SAND2019-12000PE

PANTHER

Review Meeting, Madison WI

October 8-9, 2019

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Sandia Injury Biomechanics Laboratory

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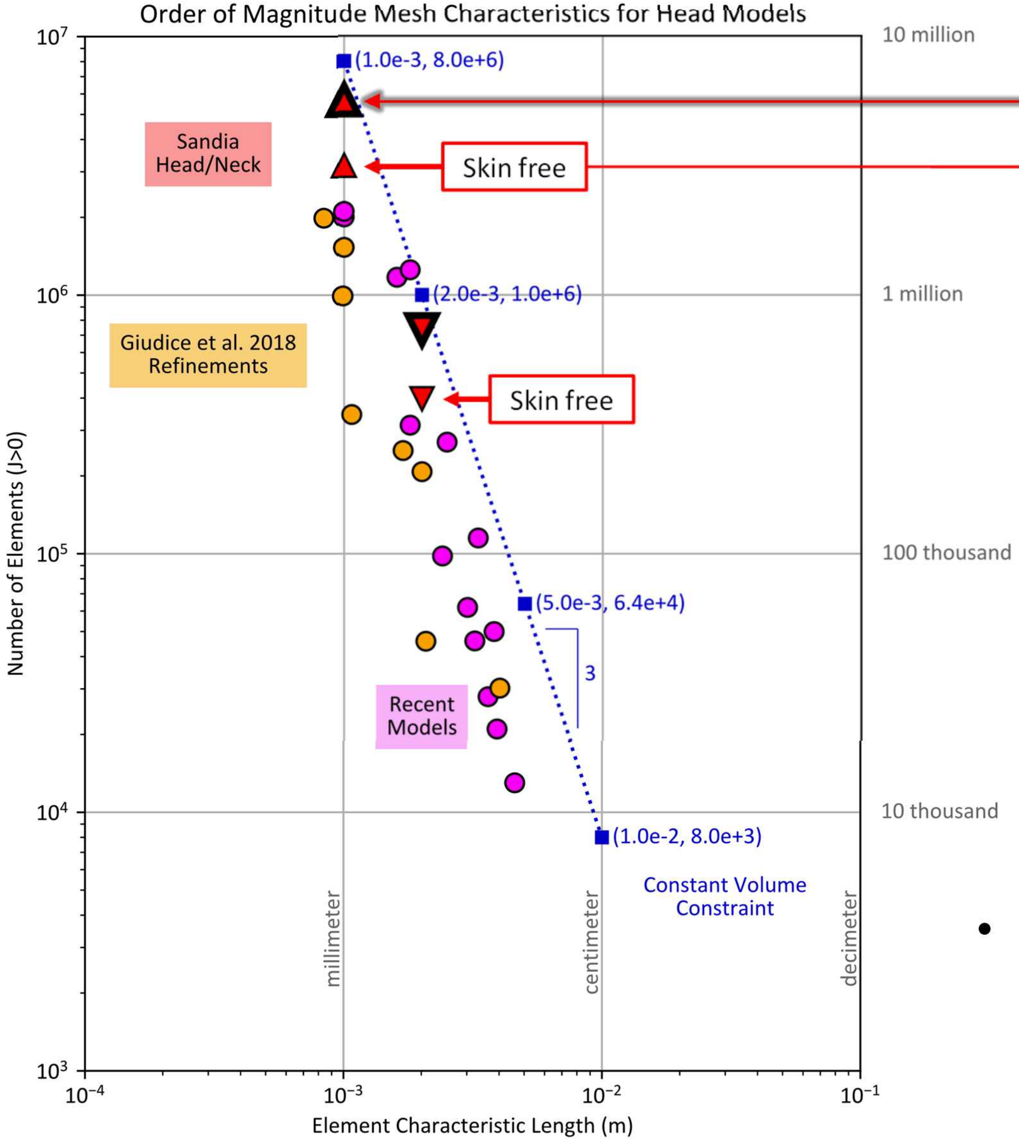
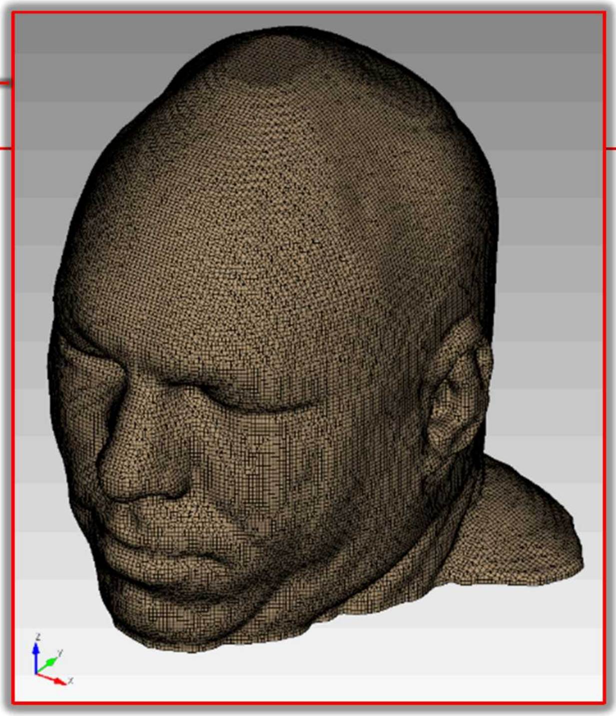
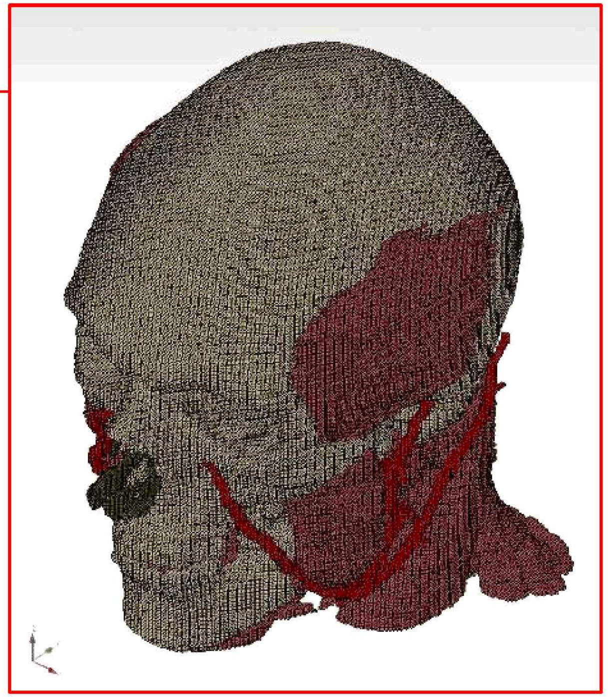
What – High Fidelity Human Surrogate Head/Neck/Torso ("Bob")



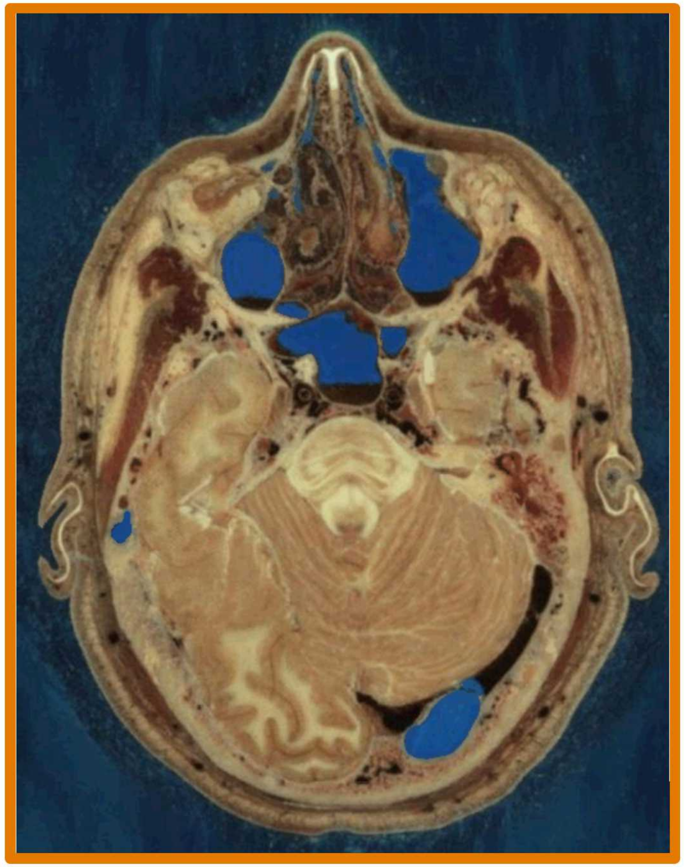




- Presented at DoD Human Body Modeler Performers' Workshop

Reference: Guidice et al. 2018, other human body model.

Introduction



Section A-A

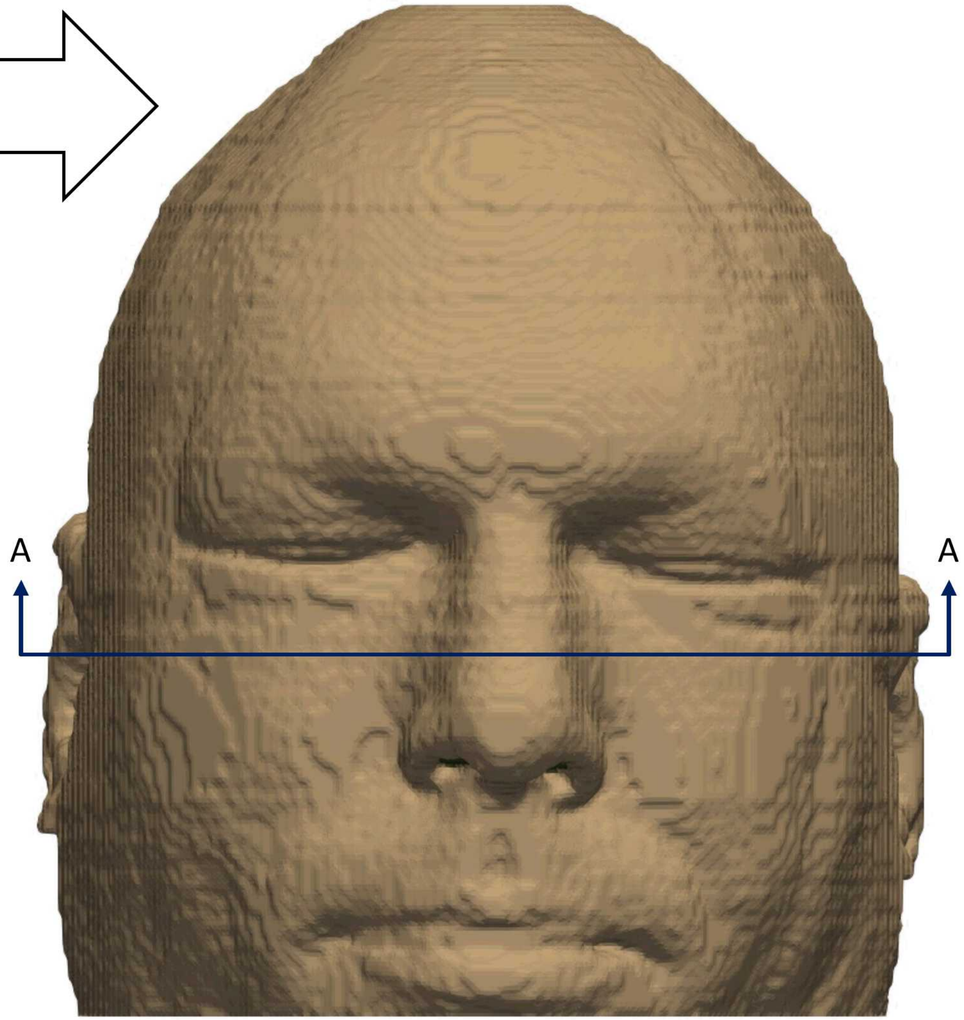
Manual Segmentation

CT and digital photography scan entire body

- full body 1,871 axial slices at 1 mm intervals
- CT: 512 x 512 pixels; 12 bit gray
- Photo: 4,096 x 2,700 pixels; 24 bit color

MR head and neck

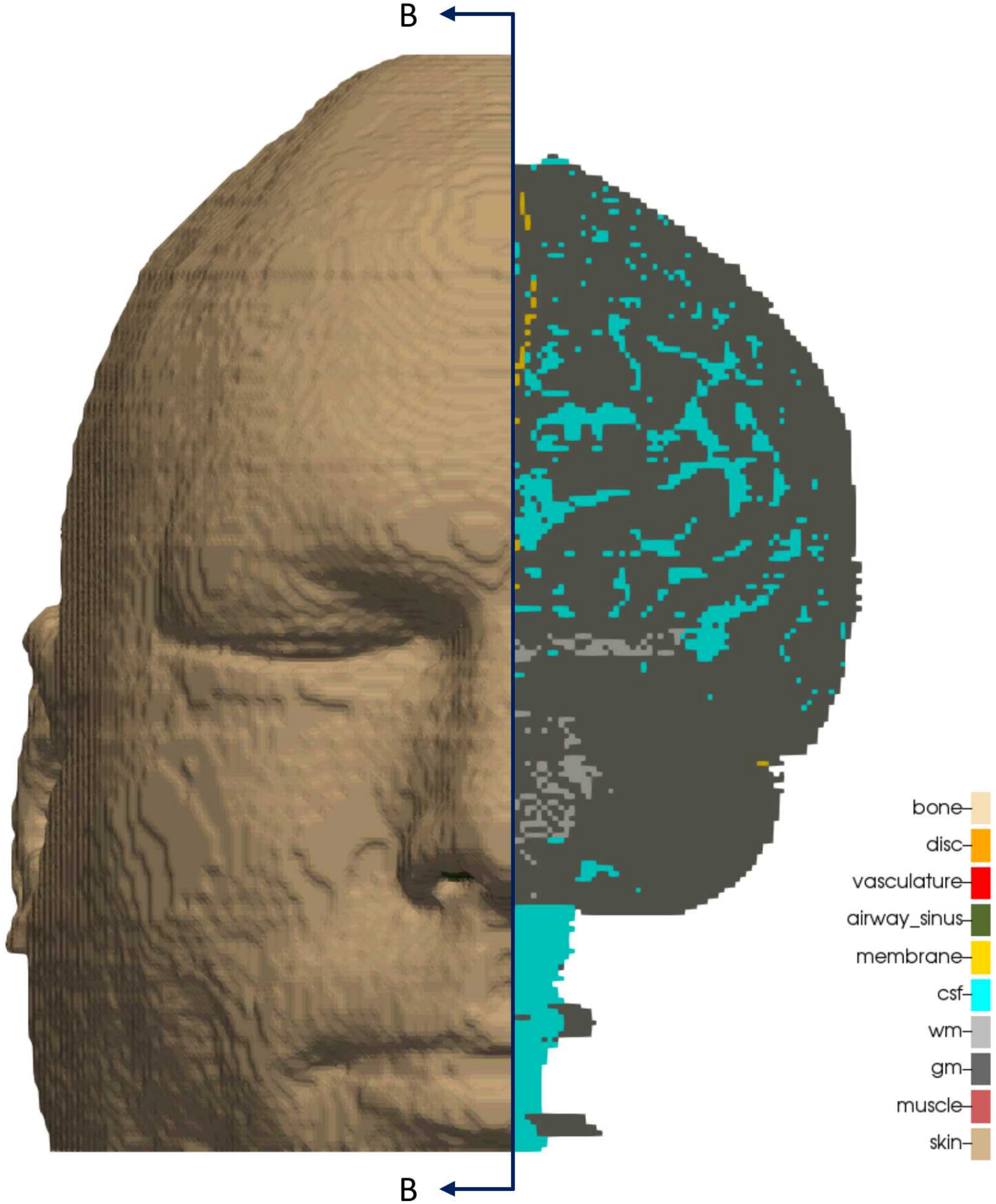
- axial slices at 4 mm intervals
- 256 x 256 pixels; 12 bit gray

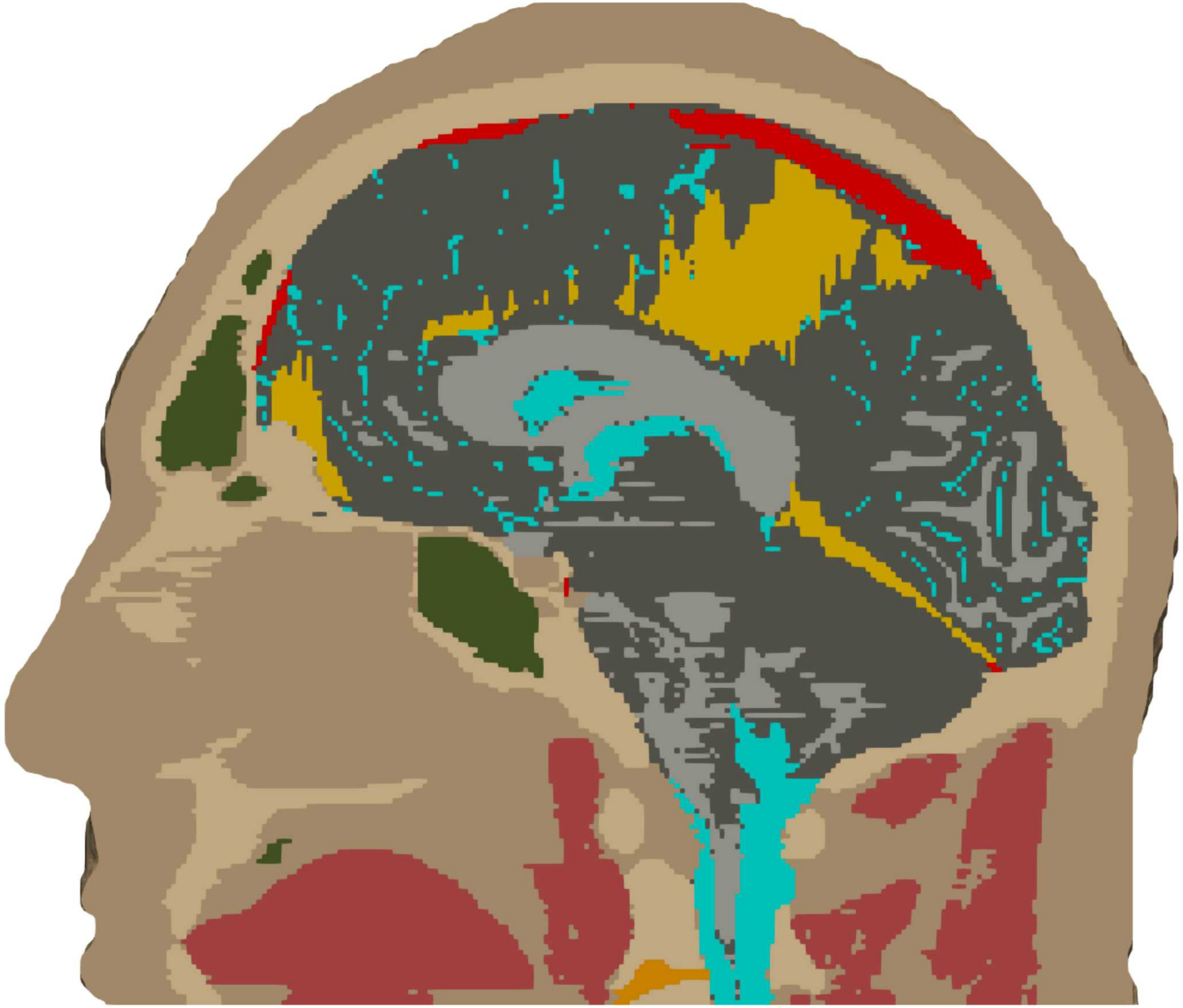


Sandia Injury Biomechanics Laboratory (SIBL)
5-kg head model ("**Bob**")

NIH U.S. National Library of Medicine

Introduction





Section B-B

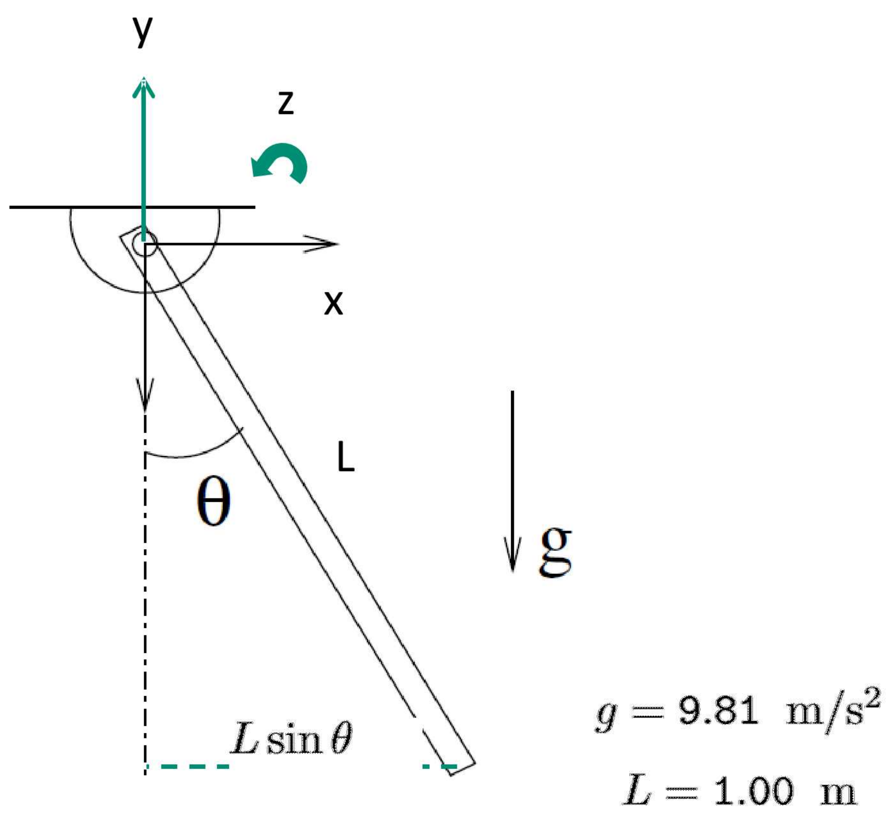


Figure 1. Geometry of the pendulum.

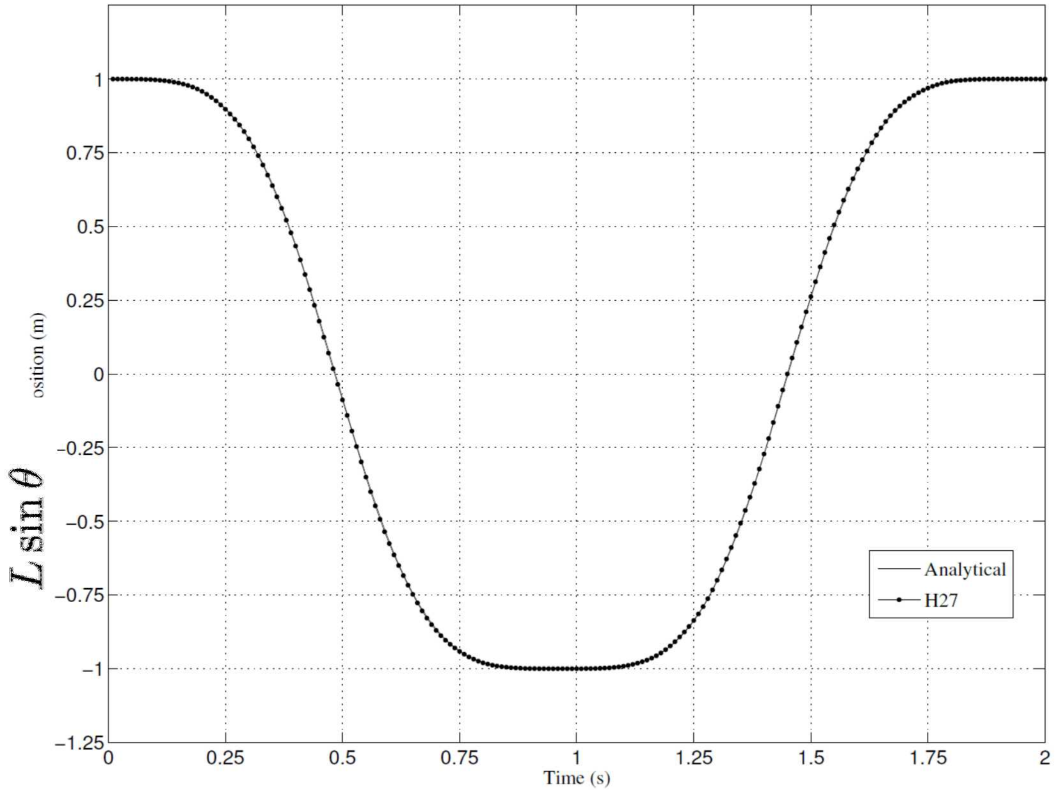


Figure 2. Comparison of the numerically obtained tip displacement of the pendulum with the analytical solution under Case I.

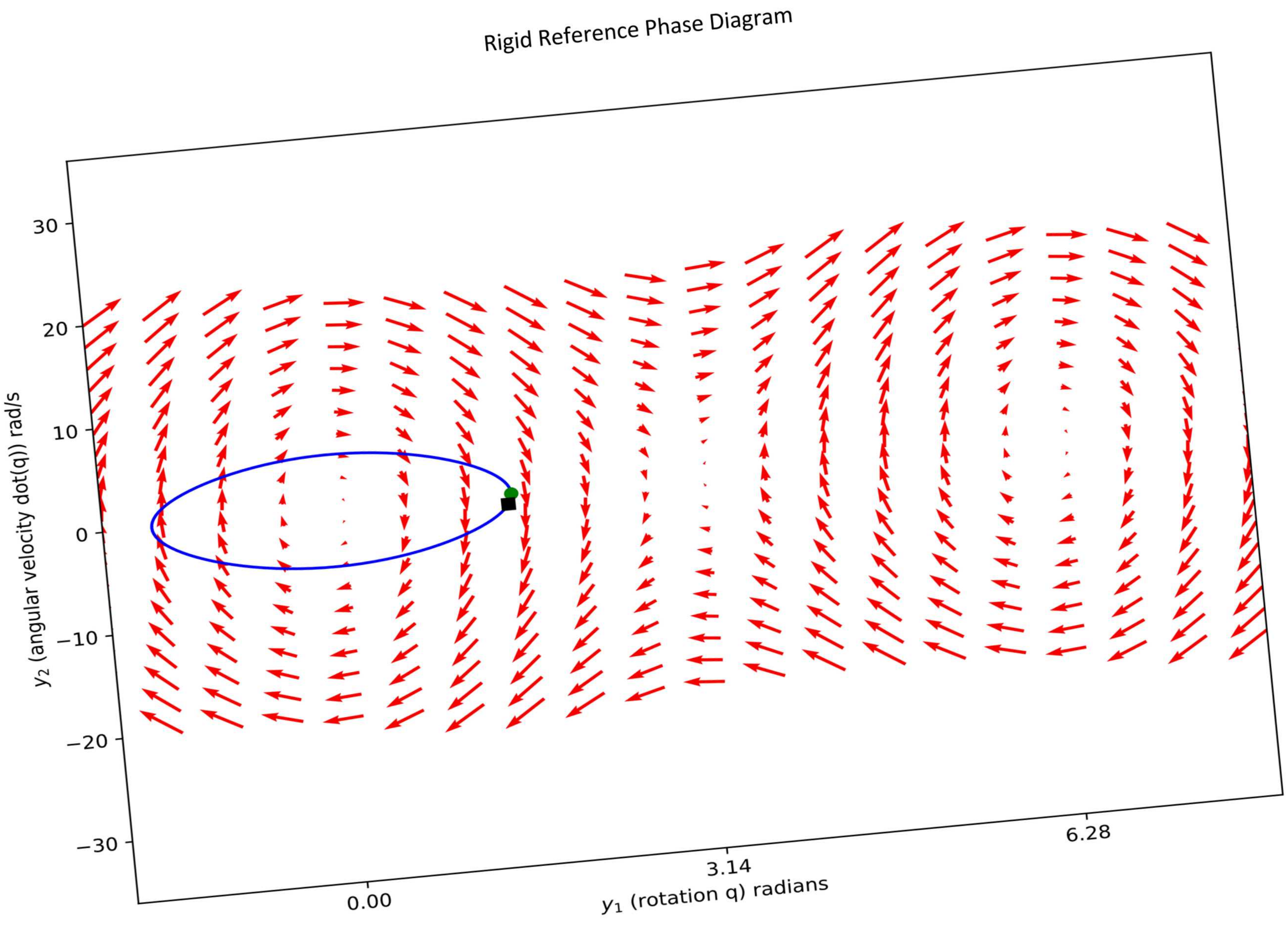
$$\ddot{\theta} + \frac{3g}{2L}\sin\theta = 0$$

$$\theta_0 = \frac{\pi}{2}$$

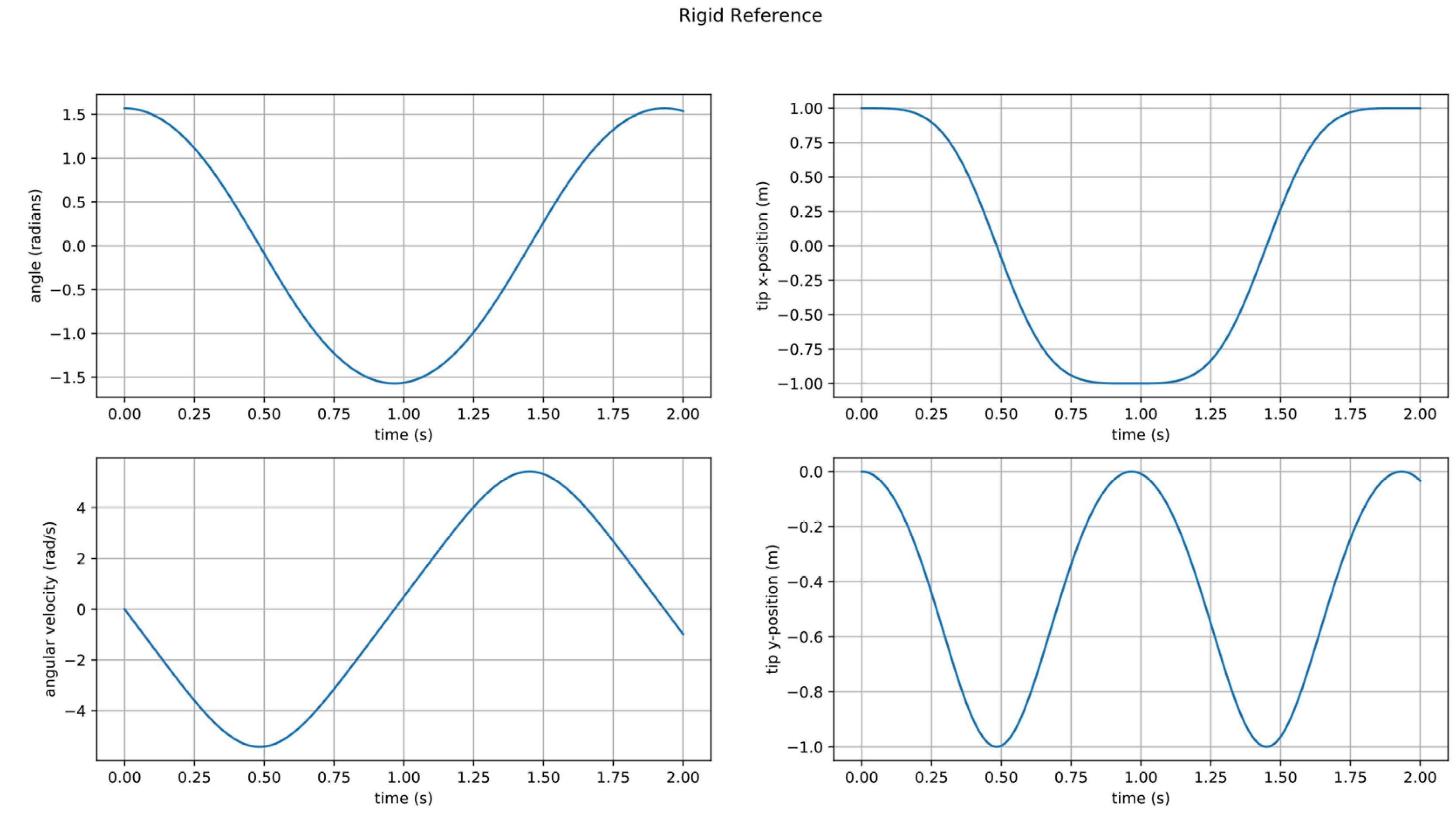
$$\dot{\theta}_0 = 0$$

$$\theta(t) = 2\sin^{-1}\left[\frac{1}{\sqrt{2}}\,\mathrm{sn}\left(\sqrt{\frac{3g}{2l}}t, \frac{1}{\sqrt{2}}\right)\right]$$

Reference: Jog CS, Motamarri P. An energy-momentum conserving algorithm for nonlinear transient analysis within the framework of hybrid elements. Journal of Mechanics of Materials and Structures. 2009 Apr 8;4(1):157-86. (LaTeX: http://www.tlhiv.org/ltxpreview/)



Reference: casco_sim/simo/pendulum_rigid_reference.py



Reference: casco_sim/simo/pendulum_three_points.py

Particle Moving on a Rigid Body

Rotation and Stretch of a Deformable Body

Result 2.5.7 The angular velocity $\boldsymbol{\omega}$ of a body $\tilde{B}$ that undergoes finite rotations and infinitesimal deformations may be approximated as a least squares projection of the body's configuration column space onto the body's velocity space as

$$\boldsymbol{\omega} = -\left(\mathsf{A}^{\mathsf{T}}\mathsf{A}\right)^{-1}\mathsf{A}^{\mathsf{T}} \cdot \{\boldsymbol{v}_P - \boldsymbol{v}_Q\}\,, \text{ where} \tag{2.53}$$

$$\mathsf{A} = [\,\boldsymbol{x}_P - \boldsymbol{x}_Q\,]_{\times}\,. \tag{2.54}$$

Proof.

Let body $\tilde{B}$ undergo finite rotations and infinitesimal deformations in reference frame F. Using the velocity of two points Q and P, with a particle moving on rigid body B,

$$\boldsymbol{v}_{P/F} = \boldsymbol{v}_{Q/F} + \boldsymbol{v}_{P/Q} + \boldsymbol{\omega}_{B/F} \times \boldsymbol{r}_{QP} \tag{2.55}$$

$$\boldsymbol{v}_{P} = \boldsymbol{v}_{Q} + \boldsymbol{v}_{P/Q} + \boldsymbol{\omega}_{B} \times \boldsymbol{r}_{QP} \quad \text{dropping } F \text{ where implied.} \tag{2.56}$$

Note the term $\boldsymbol{v}_{P/Q}$ is the *relative* velocity between points P and Q. Assuming infinitesimal deformations, it is reasonable to assume the time derivatives of these quantities are also small, thus $\boldsymbol{v}_{P/Q} \approx \boldsymbol{0}$. Thus for body $\tilde{B}$

$$\boldsymbol{v}_P - \boldsymbol{v}_Q \approx \boldsymbol{\omega}_B \times \boldsymbol{r}_{QP}, \tag{2.57}$$

$$= -\boldsymbol{r}_{QP} \times \boldsymbol{\omega} \tag{2.58}$$

$$= -\left(\boldsymbol{\varphi}(\boldsymbol{X}_P, t) - \boldsymbol{\varphi}(\boldsymbol{X}_Q, t)\right) \times \boldsymbol{\omega} \tag{2.59}$$

$$= -\left(\boldsymbol{X}_P + \boldsymbol{u}(\boldsymbol{X}_P, t) - (\boldsymbol{X}_Q + \boldsymbol{u}(\boldsymbol{X}_Q, t))\right) \times \boldsymbol{\omega} \tag{2.60}$$

if displacements $\boldsymbol{u}$ are used; or,

$$= -\left(\boldsymbol{x}_P - \boldsymbol{x}_Q\right) \times \boldsymbol{\omega} \quad \text{if current placements } \boldsymbol{x} \text{ are used,} \tag{2.61}$$

$$= -\left[\, \boldsymbol{x}_P - \boldsymbol{x}_Q \,\right]_\times \boldsymbol{\omega}, \tag{2.62}$$

where the skew-symmetric matrix, defined in Eq. (1.22), is used. Explicitly, this is

$$\left[\, \boldsymbol{x}_P - \boldsymbol{x}_Q \,\right]_\times = \begin{bmatrix} 0 & -(x_{P3} - x_{Q3}) & (x_{P2} - x_{Q2}) \\ (x_{P3} - x_{Q3}) & 0 & -(x_{P1} - x_{Q1}) \\ -(x_{P2} - x_{Q2}) & (x_{P1} - x_{Q1}) & 0 \end{bmatrix}, \tag{2.63}$$

which is solvable through a least-squares approach. ■

The skew-symmetric matrix $\mathbf{W}$ has the property

$$\mathbf{W} = -\mathbf{W}^{\mathsf{T}} \iff w_{ij} = -w_{ji}. \tag{1.15}$$

Explicitly, for $\mathbf{W}$ as a (3×3) matrix

$$\mathbf{W} = \begin{bmatrix} 0 & -w_{12} & w_{13} \\ w_{12} & 0 & -w_{23} \\ -w_{13} & w_{23} & 0 \end{bmatrix}, \tag{1.16}$$

and of the nine components of $\mathbf{W}$, only three are independent.

Remark 1.1.2. From spectral theory, the non-zero eigenvalues exist in pairs as purely imaginary numbers $0 \pm \lambda_k i$, $\lambda \in \mathbb{R}$, with

- $k = 1 \ldots n$ for $\dim(\mathbf{W}) = (n, n)$ and n even and
- $k = 1 \ldots (n-1)/2$ for $\dim(\mathbf{W}) = (n, n)$ and n odd.

For even n dimensions, there are no zero eigenvalues. For odd n dimensions, there is exactly one zero eigenvalue. In the explicit example for $\dim(\mathbf{W}) = (3, 3)$,

$$\boldsymbol{\Lambda} = \text{EIG}(\mathbf{W}) = \begin{bmatrix} 0 & \lambda & 0 \\ -\lambda & 0 & 0 \\ 0 & 0 & 0 \end{bmatrix}. \tag{1.17}$$

Result 1.1.1 All $n \times n$ skew-symmetric matrices of odd dimension are singular.

Proof.

For skew-symmetric matrices,

$$\mathbf{W} = -\mathbf{W}^{\mathsf{T}}. \tag{1.19}$$

From the properties of determinants

$$\det(\mathbf{W}) = \det(-\mathbf{W}^{\mathsf{T}}) = (-1)^n \det(\mathbf{W}), \tag{1.20}$$

which, since n is odd, becomes,

$$\det(\mathbf{W}) = -\det(\mathbf{W}) = 0, \tag{1.21}$$

■

Result 1.1.2 The rank of a skew-symmetric matrix must be even.

Proof.

For skew-symmetric matrices,

$$\mathbf{W} = -\mathbf{W}^{\mathsf{T}}. \tag{1.22}$$

From the properties of determinants

$$\det(\mathbf{W}) = \det(-\mathbf{W}^{\mathsf{T}}) = (-1)^n \det(\mathbf{W}). \tag{1.23}$$

If n is odd, then $\det(\mathbf{W}) = 0$ (see Result 1.1.1). Therefore, the rank of $\mathbf{W}$ must be even. ■

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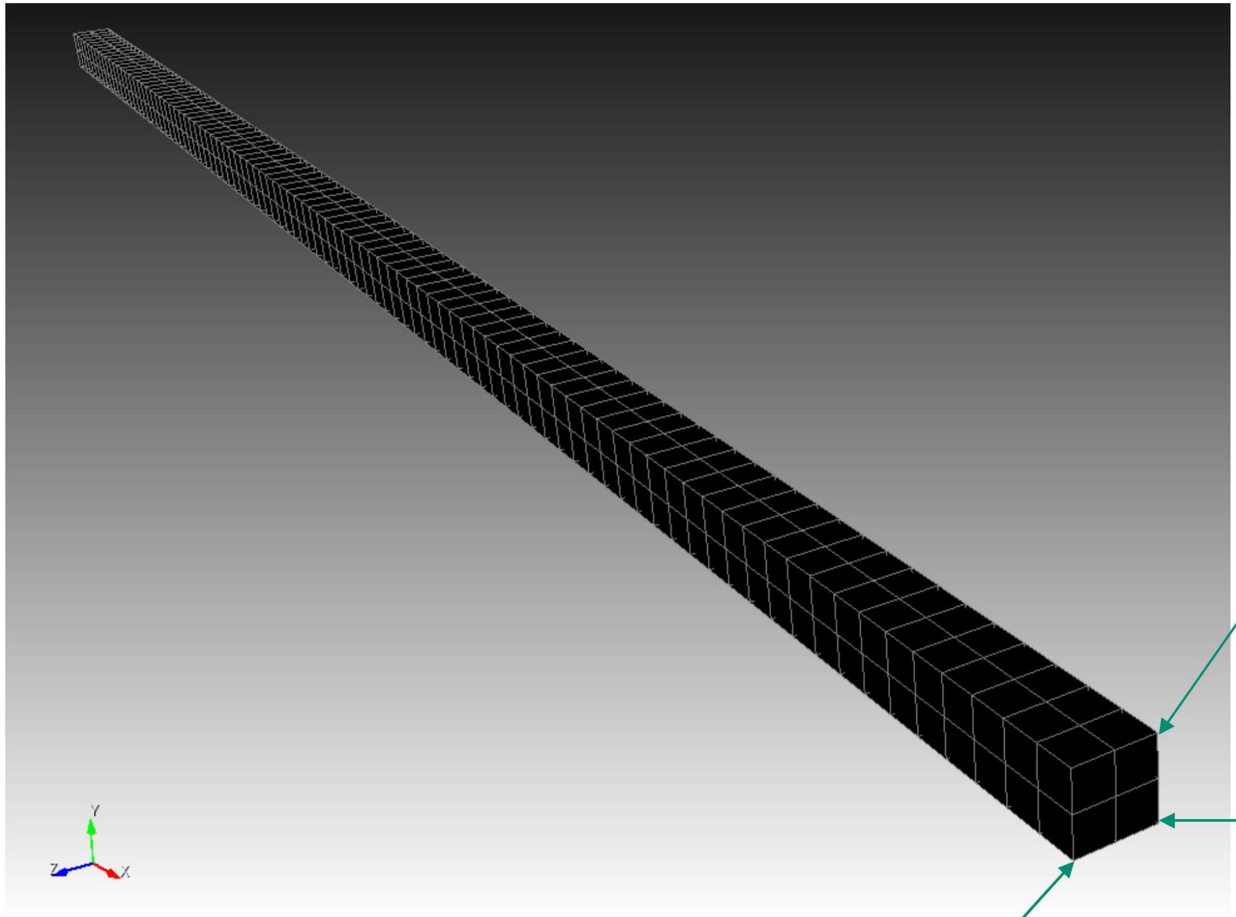
origin ***O*** [0, 0, 0]

$$\rho_0 = 7.2\text{e}3 \ \ \text{kg/m}^3$$
$$E = 2.0\text{e}9 \ \ \text{N/m}^2$$
$$\nu = 0.3$$
$$r^{OP} = (1.00, -0.01, -0.01) \text{ m}$$
$$r^{OQ} = (1.00, \ \ 0.01, -0.01) \text{ m}$$
$$r^{OR} = (1.00, -0.01, \ \ 0.01) \text{ m}$$
$$g = 9.81 \ \ \text{m/s}^2$$
$$L = 1.00 \ \ \text{m}$$
$$a = b = 0.02 \ \ \text{m}$$
$$V_0 = 0.0004 \ \ \text{m}^3$$
$$m = 2.88 \ \ \text{kg}$$
$$\texttt{nnp} = 846$$
$$\texttt{nel} = 372$$



Q = node 283
rOQ = [1.00, 0.01, -0.01] m

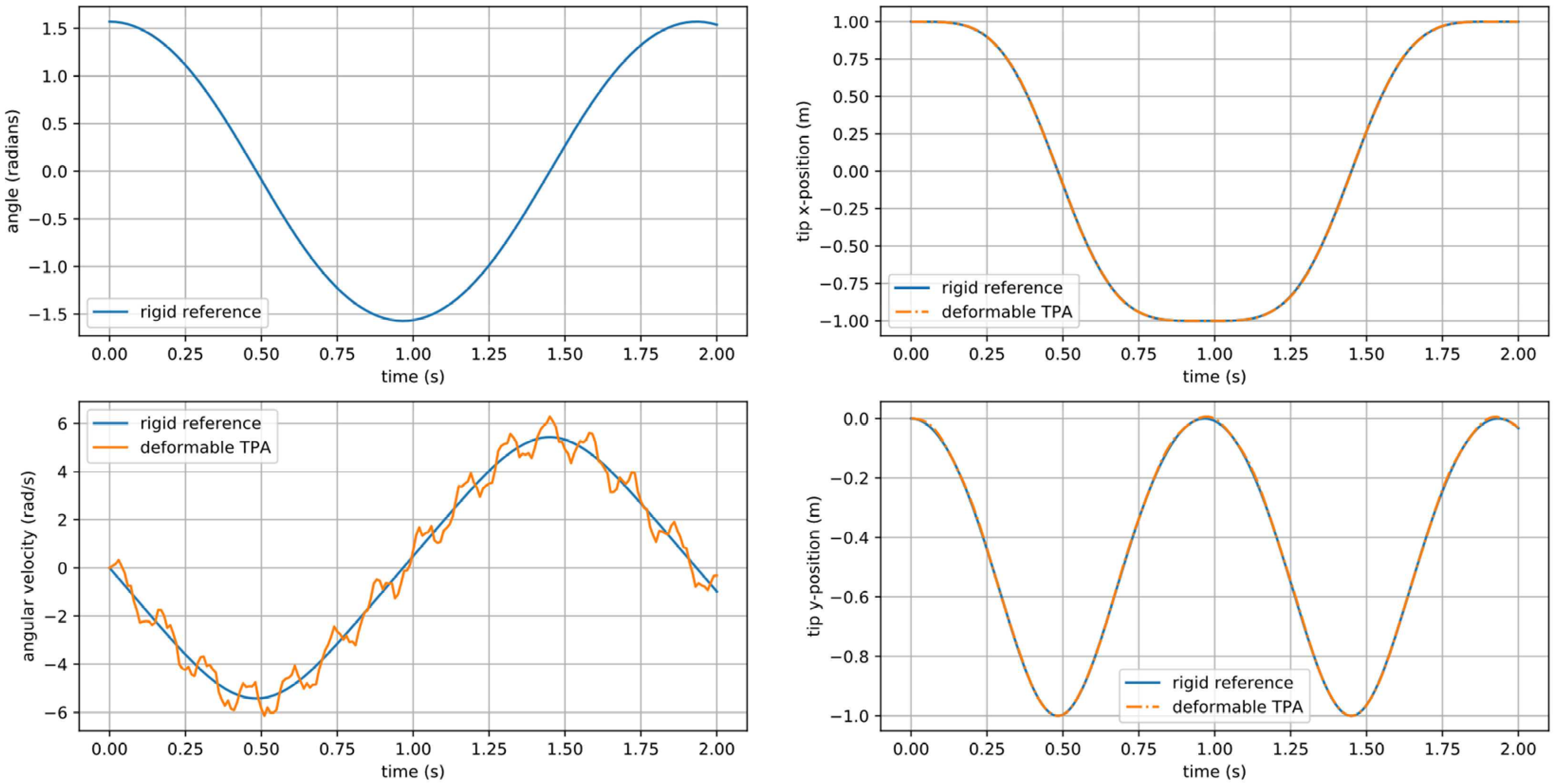
P = node 284
rOP = [1.00, -0.01, -0.01] m

R = node 1
rOR = [1.00, -0.01, 0.01] m

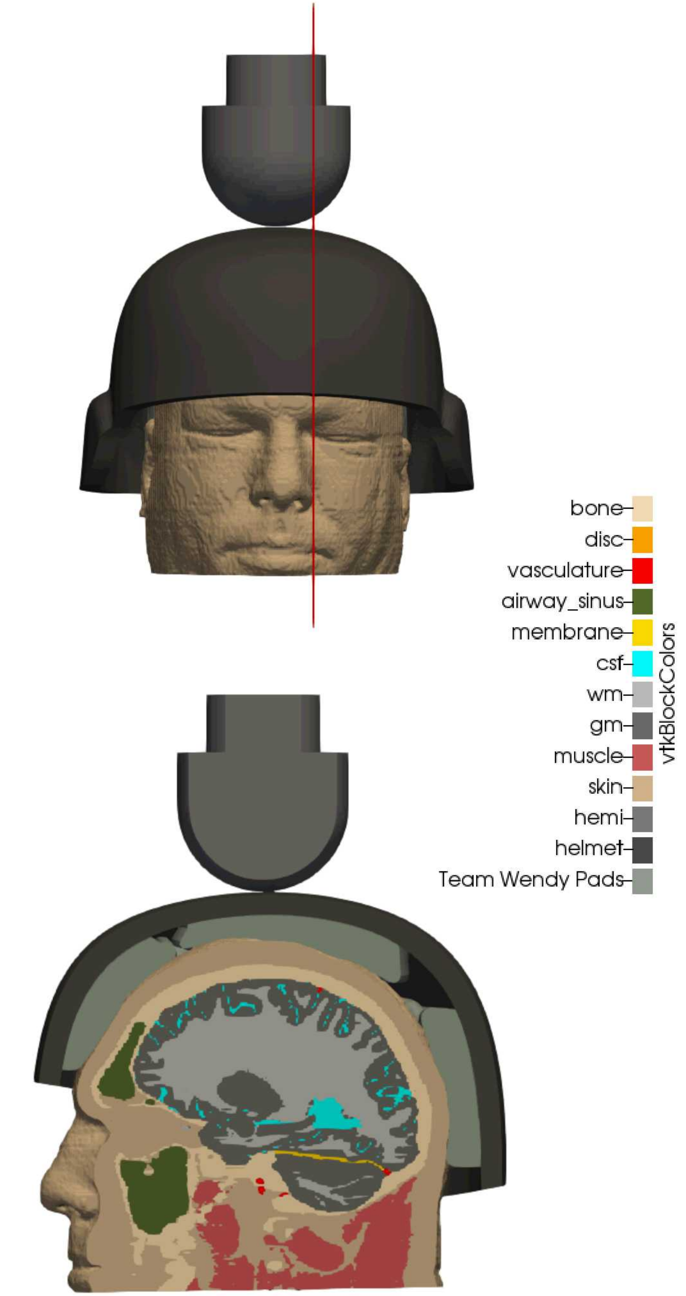
Reference: casco_sim/simo/pend-001.i


Time: 0.000000
y
z
x
Y
Z
X
max_principal_log_strain
4.8e-04
0.00045
0.0004
0.00035
0.0003
0.00025
0.0002
0.00015
0.0001
5e-5
0.0e+00

Rigid Reference vs. Deformable Three-Point Algorithm (TPA)



Reference: casco_sim/simo/pendulum_three_points.py

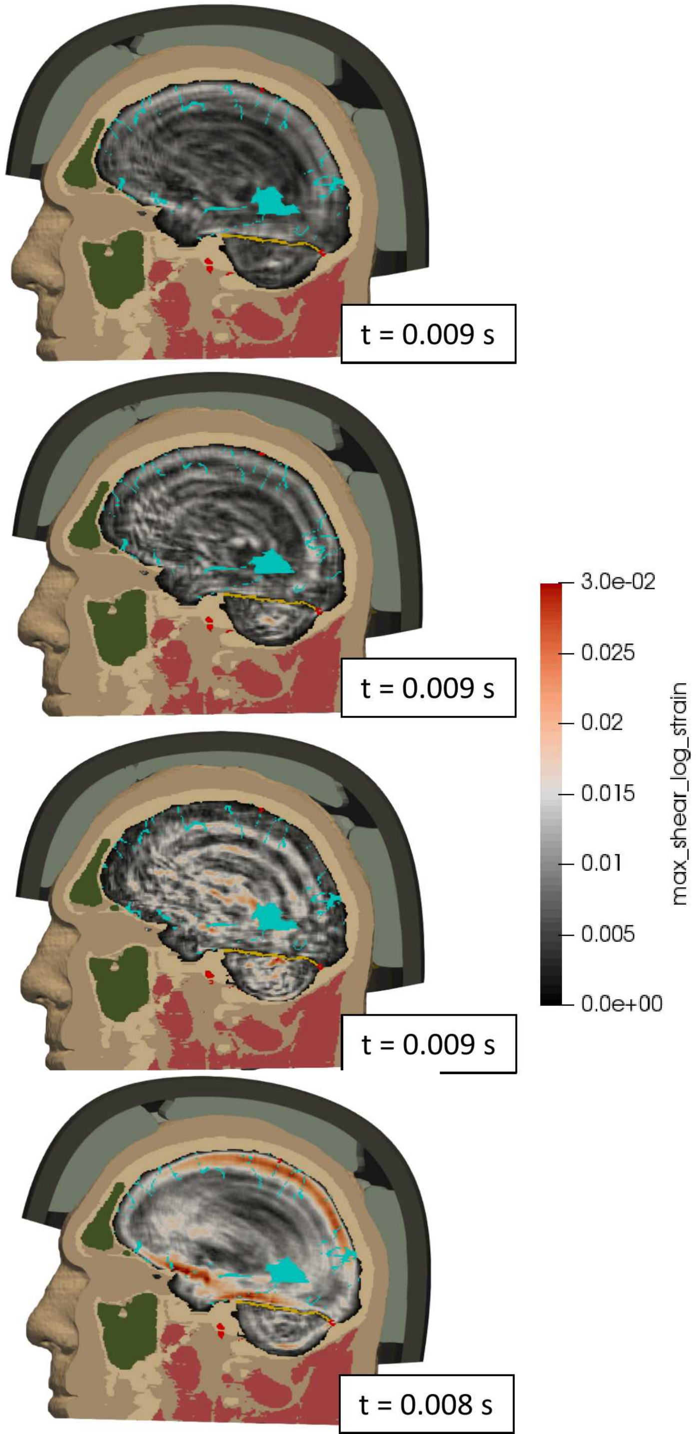


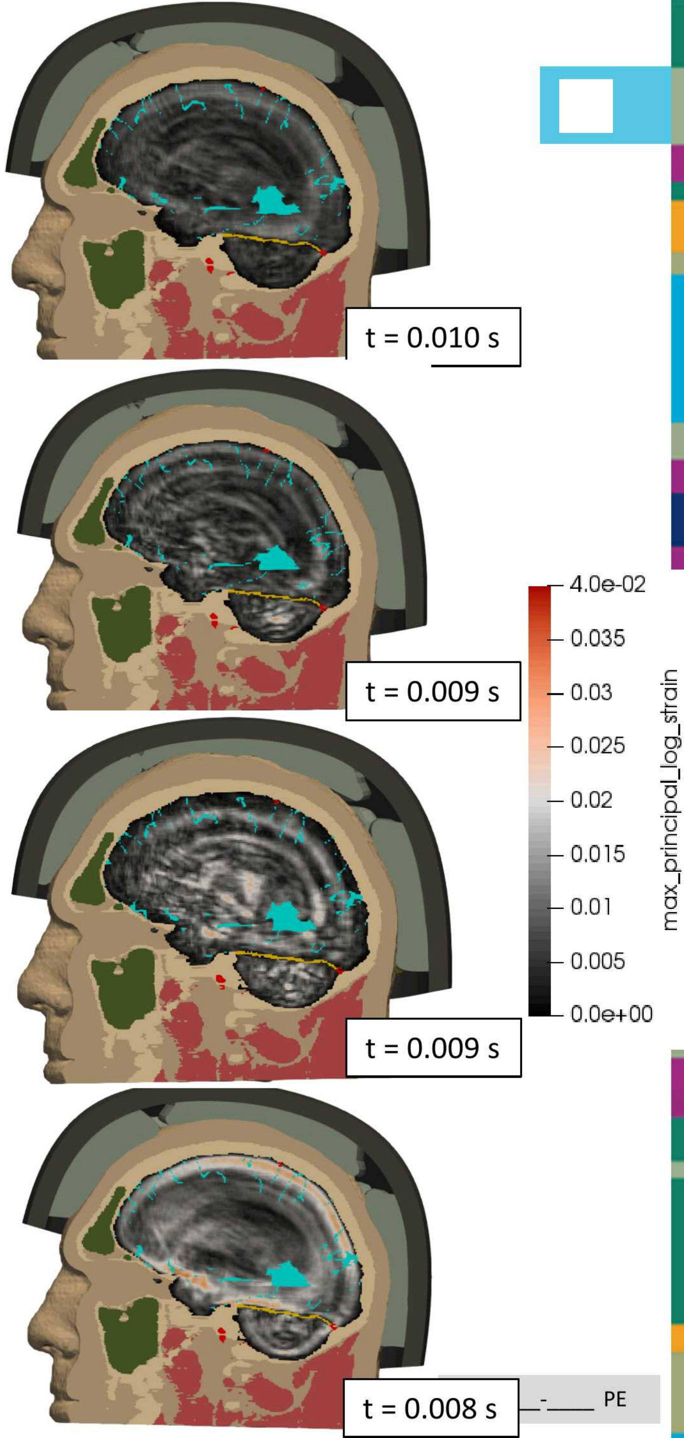
$V_{initial}$ = 10 ft/s
Inline Impact

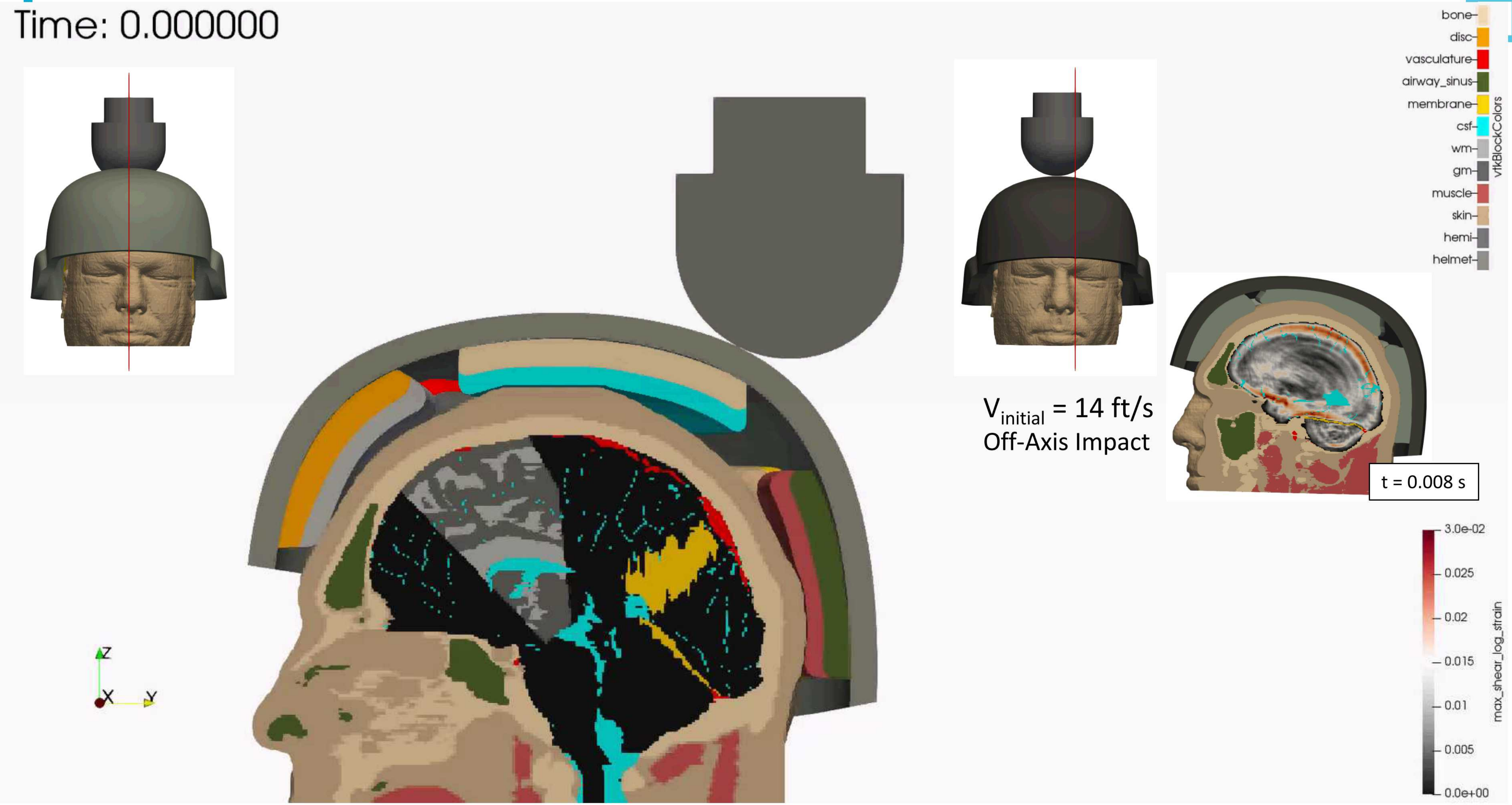
$V_{initial}$ = 14 ft/s
Inline Impact

$V_{initial}$ = 17 ft/s
Inline Impact

$V_{initial}$ = 14 ft/s
Off-Axis Impact



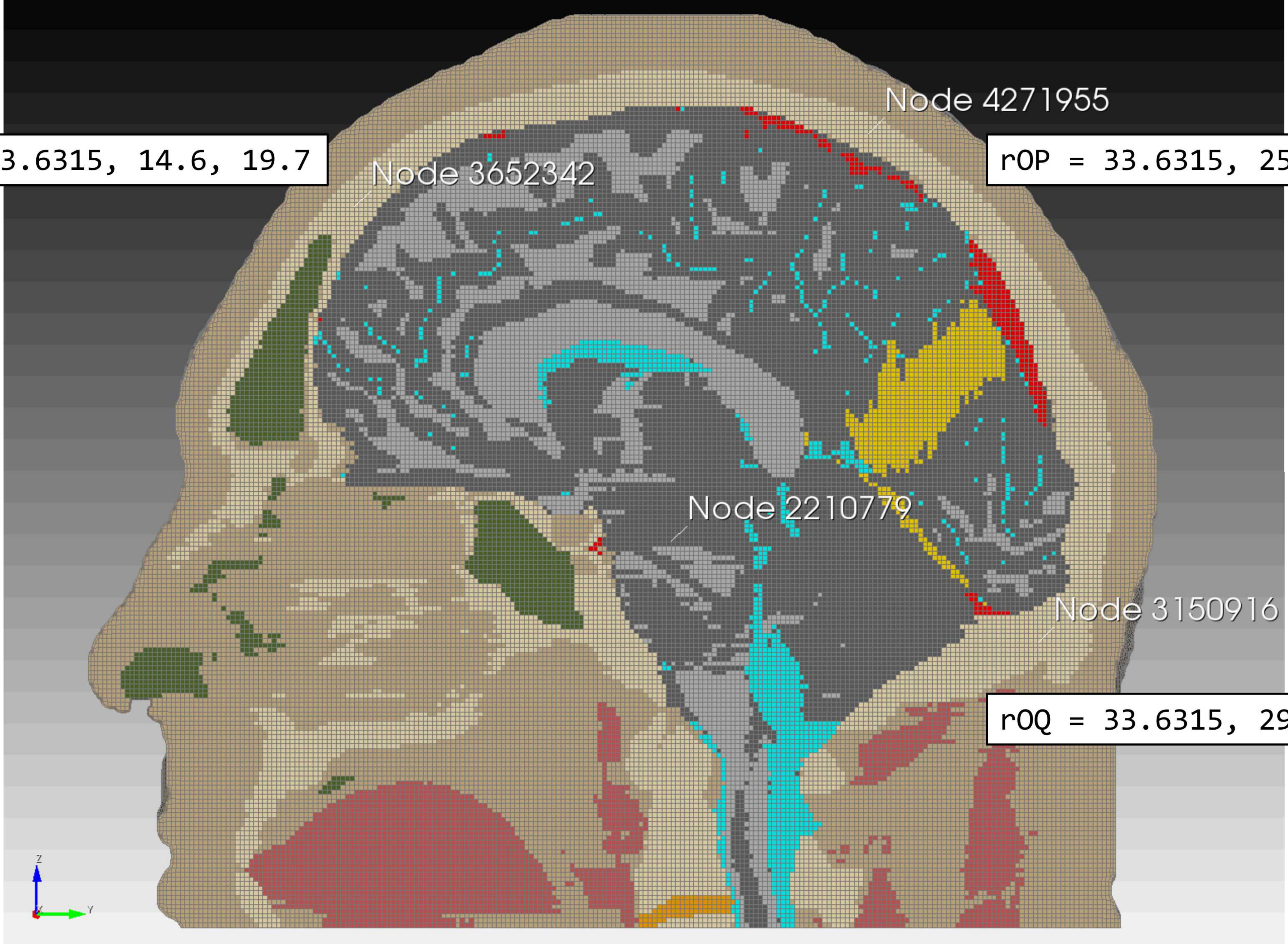



Time: 0.000000
bone
disc
vasculature
airway_sinus
membrane
csf
wm
gm
muscle
skin
hemi
helmet
vtkBlockColors
V$_{initial}$ = 14 ft/s
Off-Axis Impact
t = 0.008 s
3.0e-02
0.025
0.02
0.015
0.01
0.005
0.0e+00
max_shear_log_strain
Z
X
Y

```
4708   rcg  is node>-'coordinates' nearest 33.6315, 21.4892, 12.357 (node 2210779 on processor 93)
4709   ucg  is node>-'displacement' nearest 33.6315, 21.4892, 12.357 (node 2210779 on processor 93)
4710   vcg  is node>-'velocity' nearest 33.6315, 21.4892, 12.357 (node 2210779 on processor 93)
4711   rOP  is node>-'coordinates' nearest 33.6315, 25.8, 21.3 (node 4271955 on processor 21)
4712   uOP  is node>-'displacement' nearest 33.6315, 25.8, 21.3 (node 4271955 on processor 21)
4713   vOP  is node>-'velocity' nearest 33.6315, 25.8, 21.3 (node 4271955 on processor 21)
4714   rOQ  is node>-'coordinates' nearest 33.6315, 29.5, 10.2 (node 3150916 on processor 70)
4715   uOQ  is node>-'displacement' nearest 33.6315, 29.5, 10.2 (node 3150916 on processor 70)
4716   vOQ  is node>-'velocity' nearest 33.6315, 29.5, 10.2 (node 3150916 on processor 70)
4717   rOR  is node>-'coordinates' nearest 33.6315, 14.6, 19.7 (node 3652342 on processor 146)
4718   uOR  is node>-'displacement' nearest 33.6315, 14.6, 19.7 (node 3652342 on processor 146)
4719   vOR  is node>-'velocity' nearest 33.6315, 14.6, 19.7 (node 3652342 on processor 146)
```

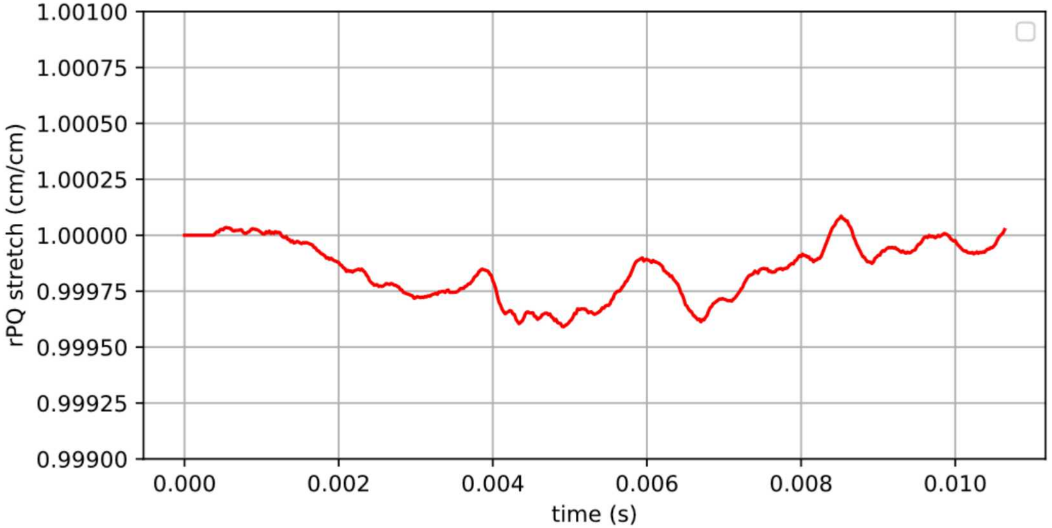
Reference: casco_sim/bob-1mm-5kg-helmet2-0427-hemi-10y-052/ bob-1mm-5kg-helmet2-0427-hemi-10y-052.log {4708:4719} rOR = 33.6315, 14.6, 19.7

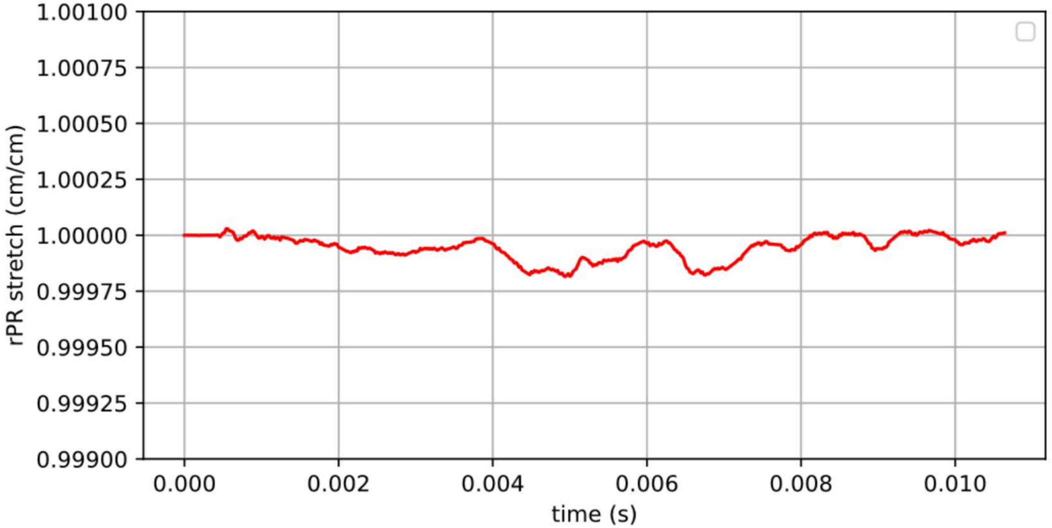
rOP = 33.6315, 25.8, 21.3

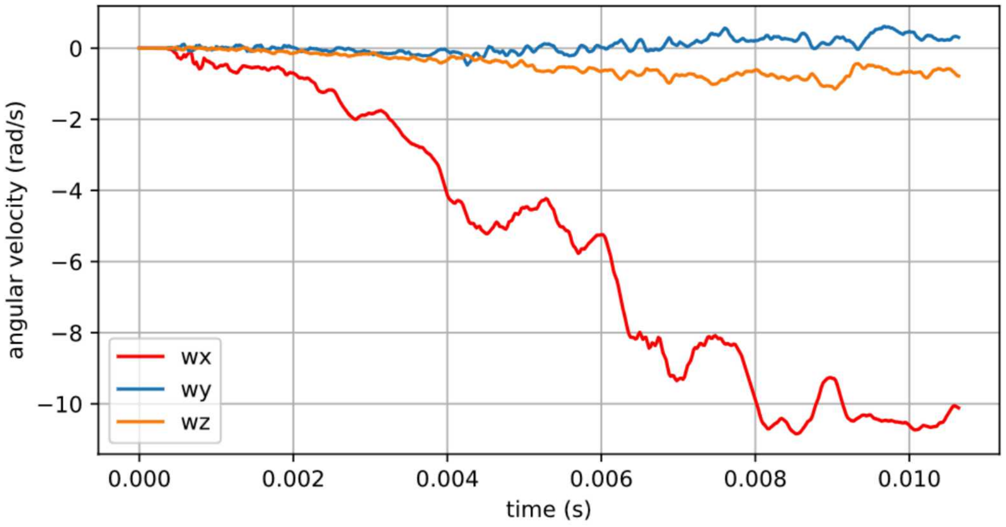


rOQ = 33.6315, 29.5, 10.2

bob-1mm-5kg-helmet2-0427-hemi-10y-052 Deformable Three-Point Algorithm (TPA)







angle_z = ½ b h = ½ 0.010 * 10 = 0.05 rad = 2.86 deg

(10 rad/s, 3500 rad/s^2)

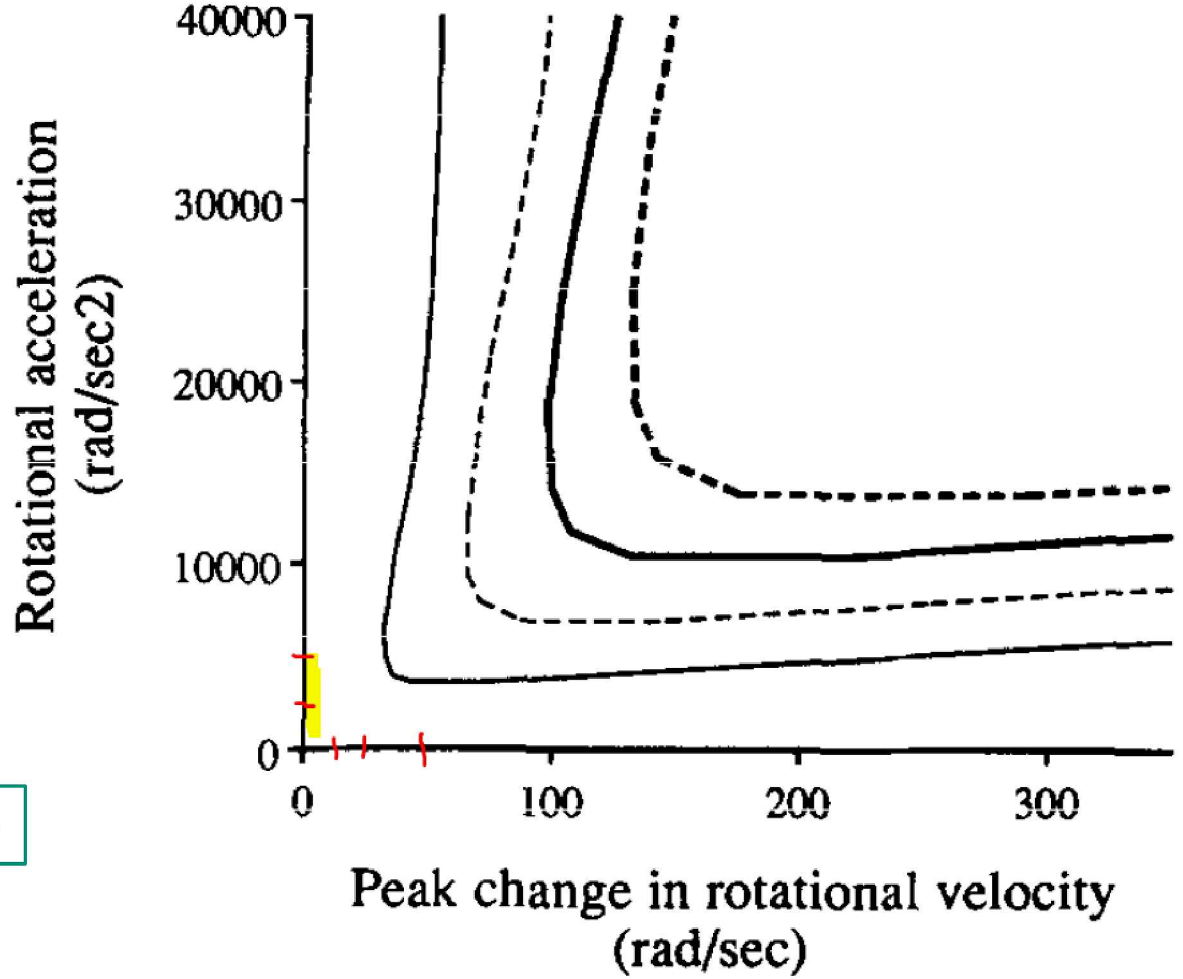
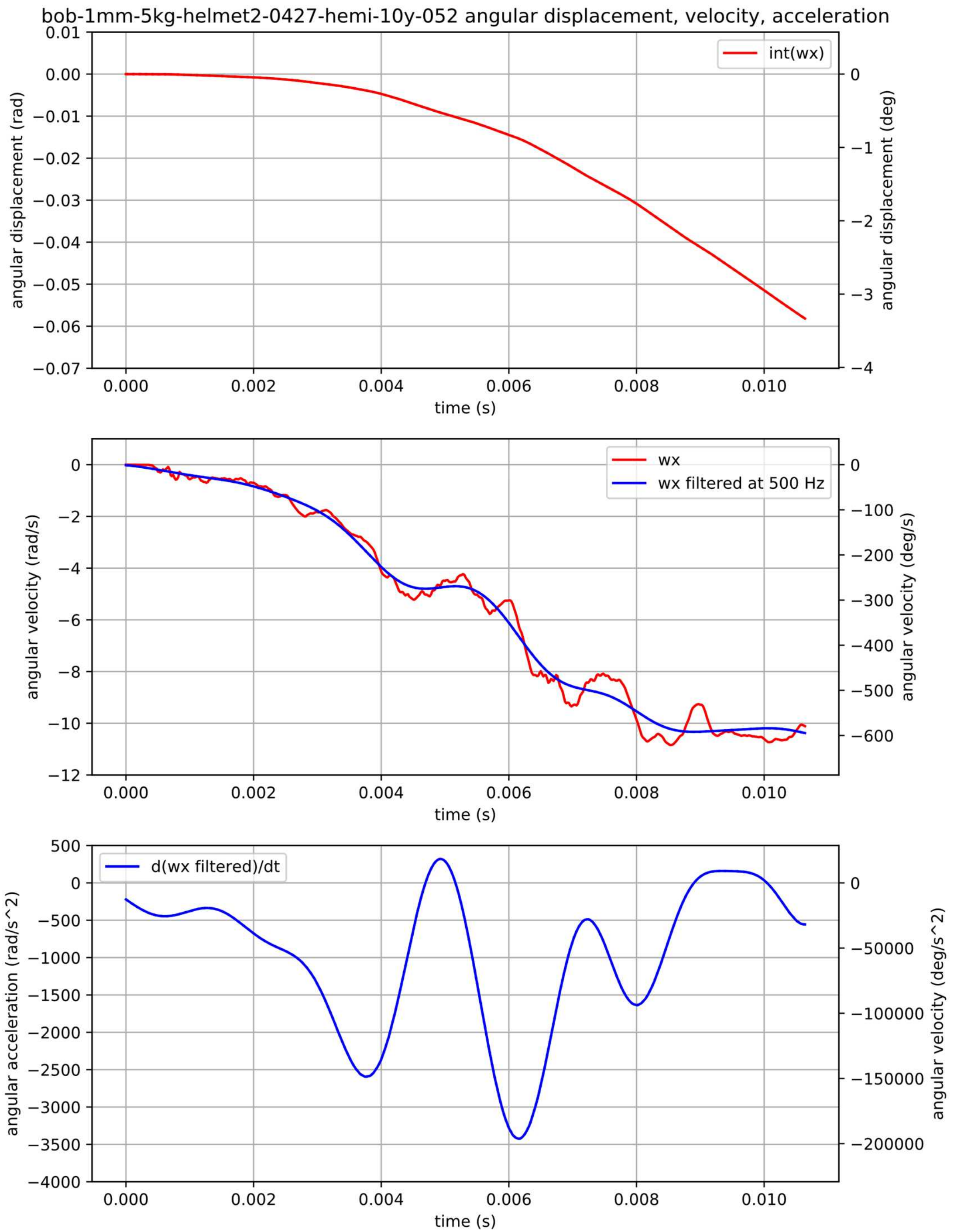
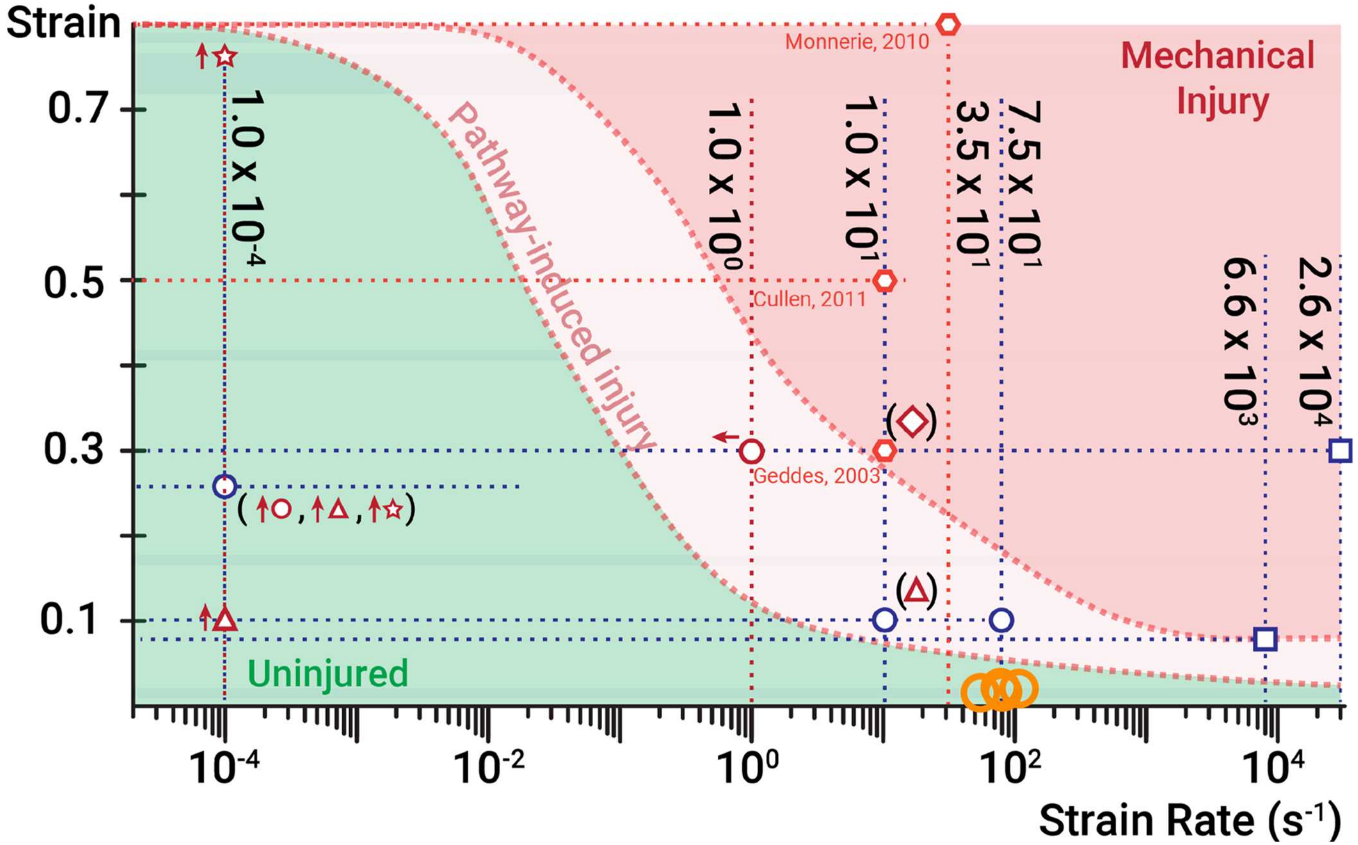


Fig. 7. Influence of critical strain value on the DAI tolerance. Small critical strain may correspond to mild forms of axonal injury, like concussion. Tolerances were derived using the analytical model and the following critical strains: 0.05 (solid line), 0.10 (dashed line), 0.15 (heavy solid line), and 0.20 (heavy dashed line).


bob-1mm-5kg-helmet2-0427-hemi-10y-052 angular displacement, velocity, acceleration
int(wx)
angular displacement (rad)
angular displacement (deg)
time (s)
wx
wx filtered at 500 Hz
angular velocity (rad/s)
angular velocity (deg/s)
time (s)
d(wx filtered)/dt
angular acceleration (rad/s^2)
angular velocity (deg/s^2)
time (s)

Study Name	bob-047 (inline)	bob-048 (inline)	bob-049 (inline)	bob-51 (eccentric)
v0	10 fps, 3.05 m/s	14 fps, 4.27 m/s	17 fps, 5.18 m/s	14 fps, 4.27 fps
KE, multiple	23.2 J, 1x	46.2 J, 2x	69.5 J, 3x	46.2 J, 2x
Peak a_cg	126 g	233 g	315 g	141 g
max(95th strain tension)	0.014	0.015	0.019	0.020
max(95th strain rate tension)	53 1/s	78 1/s	104 1/s	75 1/s
max(95th shear strain)	0.013	0.015	0.018	0.023



Path Forward by Priority

High
- Helmeted DOT simulation (verification)
- Helmet pad geometry (precise bi-layer)

Medium
- Mises strain rate
- Foam characterization
- Configuration to cause higher angular velocity/acceleration response

Low
- Bone from elastic to include fracture
- Secure helmet to head (head-to-helmet coupling, transfer function)
- Configuration to cause higher angular velocity/acceleration response

Thank you.