / one ARS screwed into anterior vertebral body
    - 2-D kinematics only
    - Requires precise alignment and measurement of initial position
  - Partial kinematics → C2, C5, T1
  - Anterior dissection of neck
    - Required fine dissection to avoid muscle disruption

Objective: Cervical Spine Instrumentation

- Proposal of a new instrumentation technique
  - Capable of measuring 3-D kinematics of entire cervical spine
    - Install 3 accels and 3 ARS on each anterior vertebral body (C2-T1)
  - Dissection of lateral aspect of neck w/ no muscular damage
  - Full body PMHS / realistic seating environment / any impact severity

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  - Dissection of lateral aspect of neck w/ no muscular damage
  - Full body PMHS / realistic seating environment / any impact severity

- Validation of instrumentation technique
  - Conduct PMHS rear impact lab tests
    - Compare kinematics from instrumentation with high speed video

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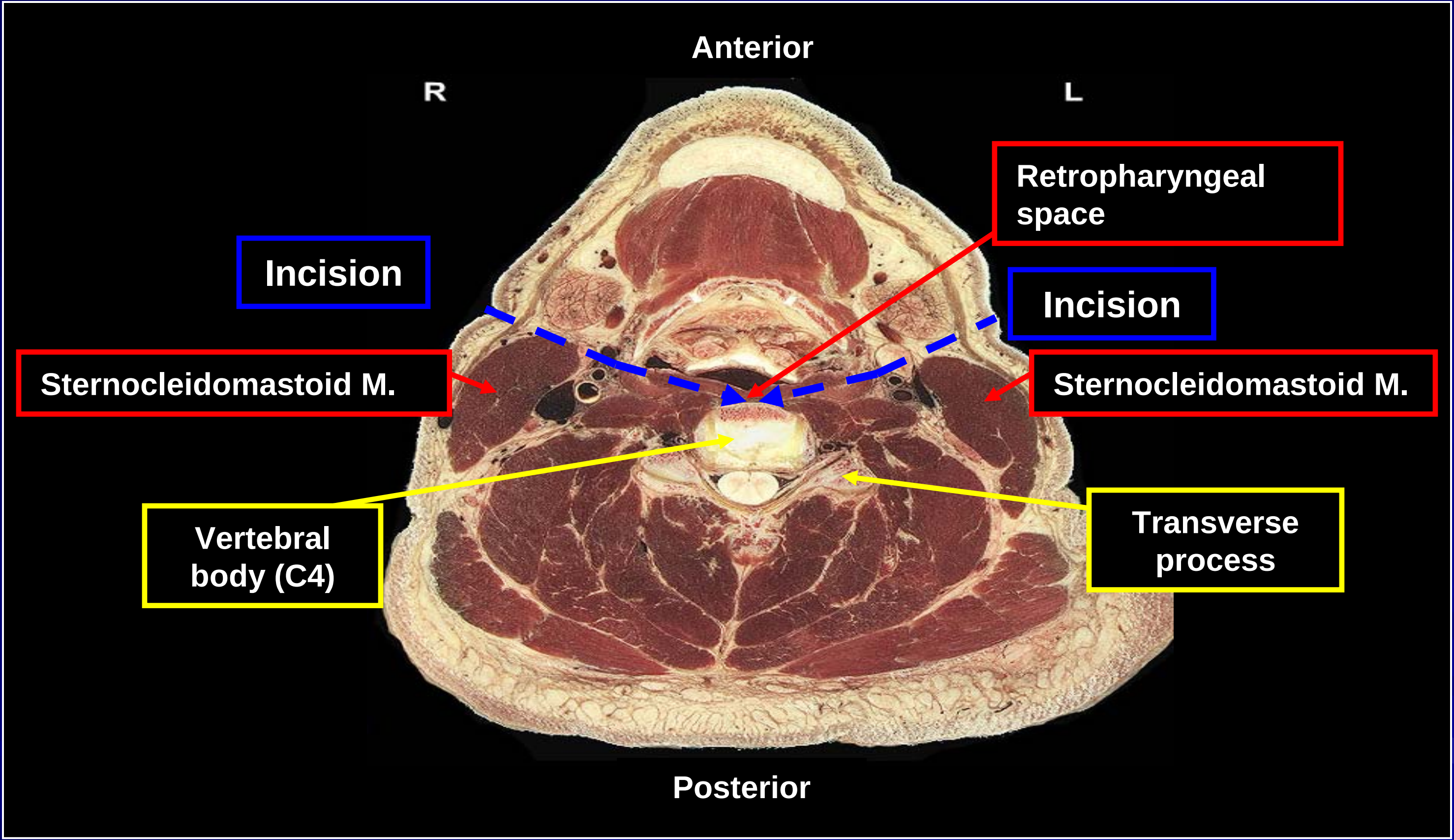
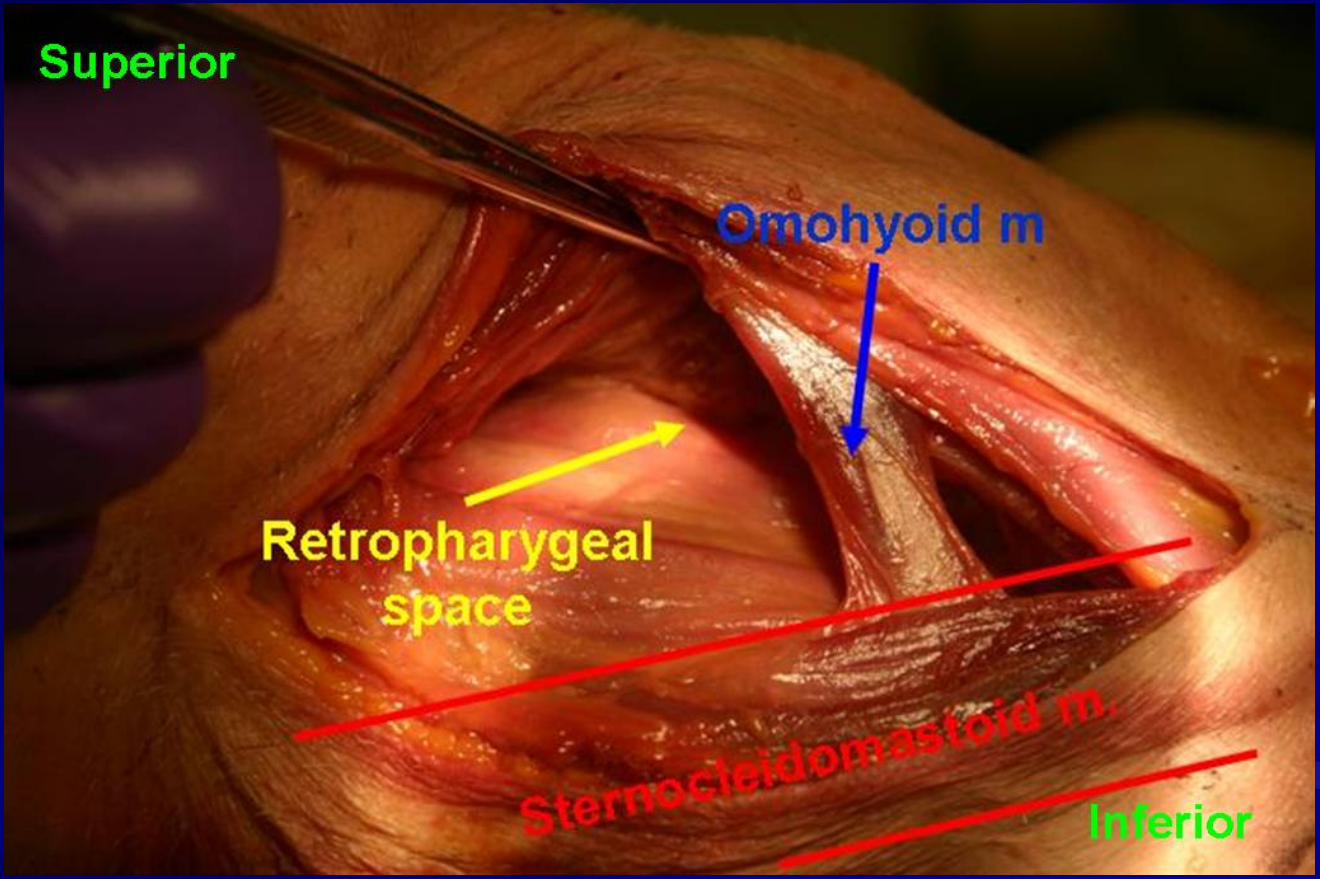
Dissection / Instrumentation Technique

- Neck anatomy (http://www.netanatomy.com)



- Enter the retropharyngeal space from the lateral aspect of neck
- Instrument the anterior vertebral bodies (C2-T1)
  - No muscle disruption

Dissection / Instrumentation Technique



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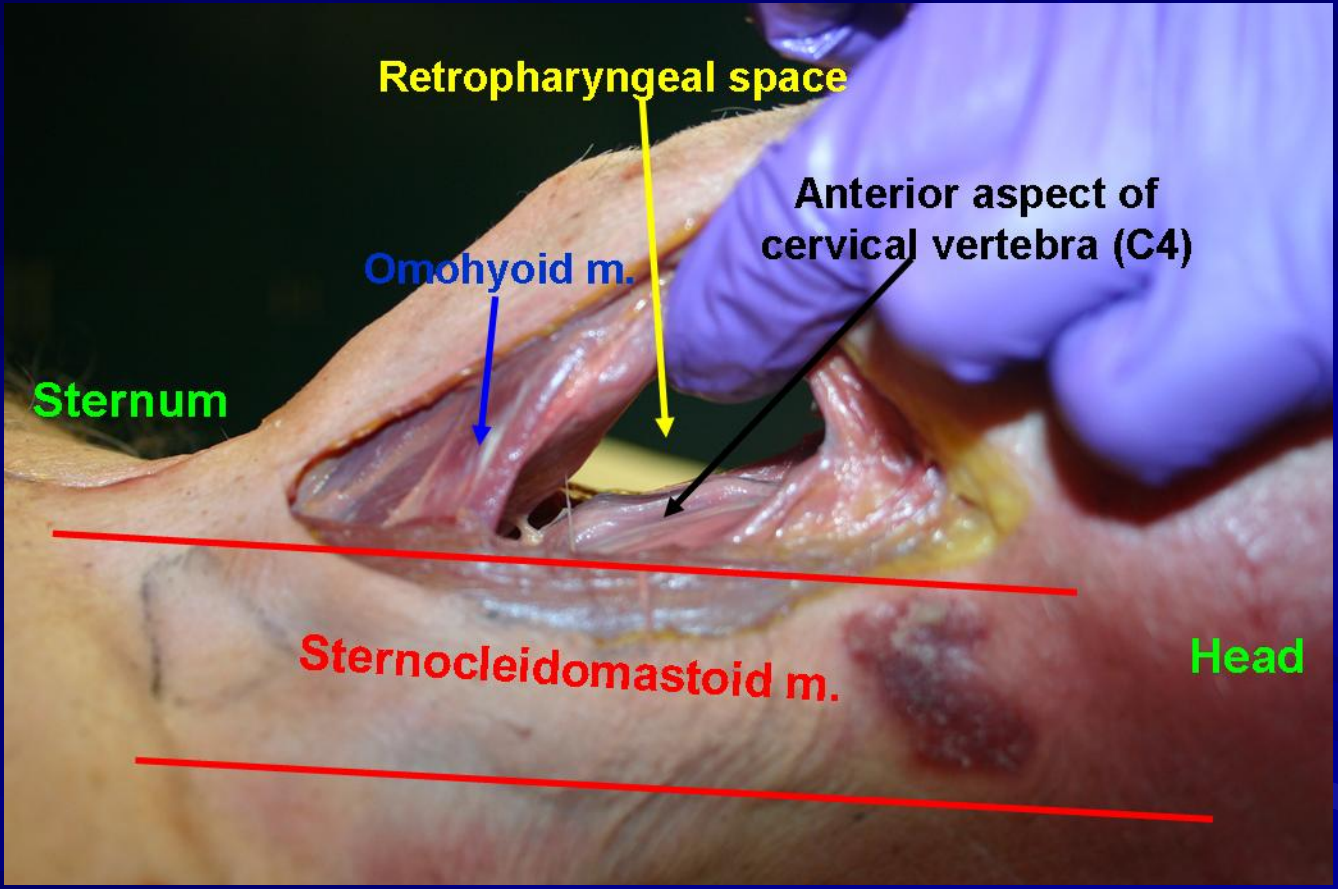
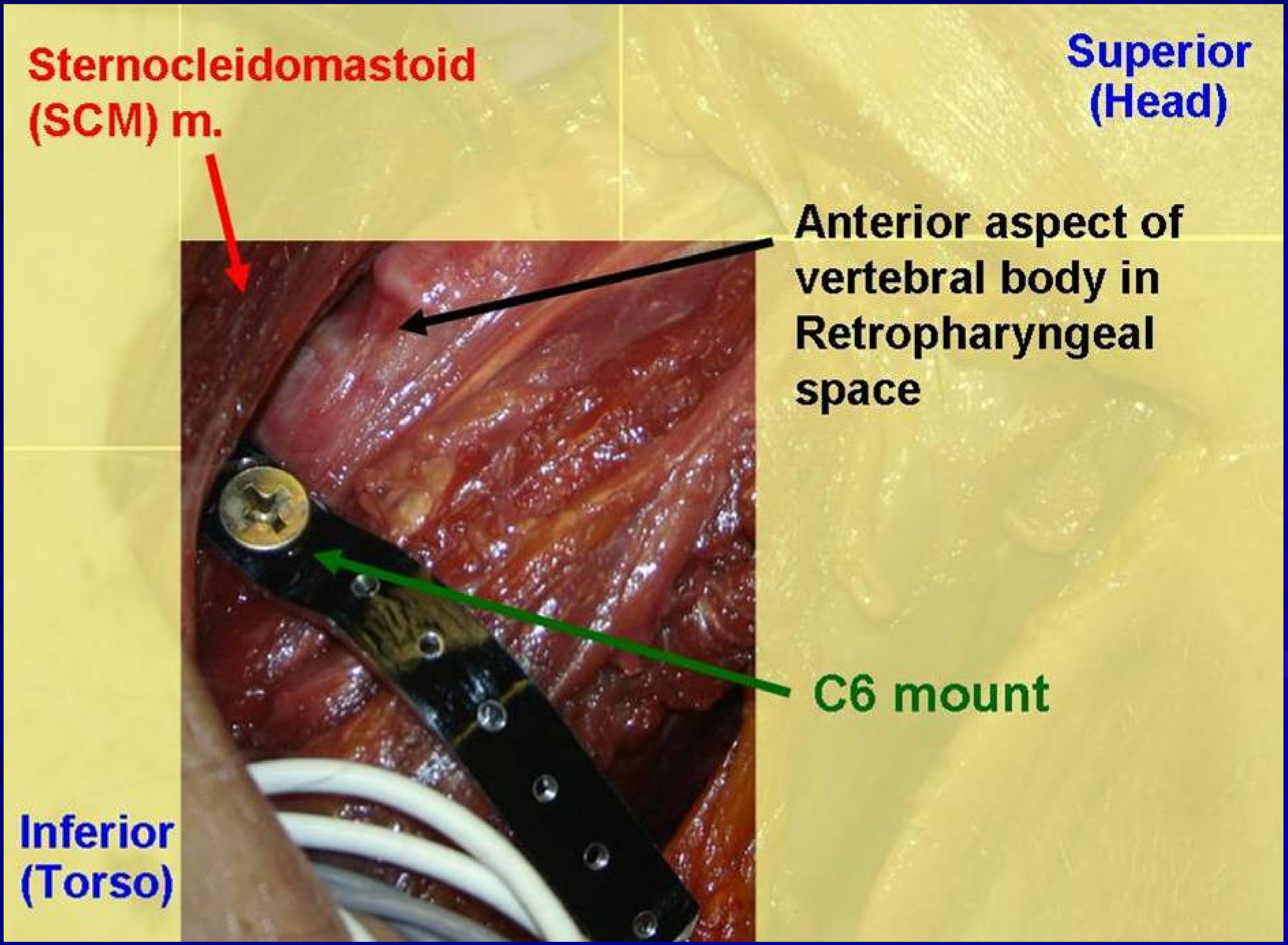
Dissection / Instrumentation Technique



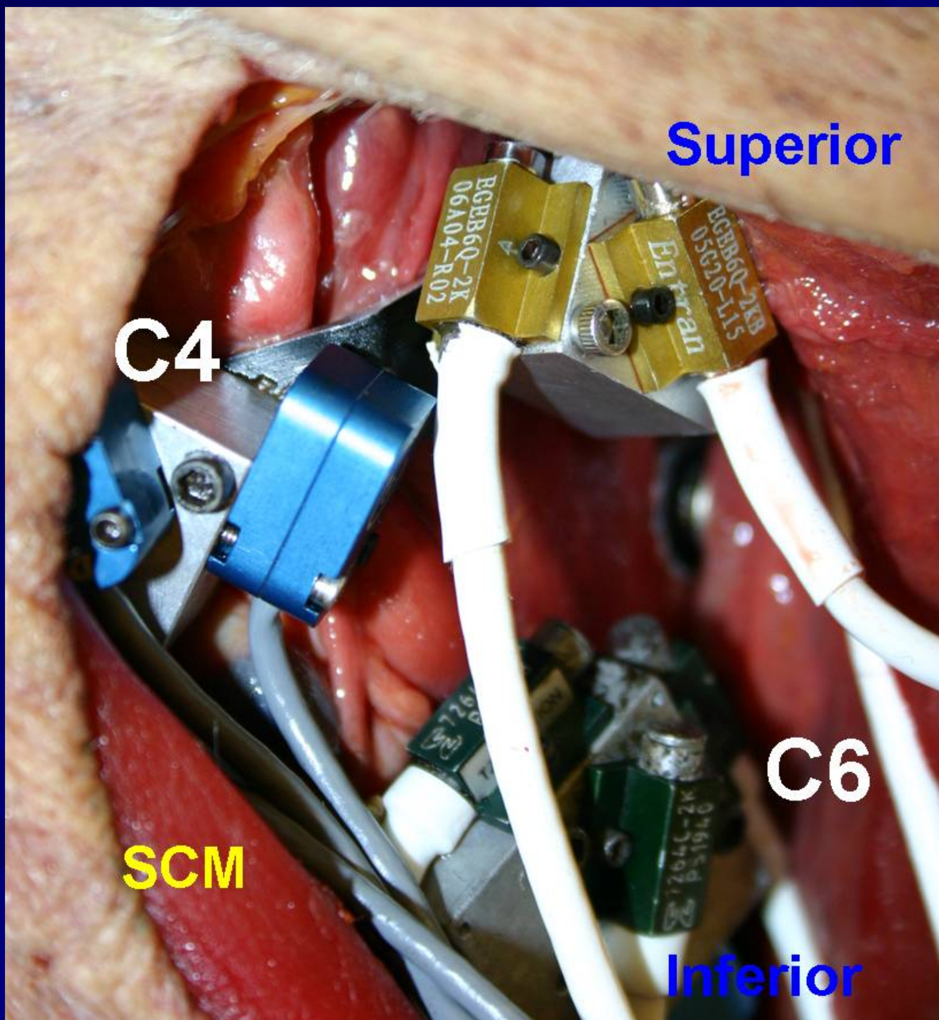
Dissection / Instrumentation Technique

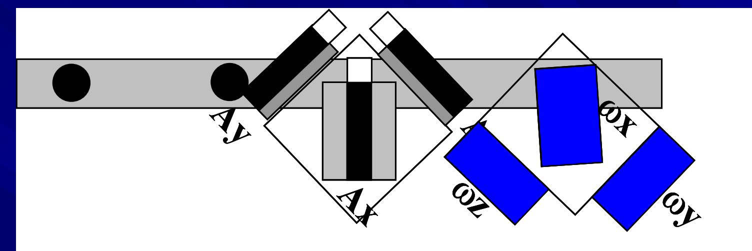
- Custom Instrumentation mount



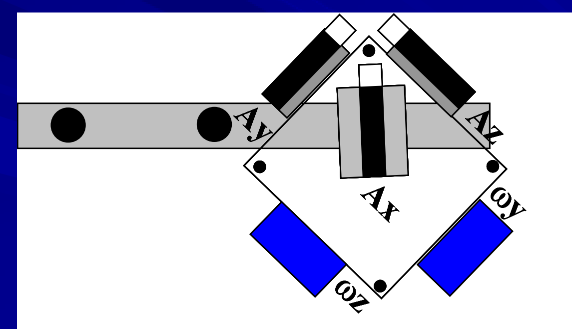
Dissection / Instrumentation Technique

- 3 accels / 3 ARS



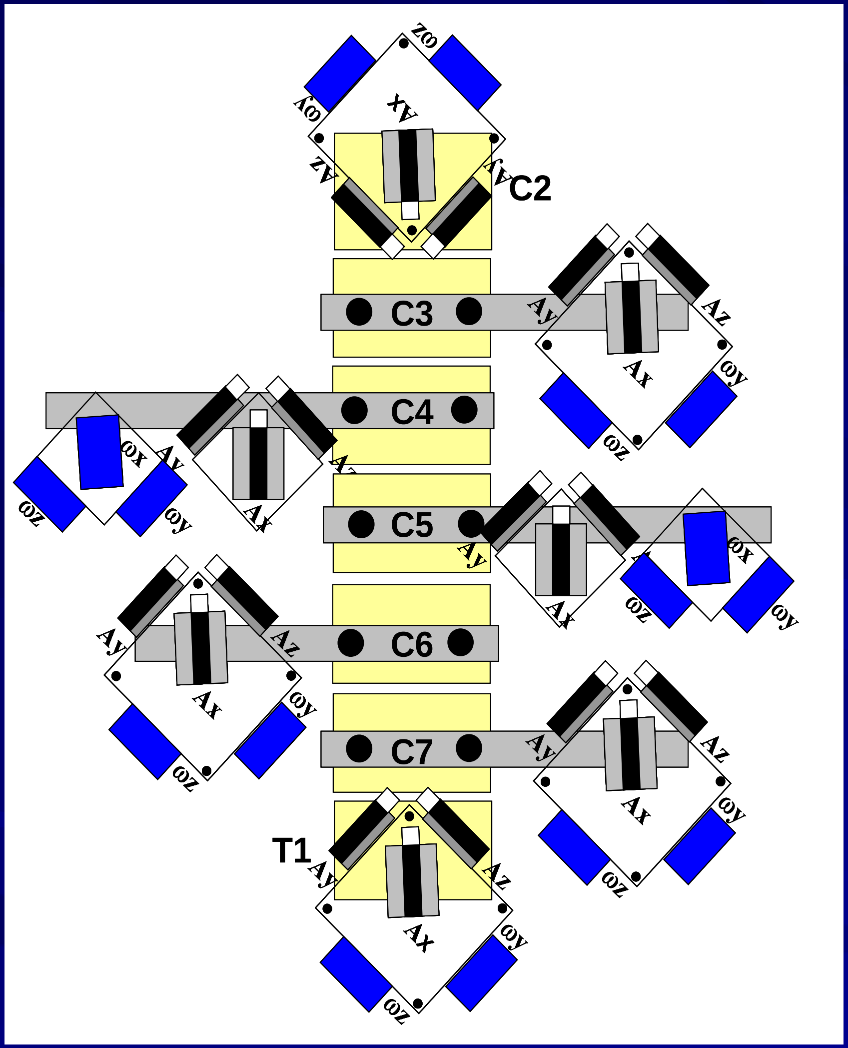


<Two accel blocks>



<3D motion block>

Dissection / Instrumentation Technique



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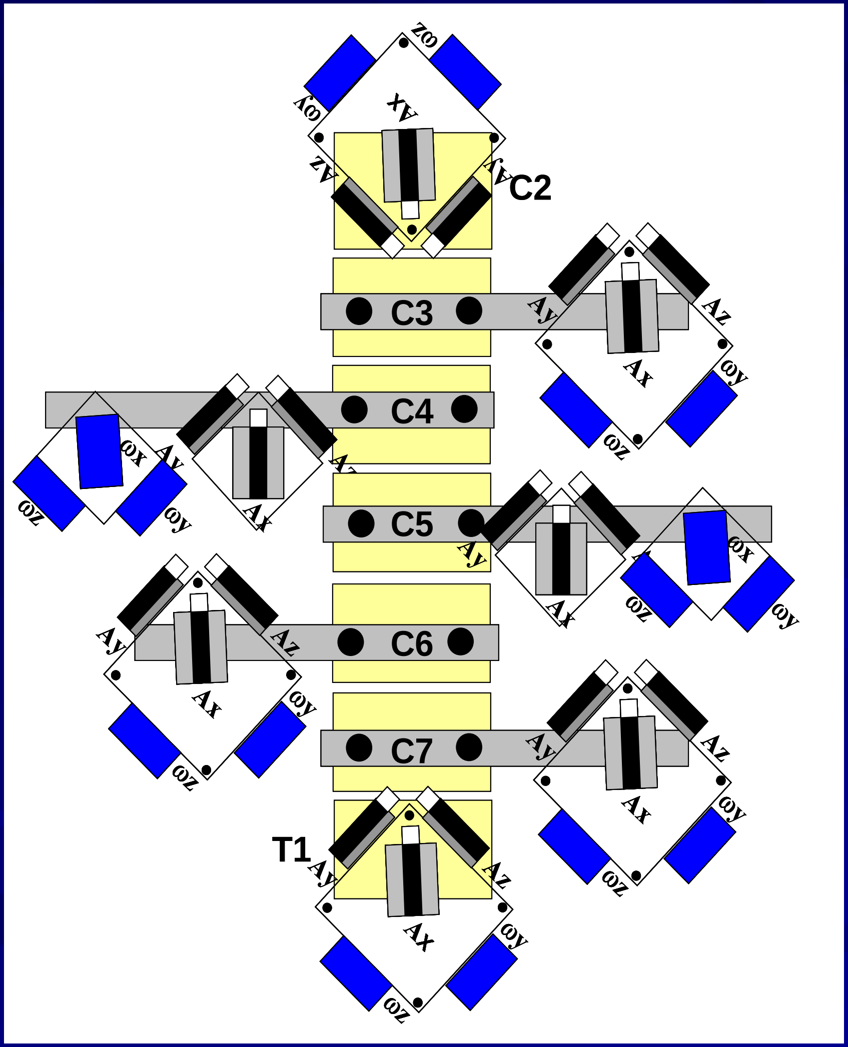
Dissection / Instrumentation Technique



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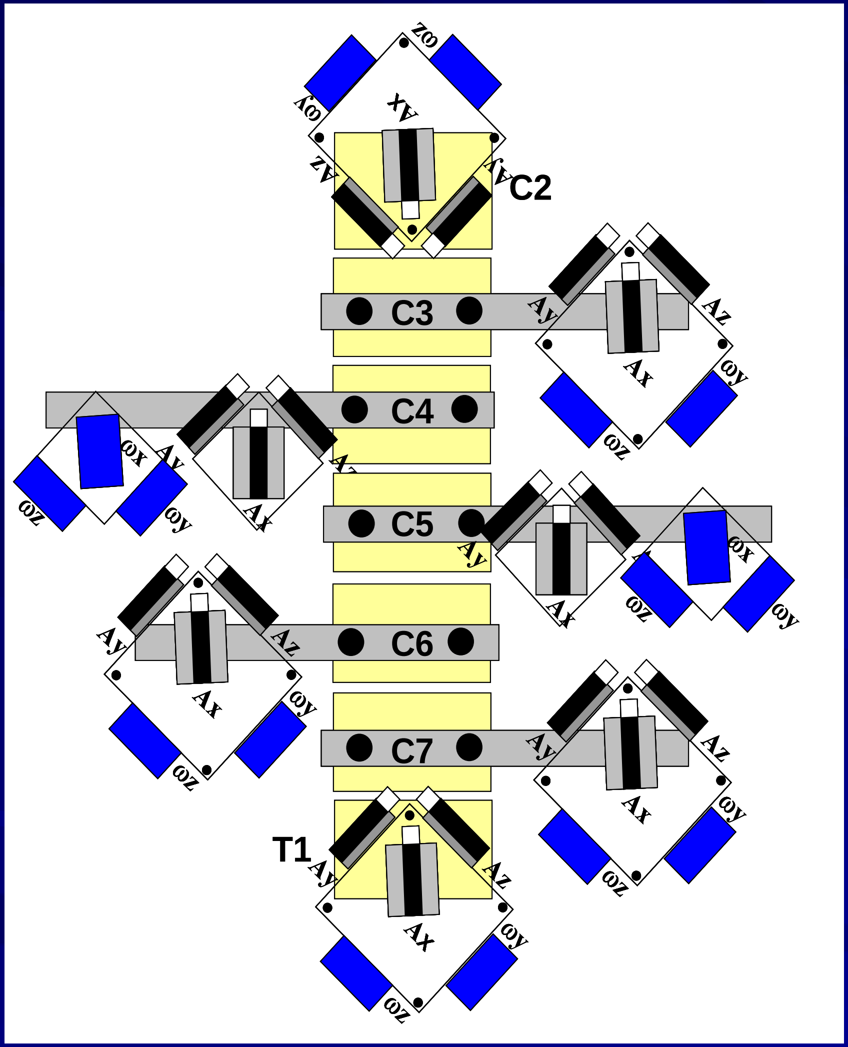
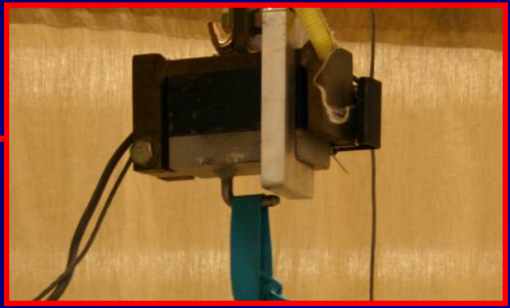
Dissection / Instrumentation Technique



Validate Cervical Spine Instrumentation

- Validation Test setup (10 kph rear impact)



Electromagnetic head release

Pneumatic Impactor

Rolling Chair

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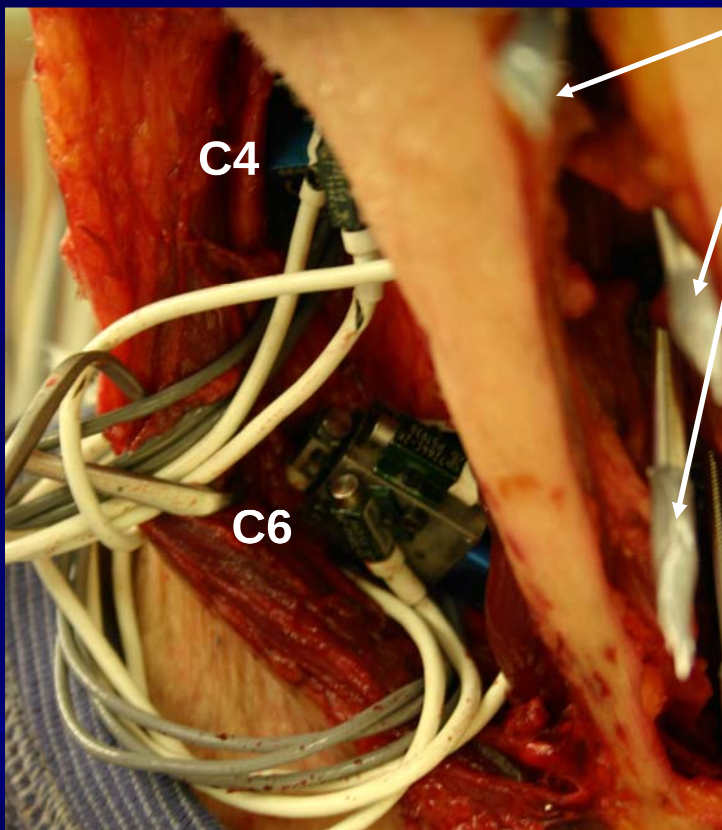
Validate Cervical Spine Instrumentation

Instrumentation

Steinmann pins



- **Steinmann pins with fiducials: high speed video (1000 fps)**
- **Instrumentation: 3 accelerometers and 3 angular rate sensors**

Validate Cervical Spine Instrumentation

- 10 kph Validation Test

Lab_Test.avi

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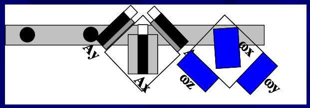
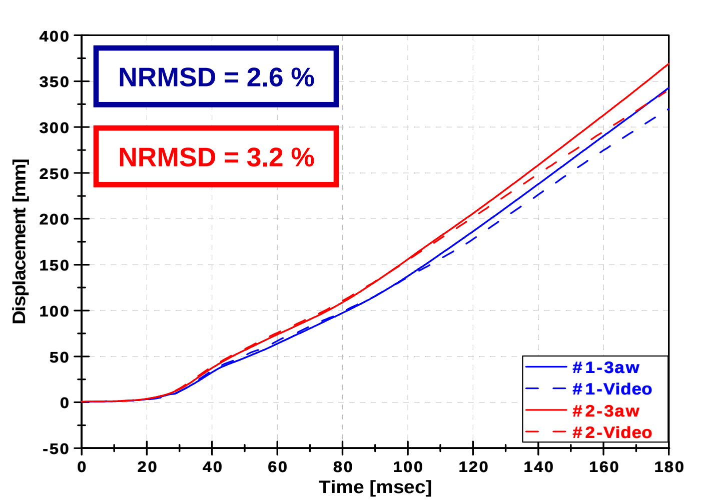
Validate Cervical Spine Instrumentation

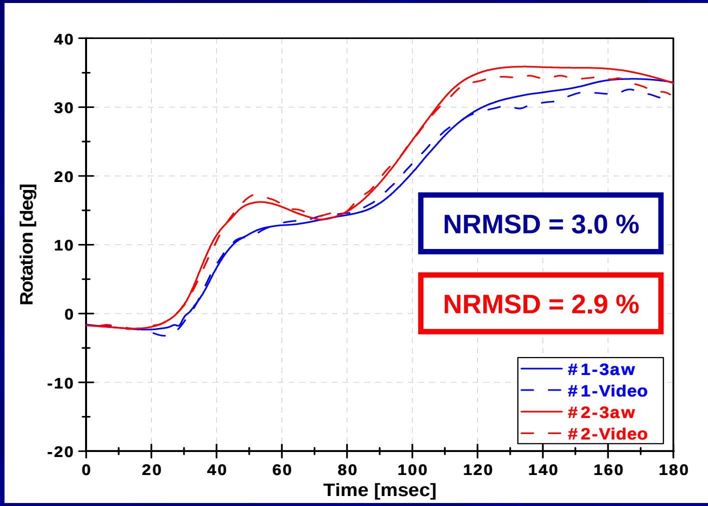
- Neck Kinematics → C4



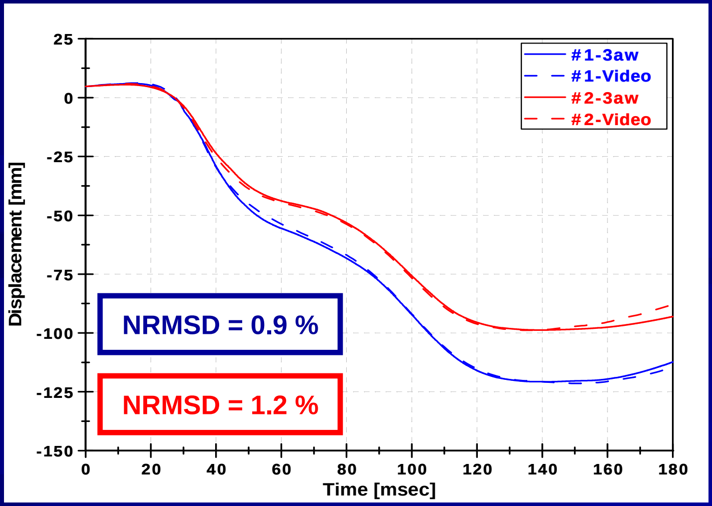
Displacement - X



Rotation - Y



Displacement - Z



Root mean square deviation (RMSD)

$$RMSD = \sqrt{\frac{\sum_{i=0}^{n} (Instrumentation_i - Video_i)^2}{n}}$$

Normalized root mean square deviation (NRMSD)

$$NRMSD = \frac{RMDS}{x_{\max} - x_{\min}}$$

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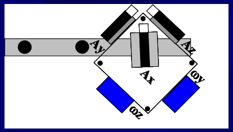
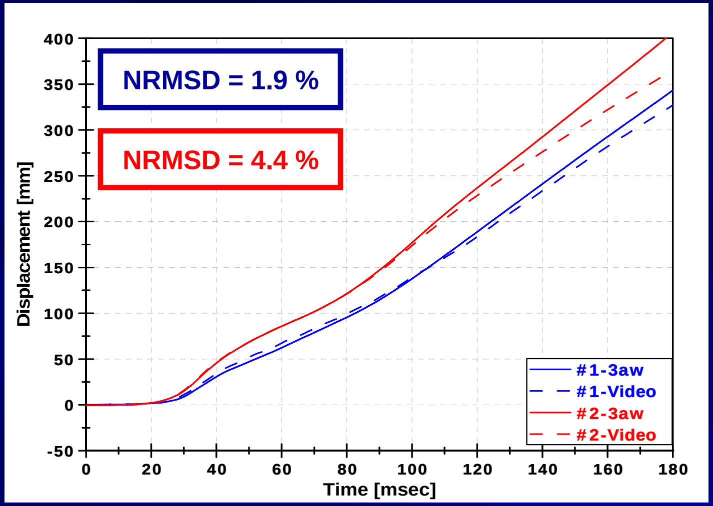
Validate Cervical Spine Instrumentation

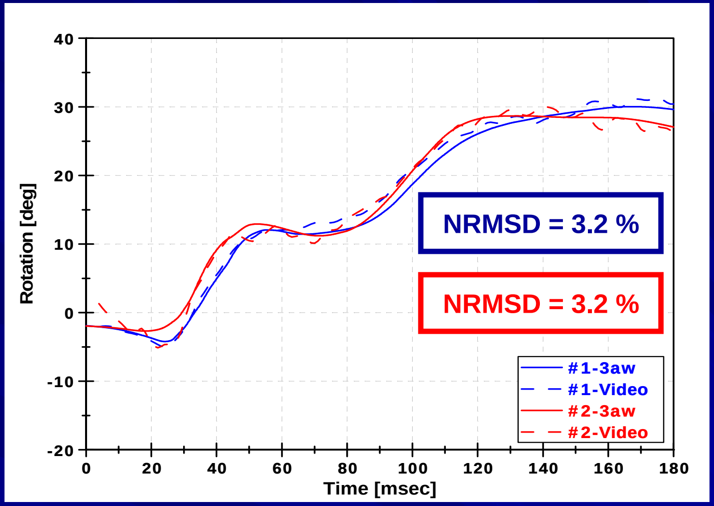
- Neck Kinematics → C6



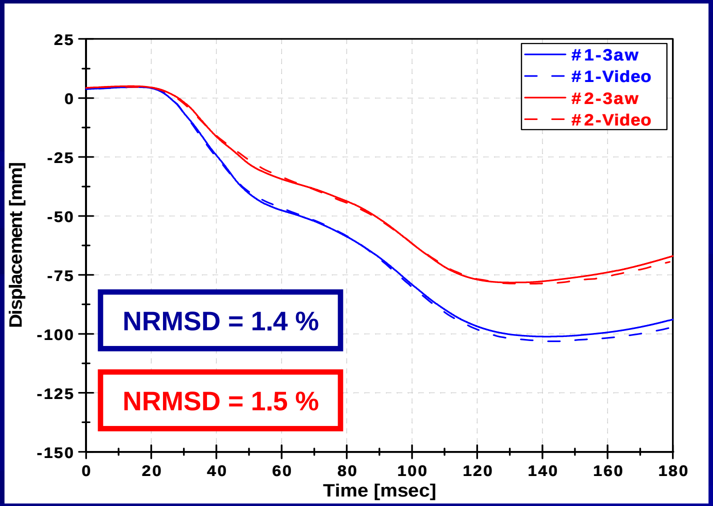
Displacement - X



Rotation - Y



Displacement - Z



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Preliminary Sled Test Results

- Sled Test (24 kph, 10.5 g)

Sled_Test.avi

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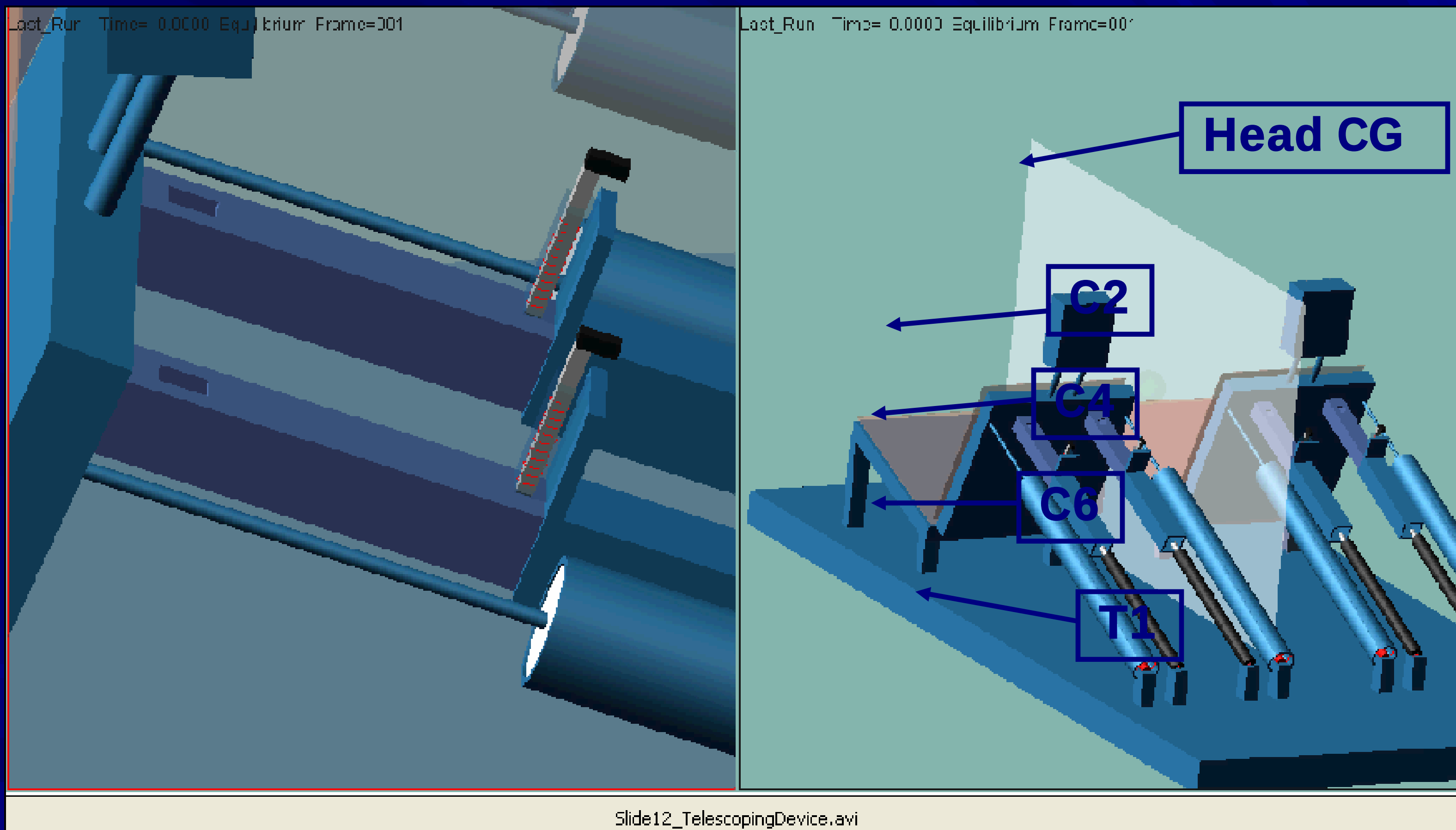
Preliminary Sled Test Results

- Sled test (24 kph, 10.5 g)

Including seat / sled translation **T1 Fixed**



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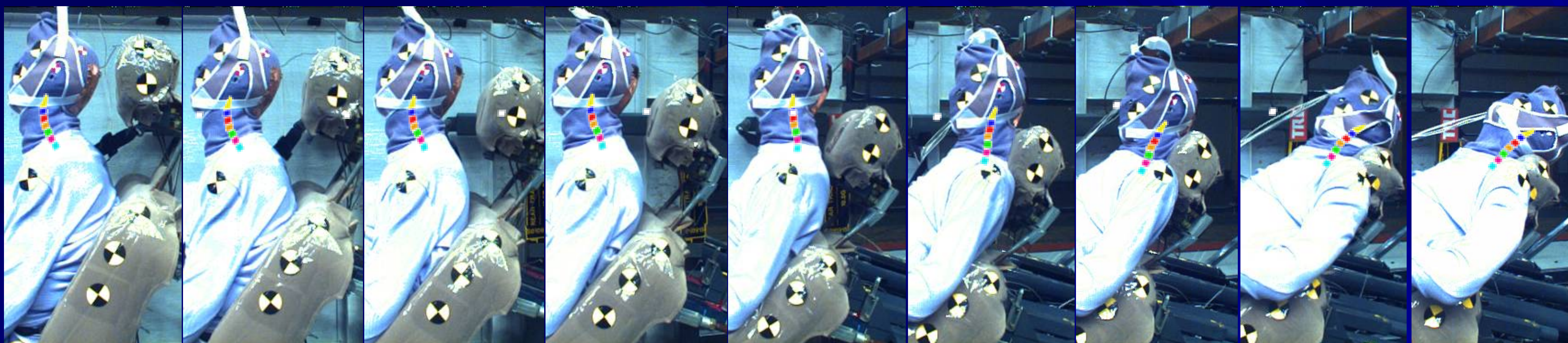
Preliminary Sled Test Results

- Sled Test (24 kph, 10.5 g)



0 50 70 80 100 120 130 150 170

Time [msec]

0 50 70 80 100 120 130 150 170

Time [msec]

Cervical Spine Instrumentation → Injury

- Identify injurious kinematics
  - Measure relative rotations and displacements at each vertebral level
  - Compare with values of non-injurious physiologic ROM (Panjabi et al, 1998; Panjabi et al, 2005)
    - Flexion and extension rotations
    - Shear and axial displacements
  - Determine likelihood and mode of injury at each vertebral level
- Compare to various injury criteria and look for best predictor
  - IV-NIC
  - NIC, N_{ij}, N_{km}, N_{te}, ND criterion, LNL index
  - Head-to-Torso rotation, upper & lower extension moment
  - Other??

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Schedule & Status

	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Jan	Feb	Mar	Apr	May
Evaluate RID Biofidelity													
Choose biofidelity test conditions	DONE												
Develop experimental seat	DONE												
Conduct dummy sled tests													
Conduct PMHS sled tests													
Assess biofidelity of dummies													
Investigate injury mechanism													
Develop and validate 3-D cervical instrumentation	DONE												
Identify injurious kinematics													
Choose dummy & appropriate injury criteria													
Assess efficacy of injury criteria													

Now

- Dummy sled tests
  - 6 exposures each dummy (3x each speed)
  - Sufficient for repeatability
- Conduct PMHS sled tests
  - 7 PMHS at both speeds
  - Sufficient for robust corridors

NASS/CDS analysis

- Search parameters for NASS/CDS
  - Used weighted data
  - 1999-2006
  - Rear impacts (PDOF 5, 6, 7 o'clock)
  - Exclusions:
    - MAIS injuries associated with frontal structure of vehicle
    - Primary vehicle damage from overturn
- Injury details

		C-spine	Head	Thorax / Lumbar	Other*
AIS 1	$\Delta V \le 18$ kph	30%	12%	29%	29%
	$\Delta V > 18$ kph	28%	10%	19%	43%
AIS 2+	$\Delta V \le 18$ kph	Limited data did not allow for breakdown**			
	$\Delta V > 18$ kph	6%	42%	12%	40%

* Other: abdomen, face, upper/lower extremity, neck/thorax (non-spinal)

** 96% of AIS2+ injuries occurred at $\Delta V > 18$ kph

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Comparison of 6aω with NAP and 3aω

- Kinematics in the global (lab) frame

Acceleration in the body fixed frame

$$\ddot{\underline{\mathbf{r}}}'^{\mathbf{P}} = \ddot{\underline{\mathbf{r}}}' + \dot{\tilde{\underline{\boldsymbol{\omega}}}}'\underline{\mathbf{s}}'^{\mathbf{P}} + \tilde{\underline{\boldsymbol{\omega}}}'\tilde{\underline{\boldsymbol{\omega}}}'\underline{\mathbf{s}}'^{\mathbf{P}}$$

$\xrightarrow{\underline{\mathbf{A}}}$

Transformation matrix

Acceleration in the global frame

$$\ddot{\underline{\mathbf{r}}}^{\mathbf{P}} = \ddot{\underline{\mathbf{r}}} + \underline{\mathbf{A}}\dot{\tilde{\underline{\boldsymbol{\omega}}}}'\underline{\mathbf{s}}'^{\mathbf{P}} + \underline{\mathbf{A}}\tilde{\underline{\boldsymbol{\omega}}}'\tilde{\underline{\boldsymbol{\omega}}}'\underline{\mathbf{s}}'^{\mathbf{P}}$$

velocity $\dot{\underline{\mathbf{r}}}^{\mathbf{P}} = \dot{\underline{\mathbf{r}}} + \underline{\mathbf{A}}\tilde{\underline{\boldsymbol{\omega}}}'\underline{\mathbf{s}}'^{\mathbf{P}}$

position $\underline{\mathbf{r}}^{\mathbf{P}} = \underline{\mathbf{r}} + \underline{\mathbf{A}}\underline{\mathbf{s}}'^{\mathbf{P}}$

Euler angle 2-1-3 (φ–θ–σ)

$$\underline{\mathbf{A}} = \begin{bmatrix} \cos\varphi\cos\sigma + \sin\varphi\sin\theta\sin\sigma & -\cos\varphi\sin\sigma + \sin\varphi\sin\theta\cos\sigma & \sin\varphi\cos\theta \\ \cos\theta\sin\sigma & \cos\theta\cos\sigma & -\sin\theta \\ -\sin\varphi\cos\sigma + \cos\varphi\sin\theta\sin\sigma & \sin\varphi\sin\sigma + \cos\varphi\sin\theta\cos\sigma & \cos\varphi\cos\theta \end{bmatrix}$$

$$\begin{bmatrix} \dot\varphi \\ \dot\theta \\ \dot\sigma \end{bmatrix} = \begin{bmatrix} \cos\theta\sin\sigma & \cos\sigma & 0 \\ \cos\theta\cos\sigma & -\sin\sigma & 0 \\ \sin\theta & 0 & 1 \end{bmatrix}^{-1} \begin{bmatrix} \omega'_x \\ \omega'_y \\ \omega'_z \end{bmatrix}$$

	NAP	3aω	6aω
Transformation matrix & Euler angles	Numerical integration (twice) $\dot{\tilde{\underline{\boldsymbol{\omega}}}}'$ → numerical integration → $\tilde{\underline{\boldsymbol{\omega}}}'$ → $\dot\varphi, \dot\theta, \dot\sigma$ → numerical integration → φ, θ, σ	**Numerical integration (once)** $\tilde{\underline{\boldsymbol{\omega}}}'$ → $\dot\varphi, \dot\theta, \dot\sigma$ → numerical integration → φ, θ, σ	**Numerical integration (once)** $\tilde{\underline{\boldsymbol{\omega}}}'$ → $\dot\varphi, \dot\theta, \dot\sigma$ → numerical integration → φ, θ, σ