THE UNIVERSITY OF BRITISH COLUMBIA

Mechanical Engineering

Wearable sensors for sports concussion research

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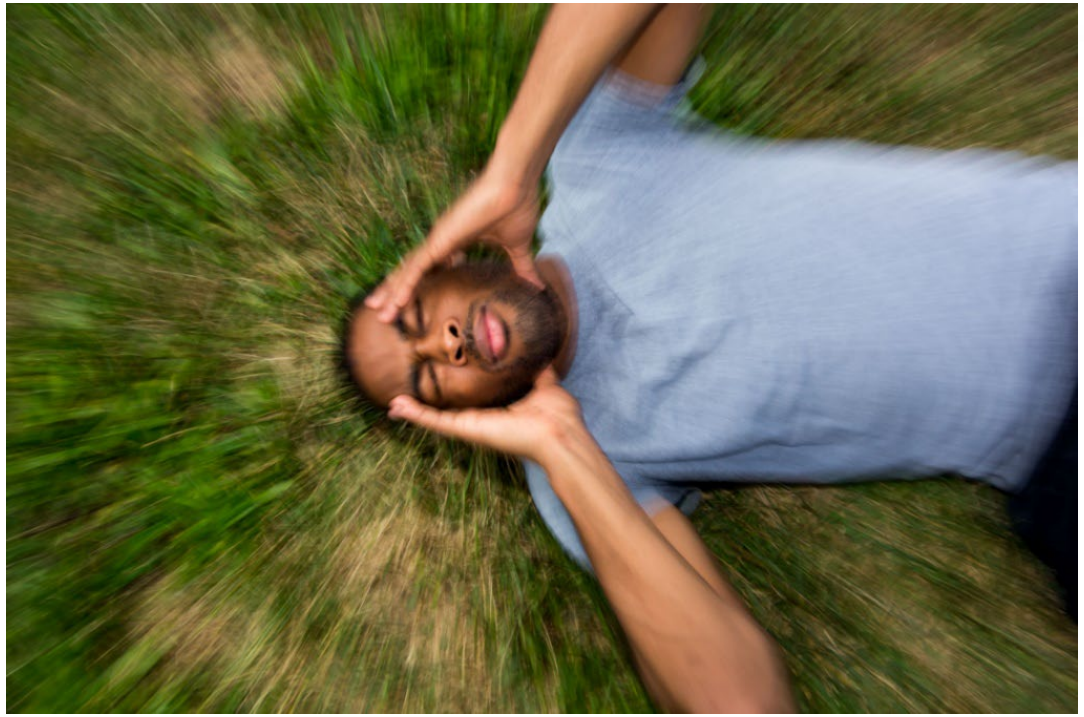
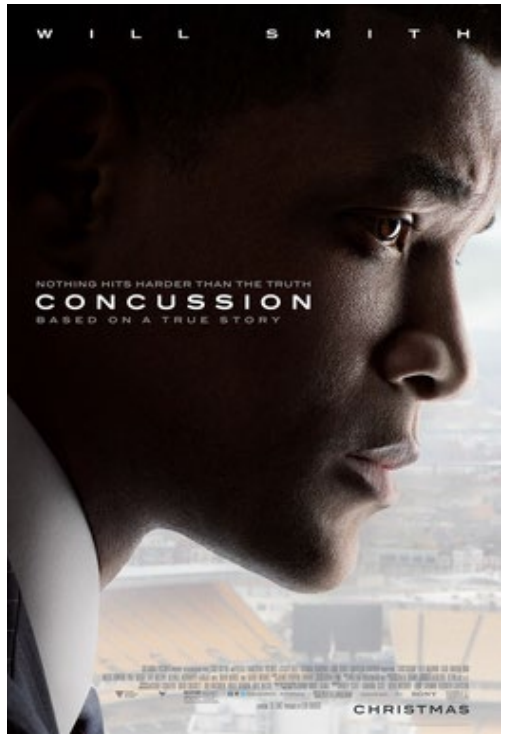
The concussion problem





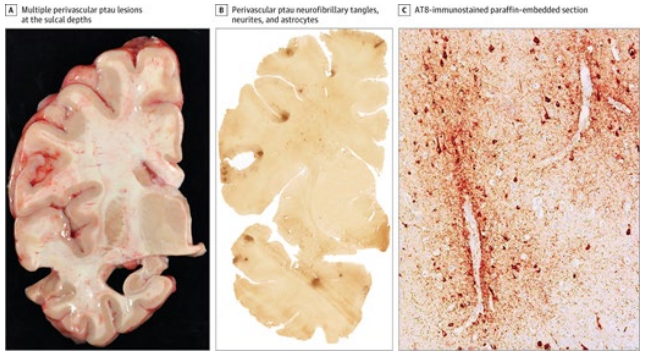
The concussion problem

Study Finds Evidence of Brain Injury in Living NFL Veterans

More than 40 percent of retired NFL players showed signs of traumatic brain injury

Pathologically Confirmed Chronic Traumatic Encephalopathy in a 25-Year-Old Former College Football Player

Jesse Mez, MD, MS[1,2]; Todd M. Solomon, PhD[1]; Daniel H. Daneshvar, MA[1,3]; Thor D. Stein, MD, PhD[1,4,5,6]; Ann C. McKee, MD[1,2,4,5,6]

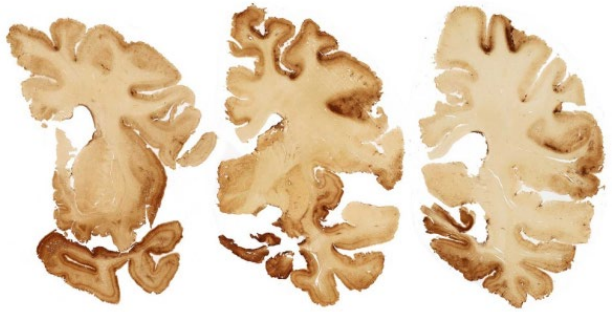


NFL acknowledges, for first time, link between football, brain disease

Concussion ⇔ Mild Traumatic Brain Injury (mTBI)

Silent epidemic

- ~75% of the 1.5M annual TBIs are ‘mild’ (CDC Report, 2003)
- Debilitating symptoms can last weeks to months



Repeat injuries exacerbate effects

- Repeat injuries -> worse outcomes (McCrory 2012)
- Associated with long-term neurodegeneration (McKee, 2010; Hart, 2013)
- Situation in sports worsened by underreporting (Booher 2003)

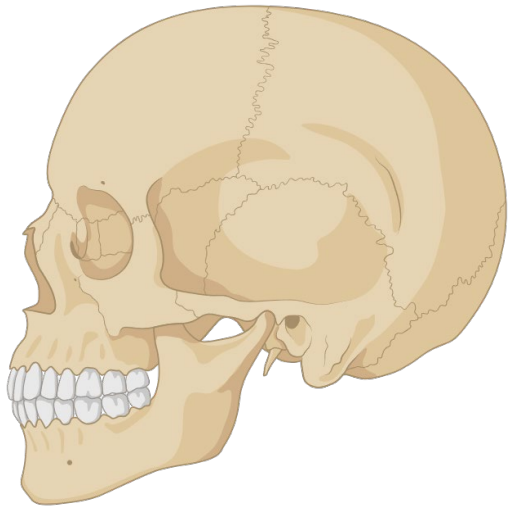
Image adapted from McKee 2010

Concussions often result from direct impact to head

https://neurotracker.net/2017/08/22/5-risks-repetitive-head-impacts/

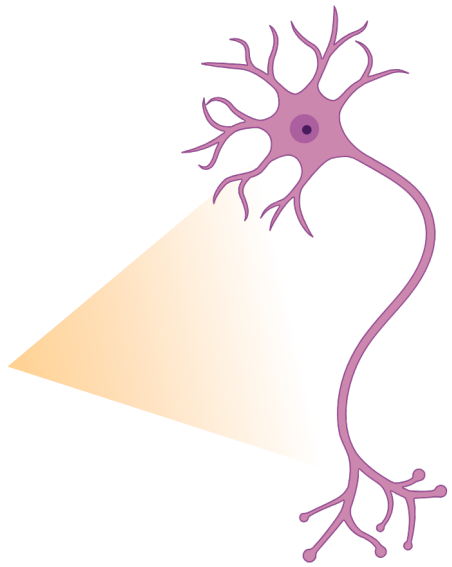
Can you see the difference?

Brain within an intact skull is affected – how?



Head acceleration event

Brain motion/deformation



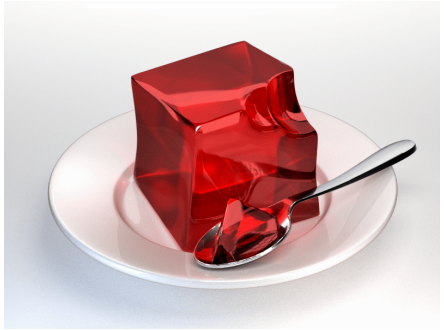
Microstructural disruption

Key questions

- When does concussion happen? How do we predict injury based on the biomechanics of the head acceleration event?

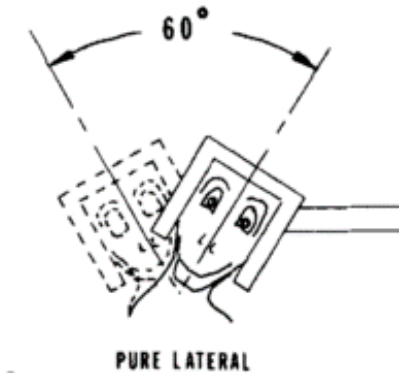
Theoretical & animal models of injury

Holbourn Hypothesis



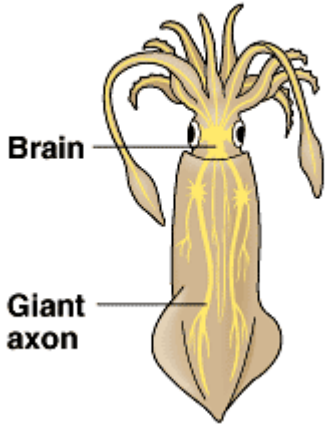
(Holbourn 1943)

Rotational Injuries in Monkeys



(Gennarelli 1982)

Axonal Injury

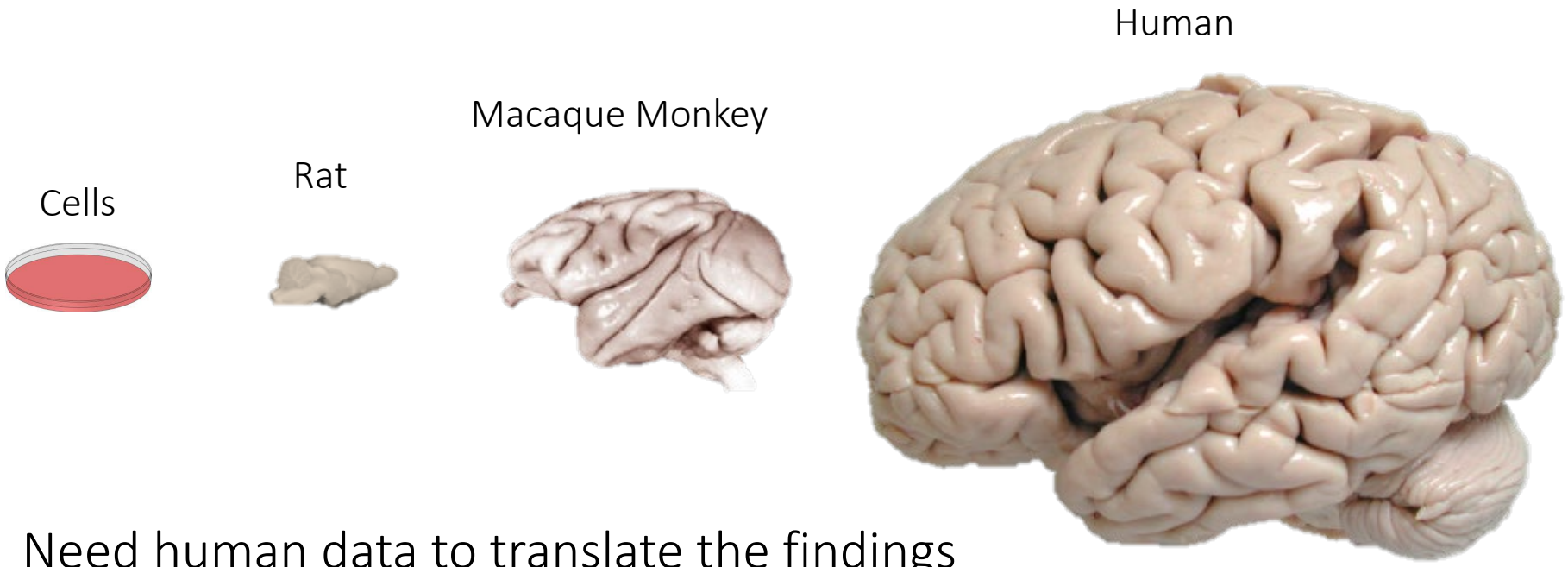


(Galbraith 1993)

Molecular/Cellular Mechanisms

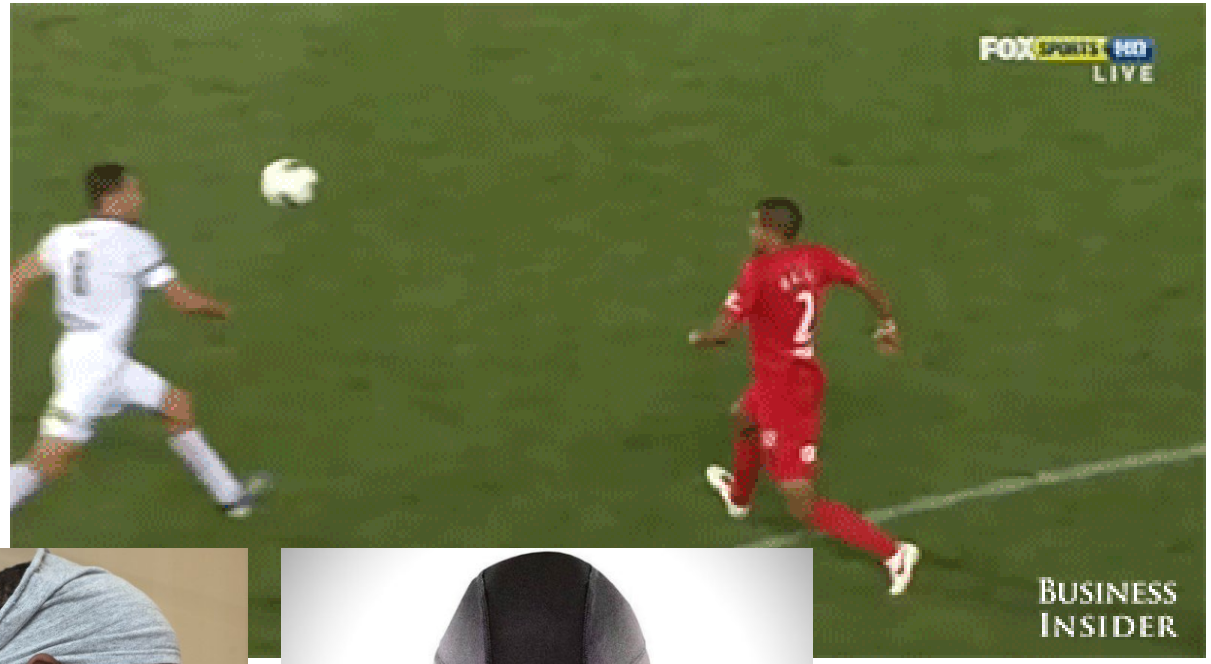
(Prins 2013)

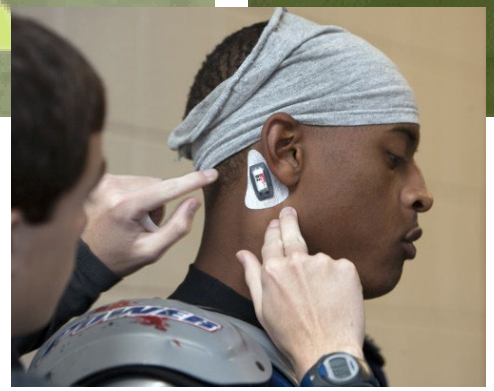
What about human injury?

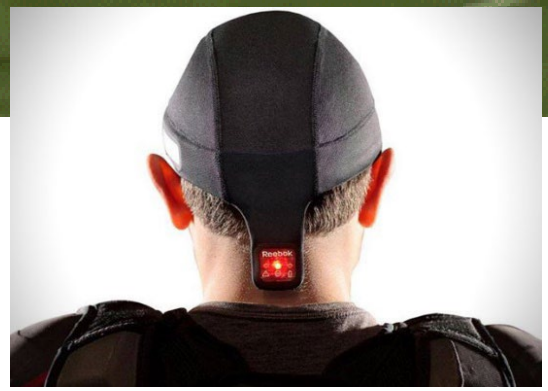


Need human data to translate the findings

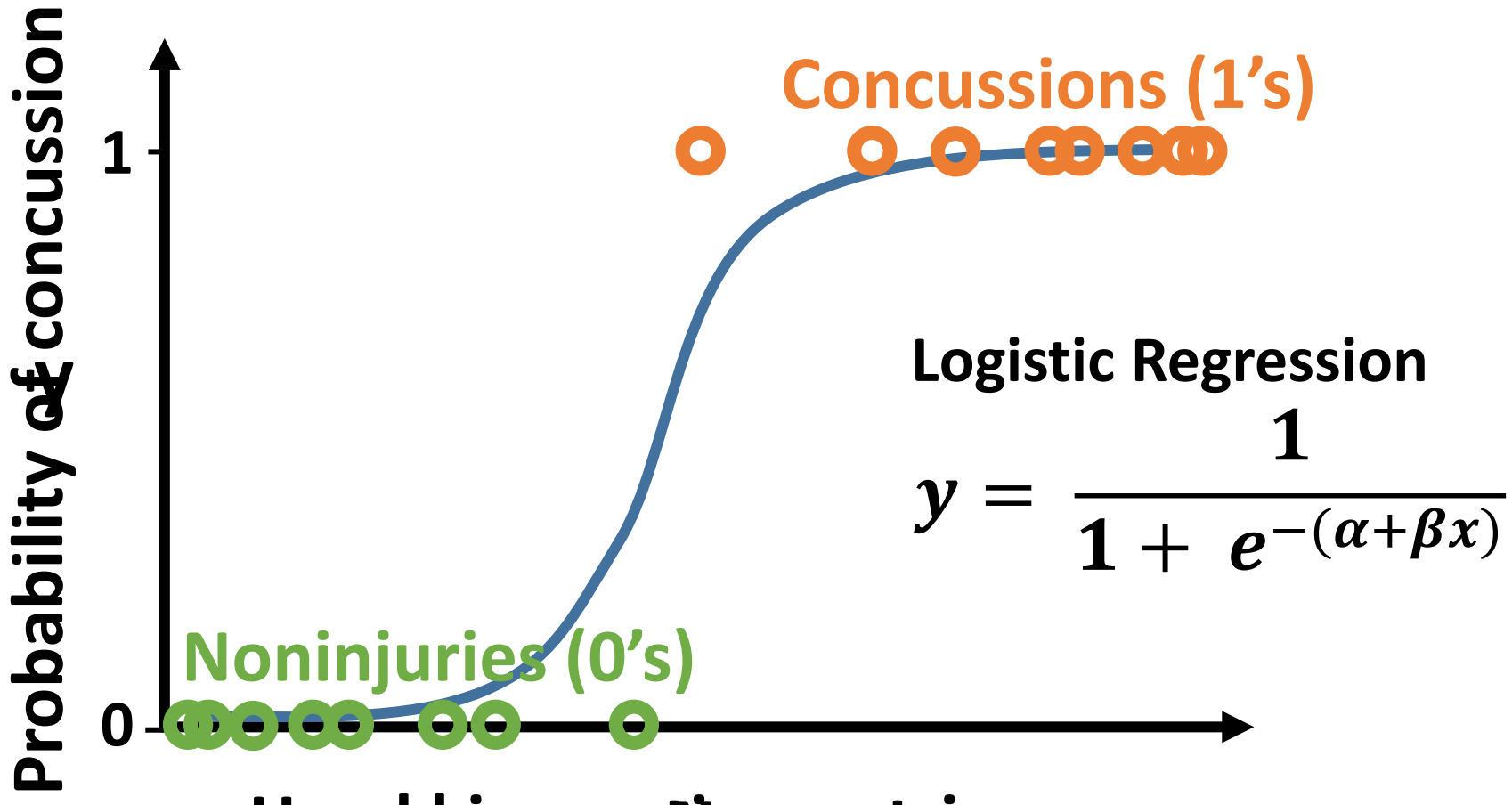
Wearable sensors gather ~~head~~ skull kinematics data, from the real world





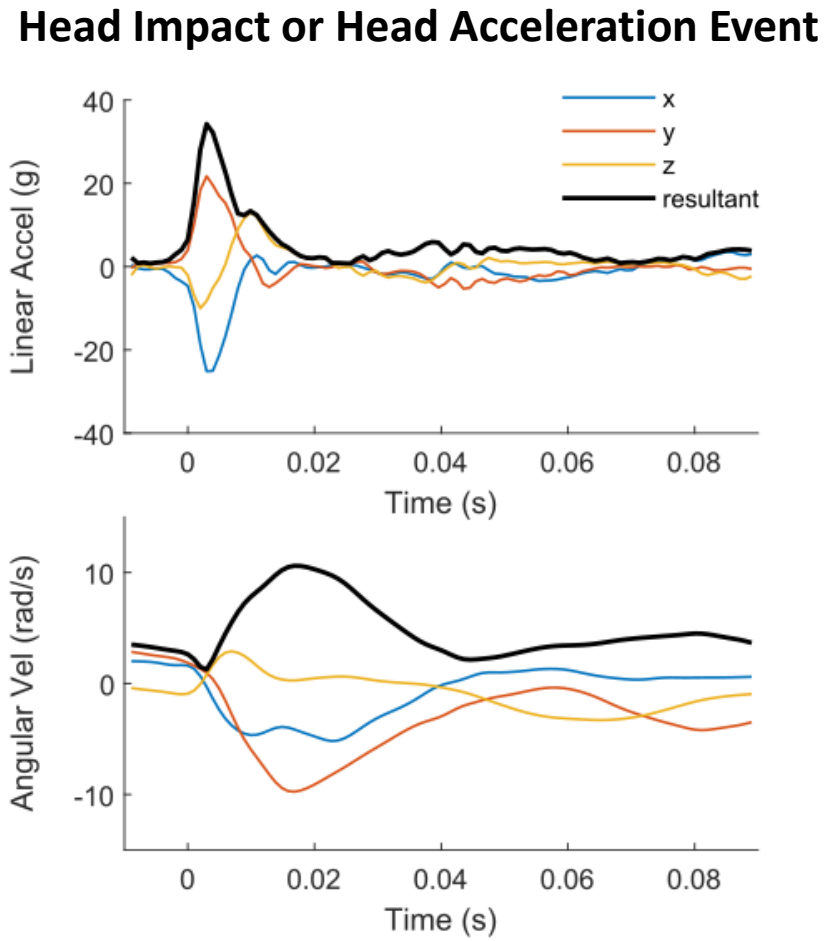


The biomechanics approach - injury risk curve

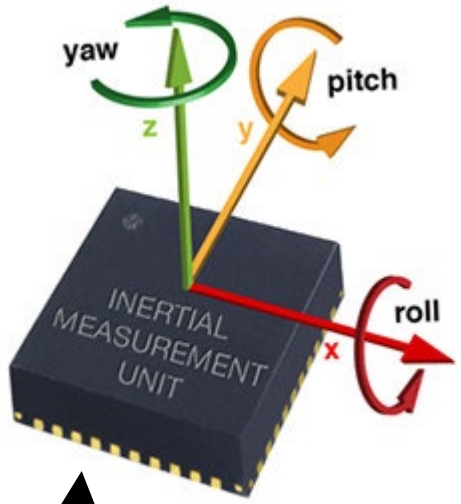


e.g., peak linear acceleration

Accurate measurement of impulsive skull accelerations is not trivial

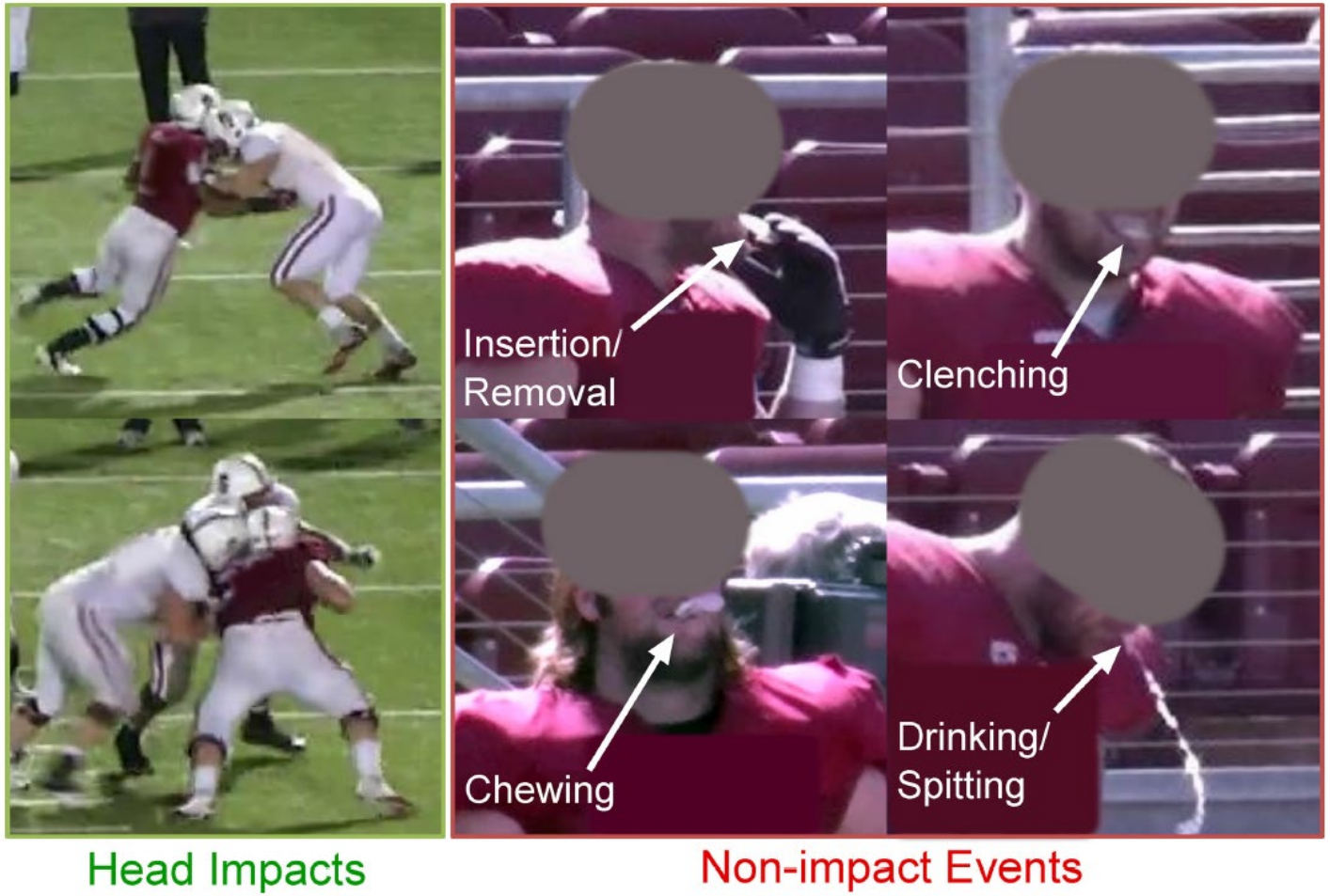


Instrumented Mouthguard

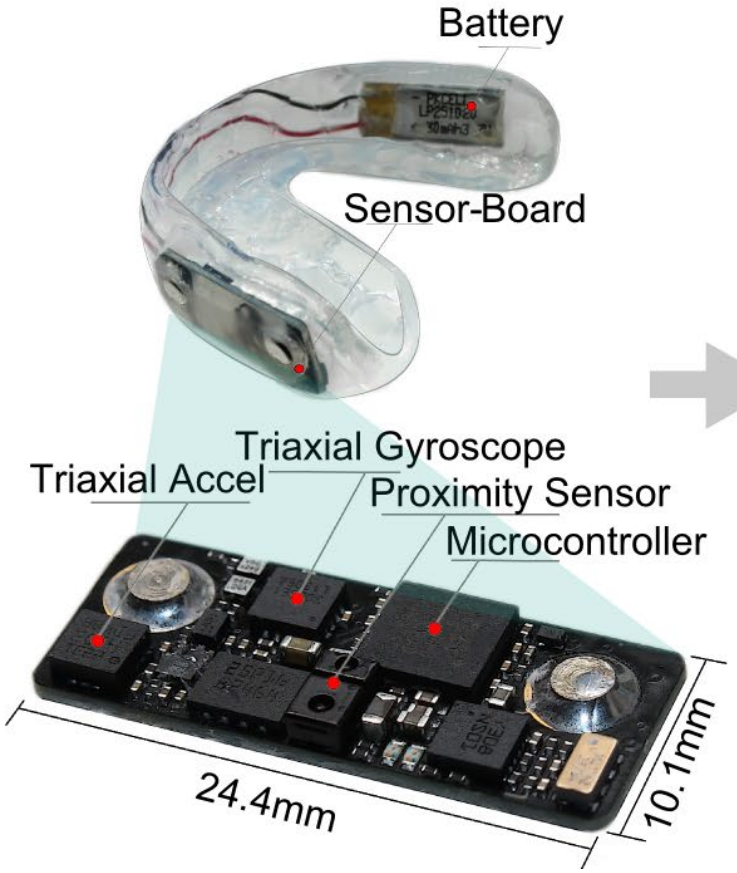


Clansey, Adam C., and Bondi, D., et al. Annals of Biomedical Engineering 52.10 (2024): 2666-2677.
Luke, David, et al. *Annals of Biomedical Engineering* (2025): 1-17.

Can the sensor detect events of interest and only events of interest?



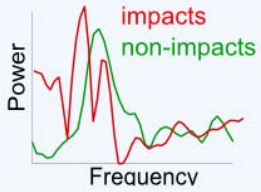
An Impact Detection System



Head Impact Classification

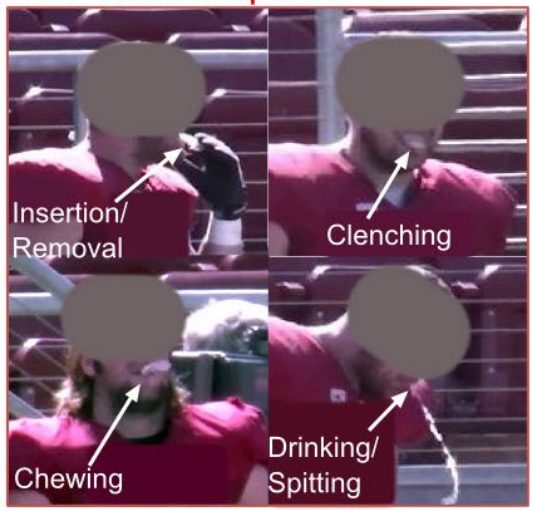
Proximity sensing to check device mounting

Machine learning classifier to distinguish events



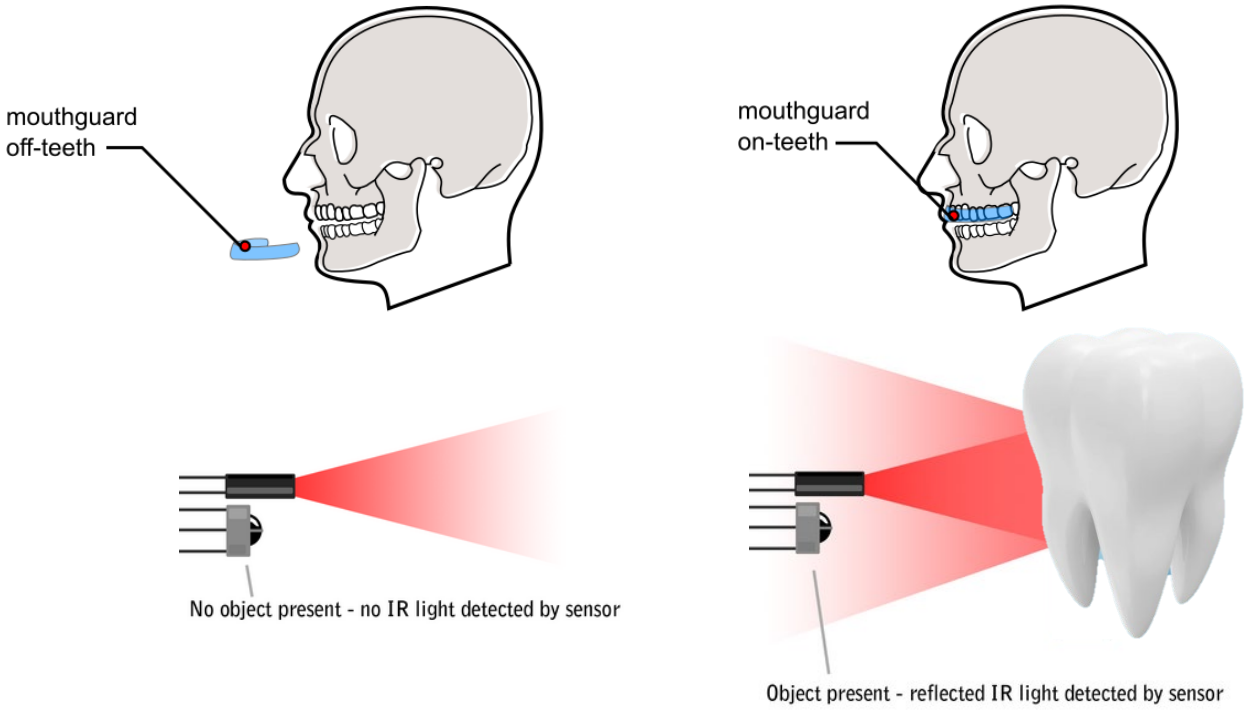
Head Impacts

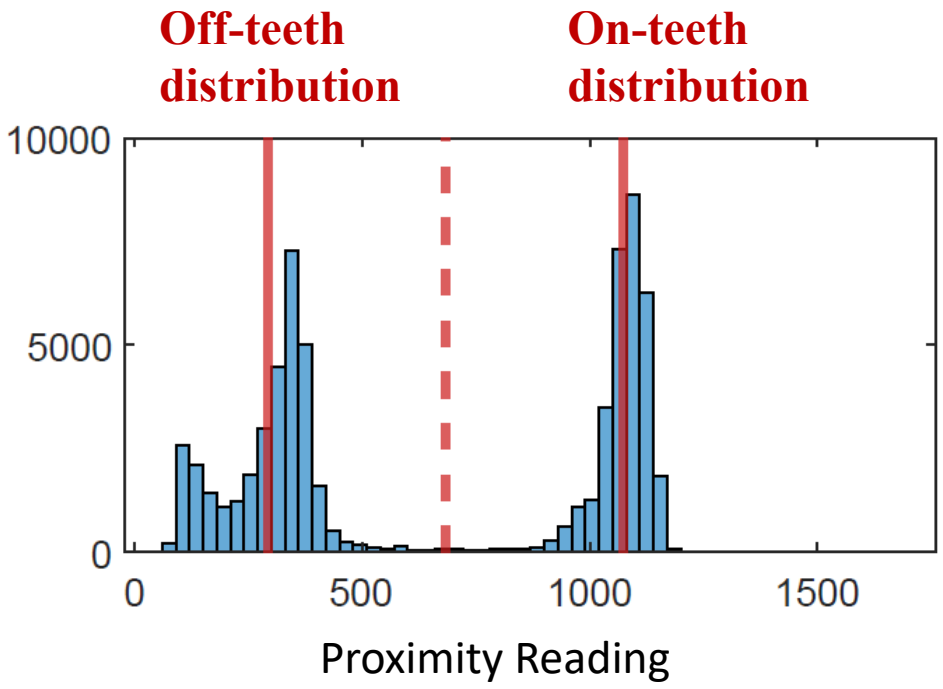
NOT Head Impacts



Wu, L.C., Zarnescu, L., Nangia, V., Cam, B., Camarillo, D. A Head Impact Detection System Using SVM Classification and Proximity Sensing in an Instrumented Mouthguard. *IEEE Transactions on Biomedical Engineering.* 61 (11), 2659–68 (2014).

On-field sensing of proper sensor usage

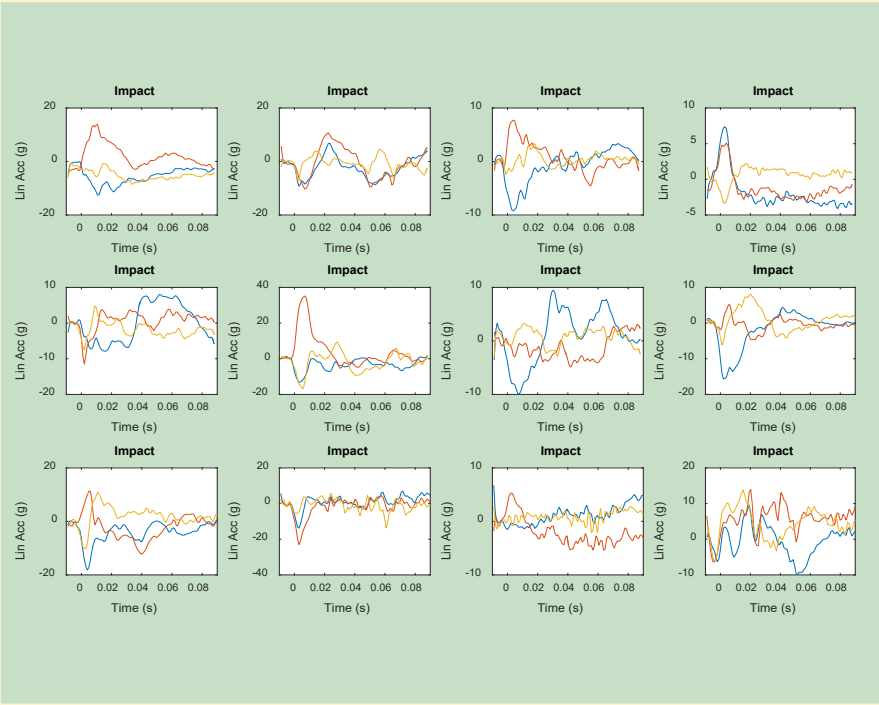




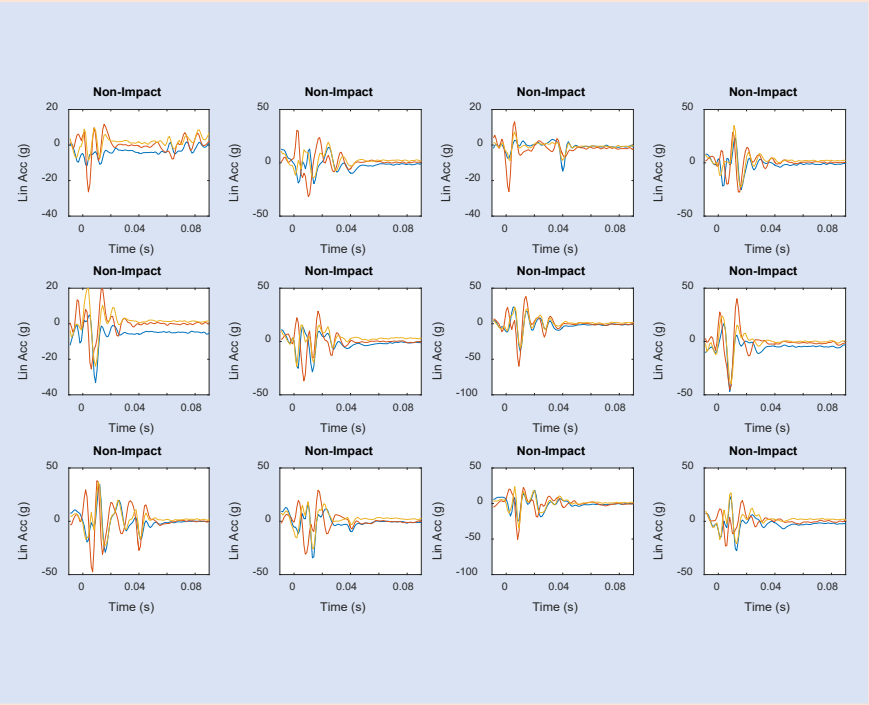
Luke, D., Kenny, R., Bondi, D., Clansey, A. C., & Wu, L. C. *Journal of biomechanics*. 2024.

Machine learning-based classification of real impacts

Head Impacts



Nonimpacts



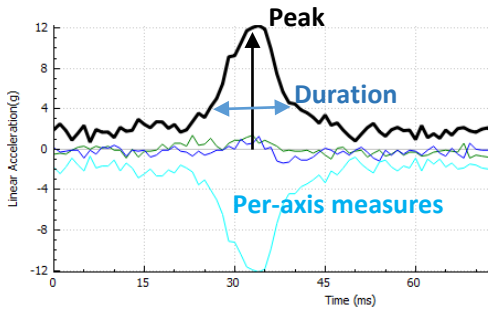
Wu, Lyndia C., et al. "Detection of American football head impacts using biomechanical features and support vector machine classification." *Scientific reports* 8.1 (2017): 855.

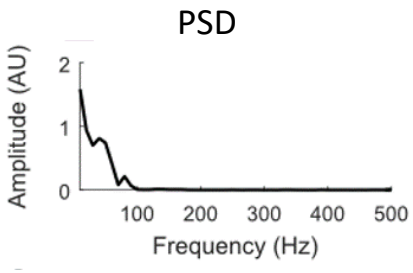
Features extracted from kinematics data

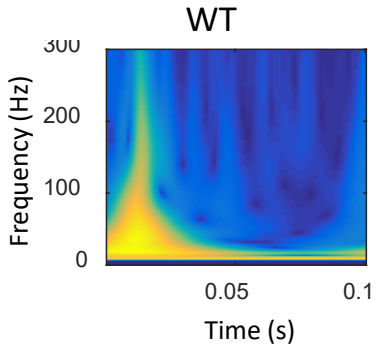
- Peak kinematics
- Impulse durations
- Power spectral density features
- Wavelet transform features
- Biomechanical feasibility features

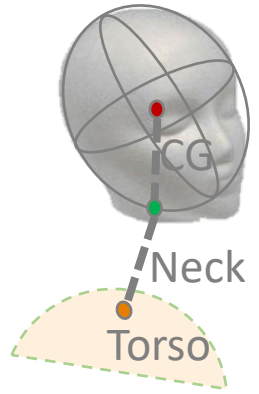
411 features

$$\begin{bmatrix} x_{1,1} & \cdots & x_{1,p} \\ \vdots & \ddots & \vdots \\ x_{m,1} & \cdots & x_{m,p} \end{bmatrix} => \begin{bmatrix} y_1 \\ \vdots \\ y_m \end{bmatrix}$$









Wu, et al., IEEE TBME, 2014
Wu, et al., Sci. Rep., 2017

Training and Validation Methods

- Support vector machine (SVM) binary classifier with radial basis function kernel
- Classifier trained and validated using 150 head impacts and 860 nonimpacts gathered from football
- Ground truth event labels verified through video analysis
- Forward feature selection to avoid overfitting
- Leave-one-out cross validation

Performance Measures

$$sensitivity = \frac{TP}{TP + FN}$$

$$specificity = \frac{TN}{TN + FP}$$

$$accuracy = \frac{TP + TN}{TP + TN + FP + FN}$$

$$precision = \frac{TP}{TP + FP}$$

TP: true positive

TN: true negative

FP: false positive

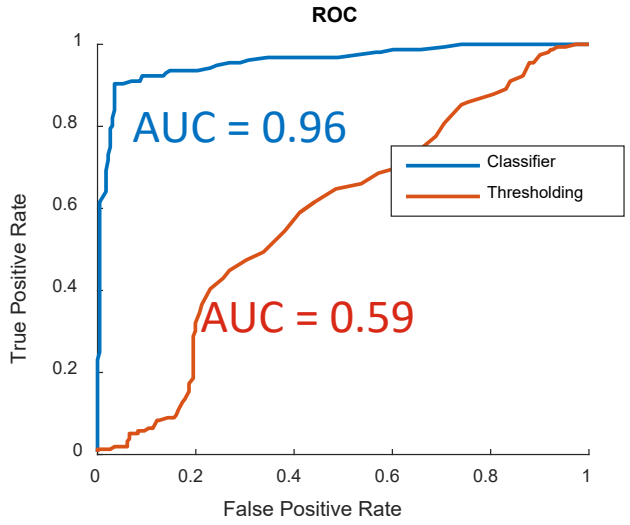
FN: false negative

Performance of Classifier

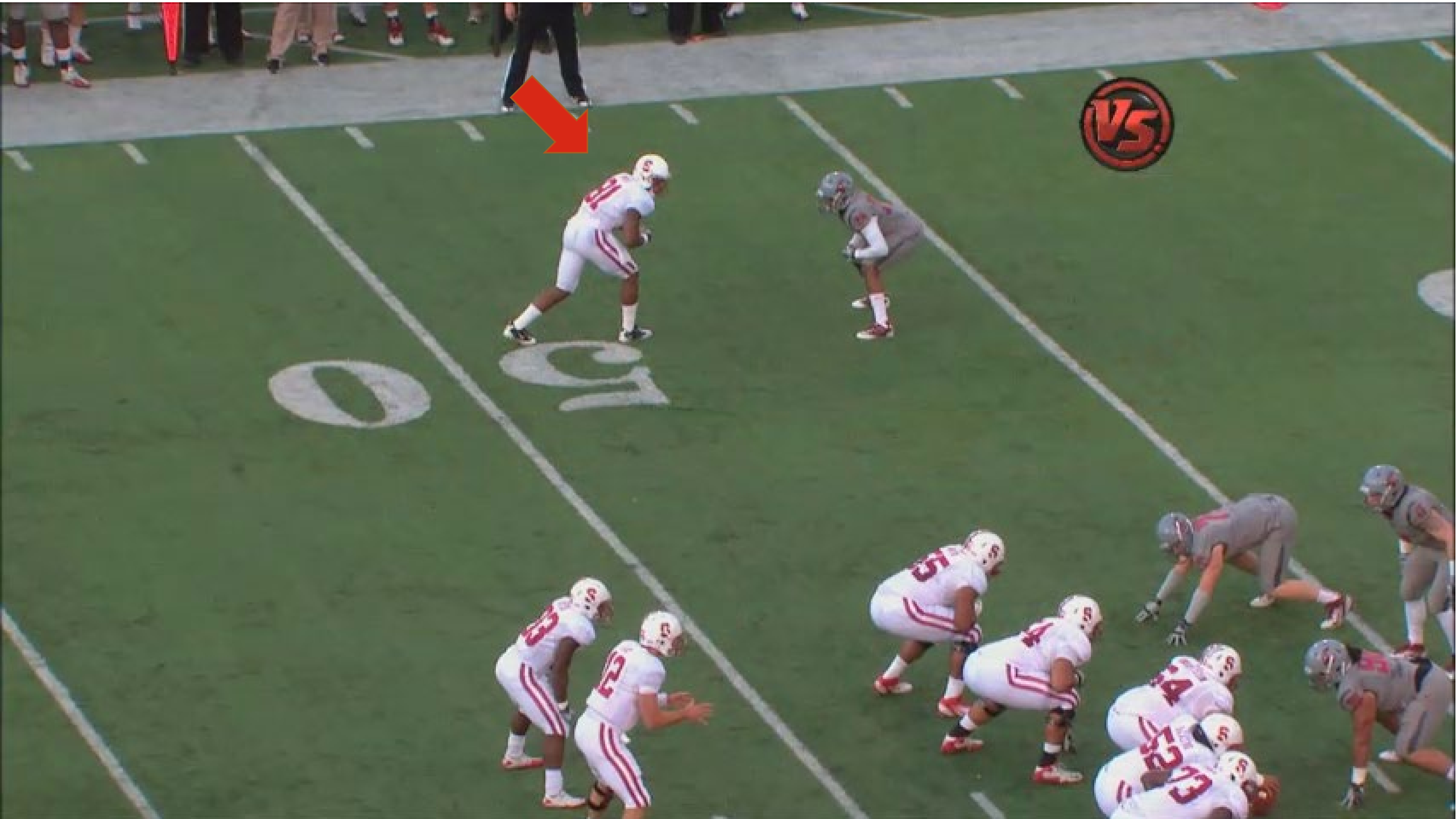
- Infrared sensing filtered out 75% of nonimpacts
- Machine learning filtered out an additional 24% of nonimpacts

SVM classifier performance

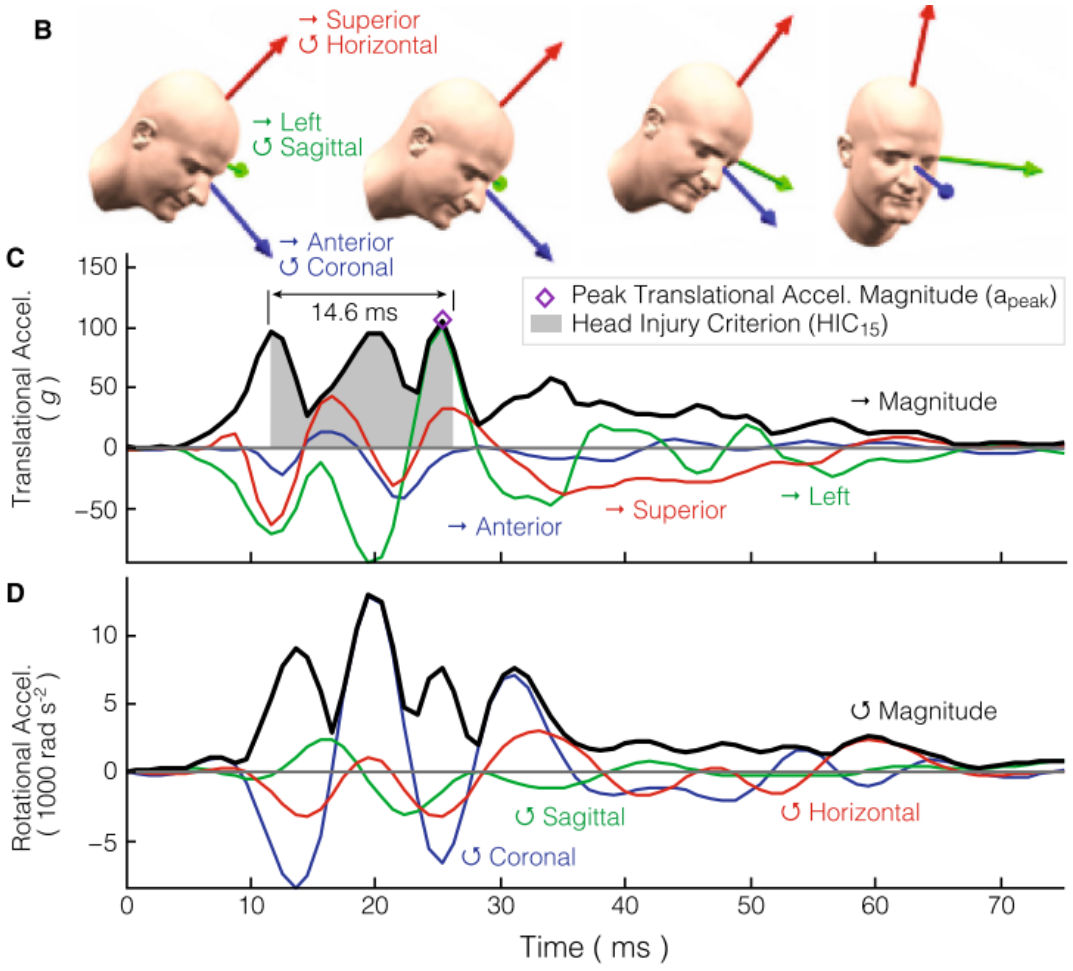
Sensitivity	90%
Specificity	97%
Accuracy	94%
Precision	95%



Wu, et al., IEEE TBME, 2014
Wu, et al., Sci. Rep., 2017

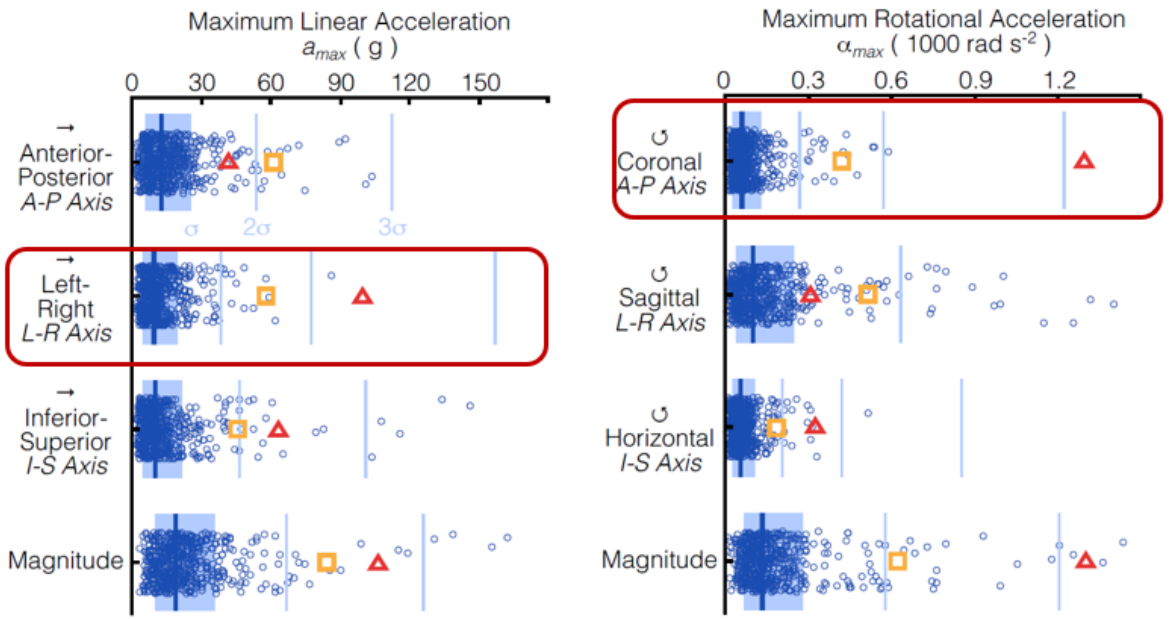


What does a concussive impact look like?



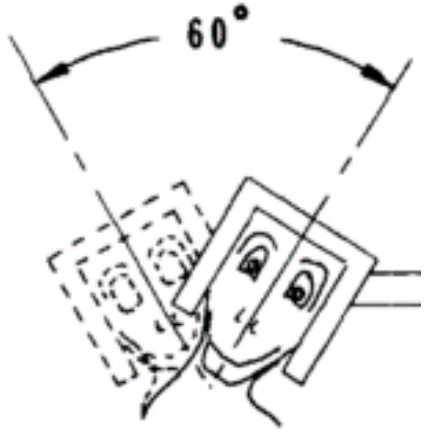
Hernandez, Wu, et al., ABME, 2015

Evidence of Injury Directional Dependence



Red triangle – loss of consciousness
yellow square – self-reported concussion
blue circle – noninjury

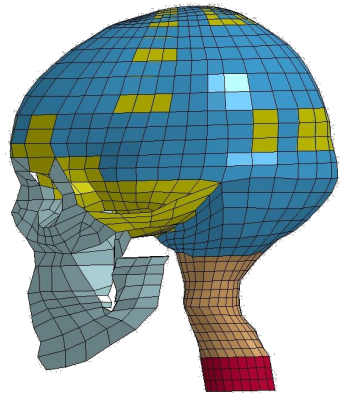
- Coronal plane of rotation found to be most dangerous in primates (Gennarelli 1982).

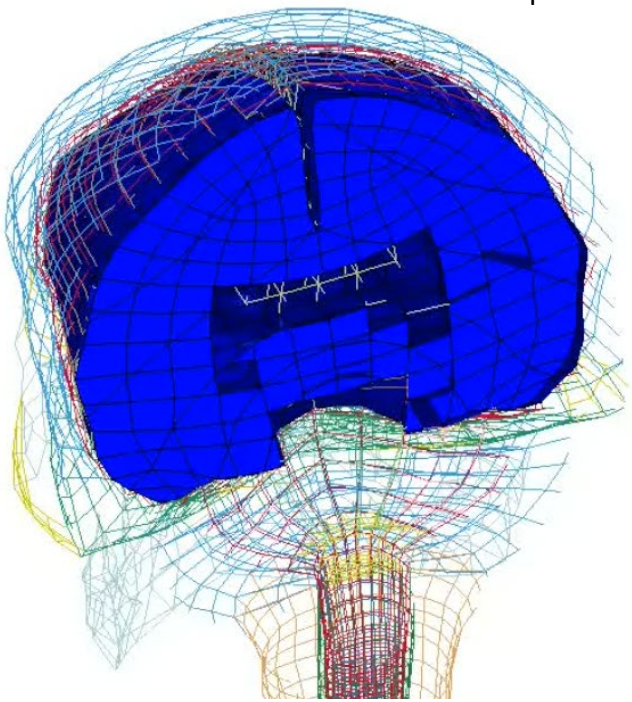


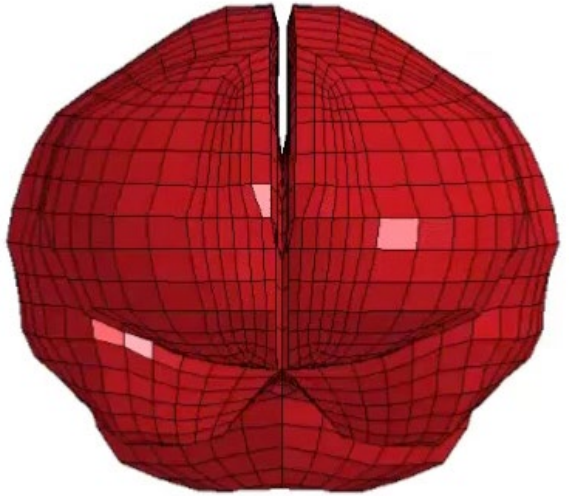
Hernandez, Wu, et al., ABME, 2015

Digging deeper – what's happening in the brain?

ε_{peak} = 52.4%







Hernandez, Wu, et al., ABME, 2015

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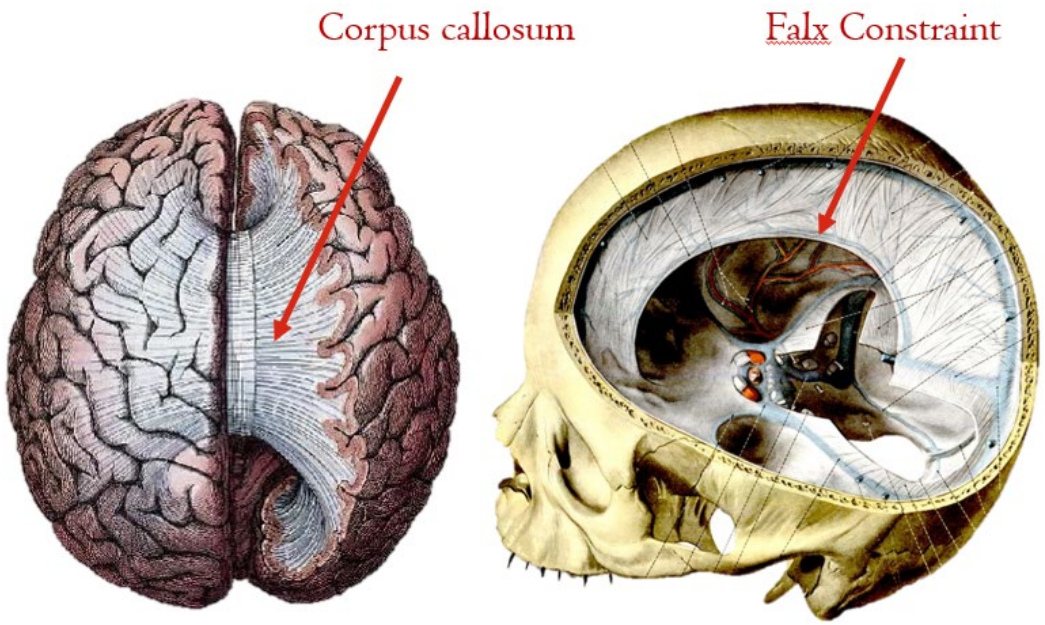


Hernandez, Wu, et al., ABME, 2015

Further studies focusing on under-represented athletes

- Head impact exposure measurements in women's soccer, women's rugby, men's and women's ice hockey
- Filling important gap: highly **biased data** in existing literature
  - <15% impact sensor study participants are female, 65% are American football [1]

Women's soccer

Women's rugby

Men's & Women's ice hockey

[1] Le Flao, et al. Sport. Med. 2021

Multidomain data collection across diverse athletes

Women's Soccer (2019-2021)

Men's Ice Hockey (2021-2024)

Women's Ice Hockey (2021-2023)

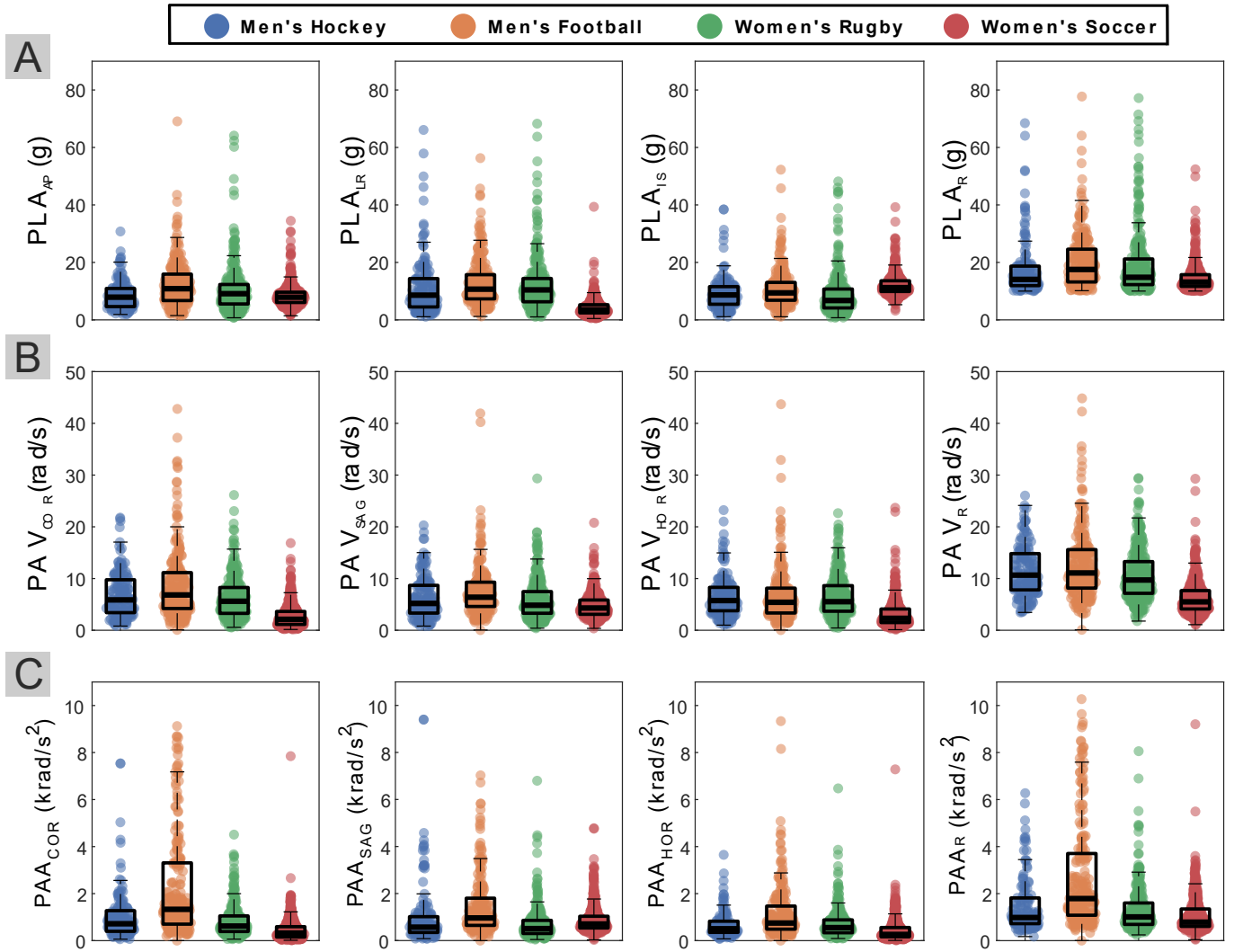
Women's Rugby (2022-2024)

Control Athletes (2021-2024)

Concussions (23 diagnosed + 1 suspected; 11 full 6DOF sensor measurements, 1 partial 3DOF)

140 contact sports athletes (96 F, 44 M); 37 control athletes (18 F, 19 M)
4283 video-verified, iMG-recorded head acceleration events, with ongoing verification and screening
300 pre/post season + 60 post-concussion multidomain MRI and neurological assessments
60 blood samples from hockey and rugby athletes

Comparing impact biomechanics across sports



The concussion impacts

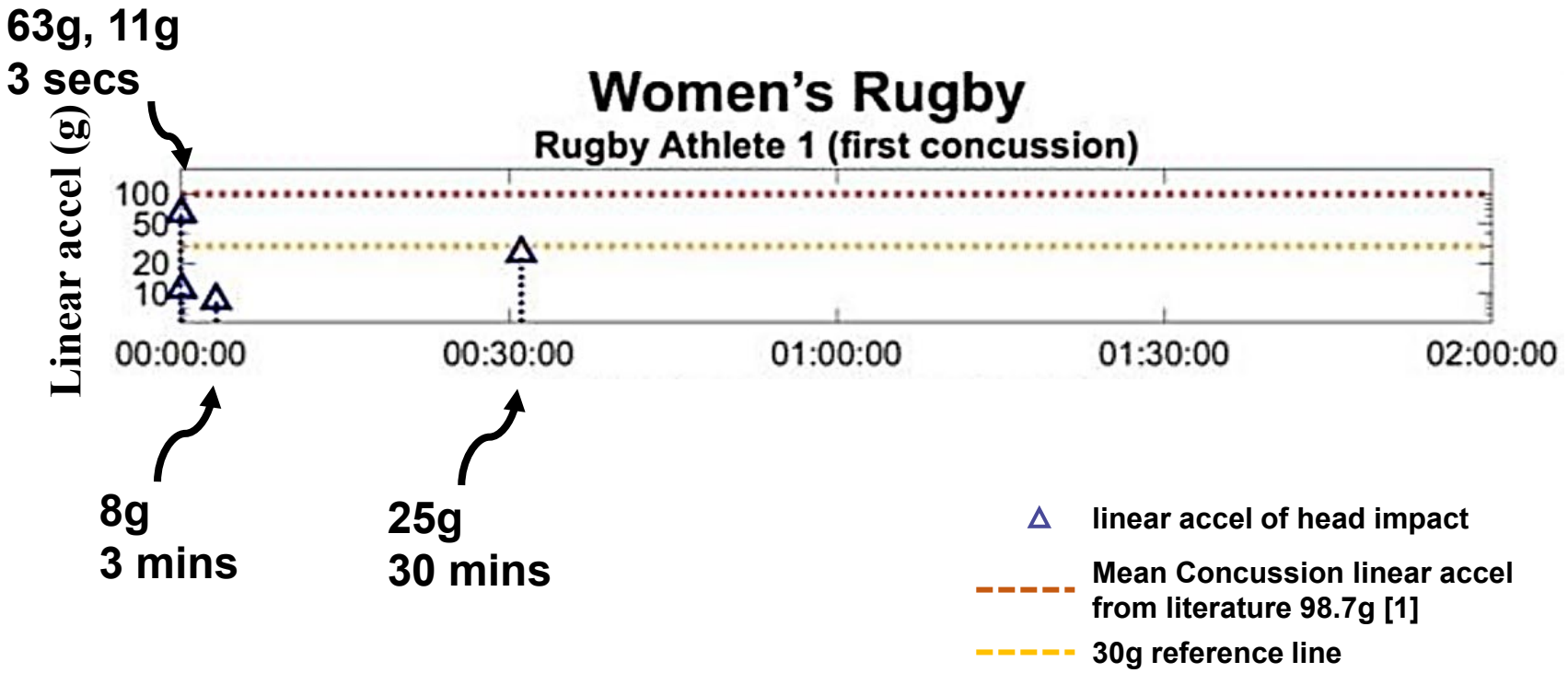
Men's Ice Hockey Concussions

Peak linear accel	Peak angular accel
67g	11,000 rad/s^2
87g	7,000 rad/s^2
9g	880 rad/s^2
40g	4,000 rad/s^2

Women's Rugby Concussions

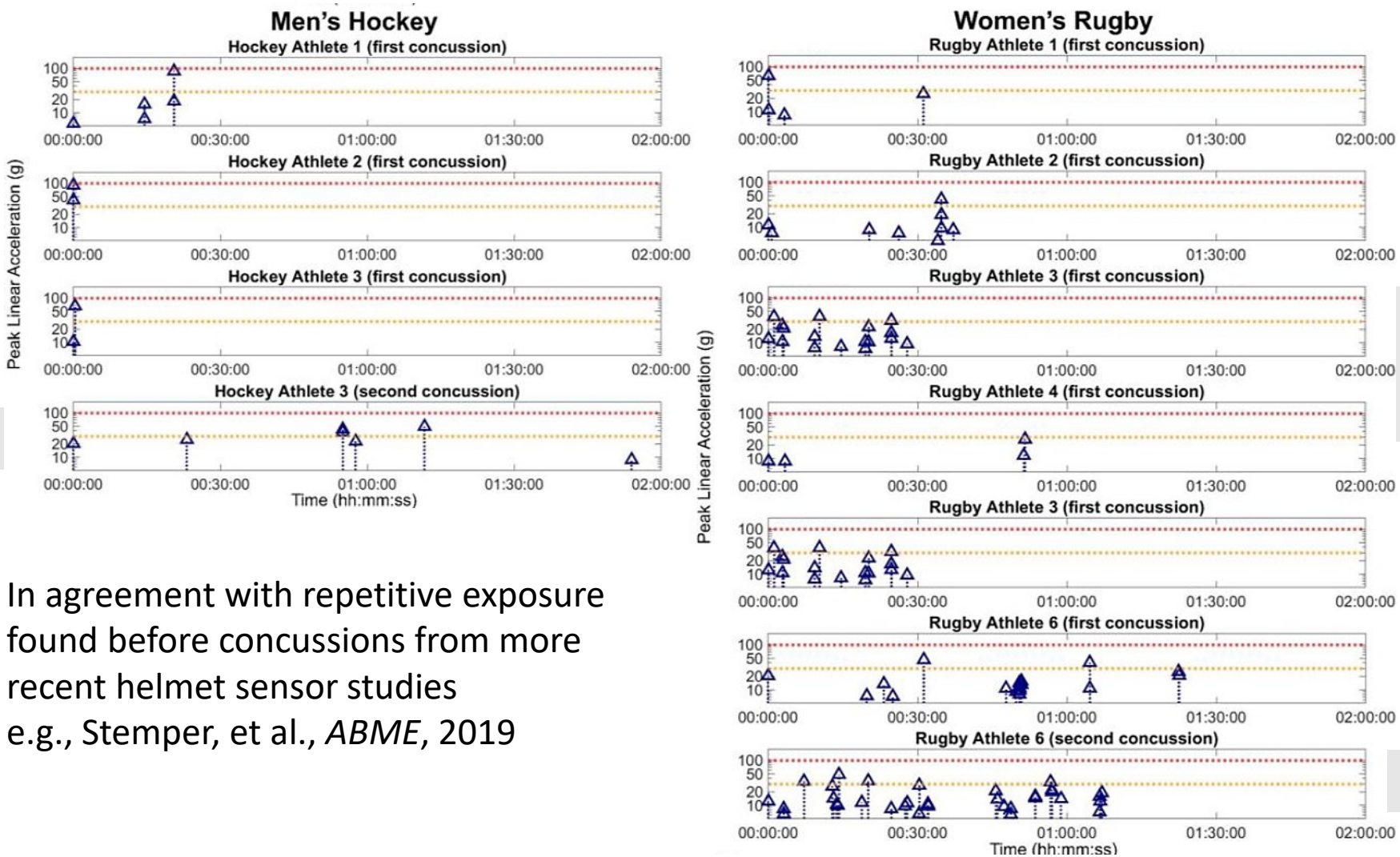
Peak linear accel	Peak angular accel
21g	2,200 rad/s^2
25g	1,300 rad/s^2
9g	490 rad/s^2
9g	990 rad/s^2
19g	1,400 rad/s^2
27g	2,800 rad/s^2
40g	4,400 rad/s^2

Head impact exposure on concussion days



Luke, D. (2023). Thesis. University of British Columbia.
[1] Brennan, Sports Med, 2017.

Head impact exposure on concussion days



Repeat concussion

In agreement with repetitive exposure found before concussions from more recent helmet sensor studies
e.g., Stemper, et al., *ABME*, 2019

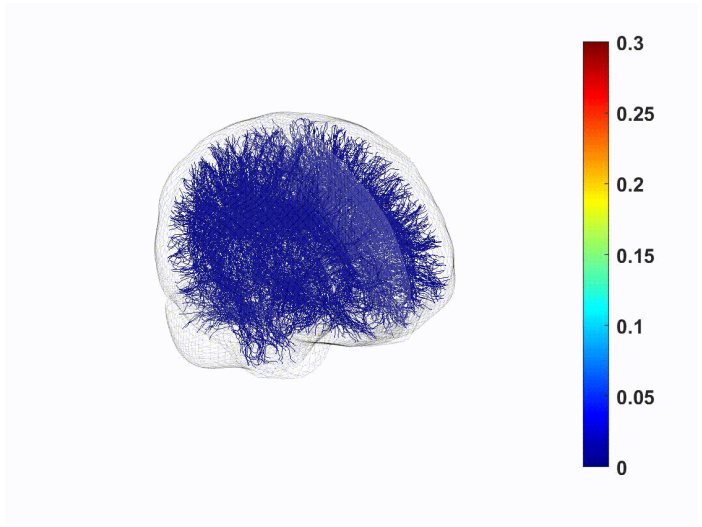
Lower severity, but repetitive impacts

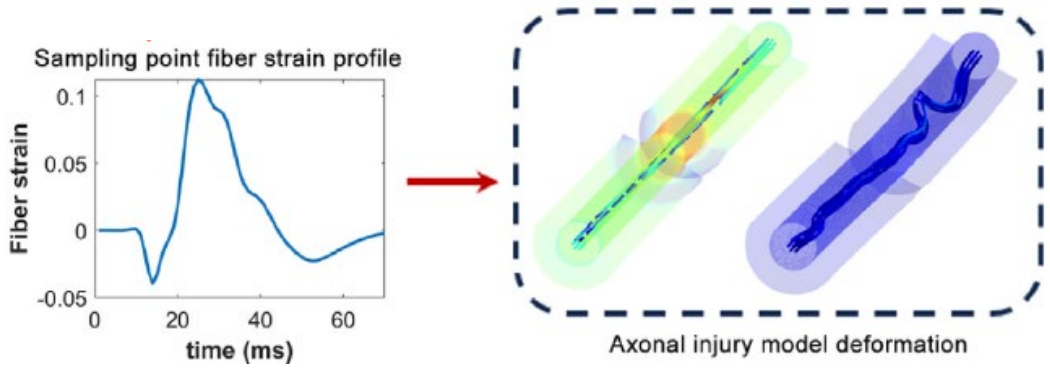
Repeat concussion

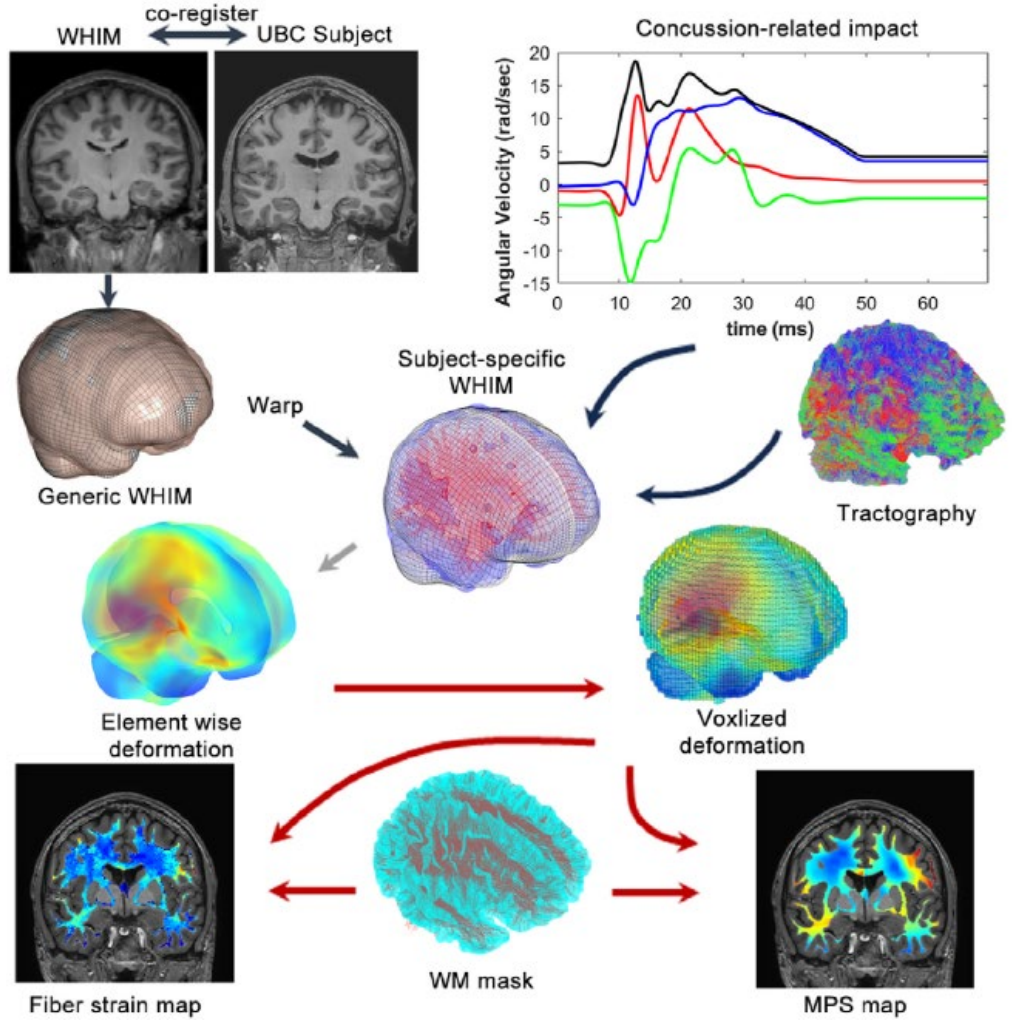
Luke, D. (2023). Thesis. University of British Columbia.

Developing more advanced brain models

Worcester head injury model







Zhang, C., et al., Wu, L.C., Rauscher, A., Ji, S. *Computers in Biology and Medicine*. 2024.

Brain response can be even more complex

Symptomatology
- Neurobehavioral symptom inventory

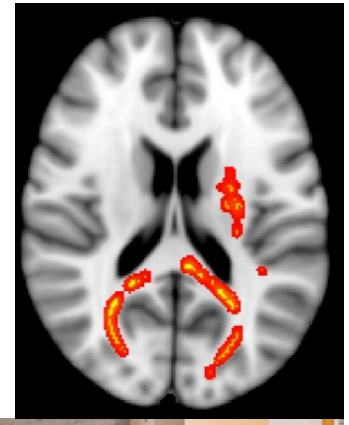
Neuroimaging:
- Myelin water
- Diffusion
- Lesions
- Microbleeds
- Functional MRI

Neuropsychological
- Depression scale
- Satisfaction with life

Sensorimotor
- Standing balance
- Tandem gait
- Eye tracking

Neurocognitive
- Executive function
- Working memory
- Processing speed

Blood biomarkers
- p-tau
- GFAP
- NF-L



Take home messages

- Wearable sensors enable capture of real-world injury events
- Real-world sensor data require extra screening to ensure quality
- Severity, frequency, timing can all contribute to injury risk
- Need to further investigate complexity in both mechanics and brain outcomes