THE BENEFITS OF INERTIAL MEASUREMENT UNITS IN CHARACTERIZING *HULL PEFORMANCE* AND *HUMAN IMPACT EXPOSURE* IN HIGH-SPEED BOAT OPERATIONS

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- HSBO Forum 2023 -

Presentation Overview

1. Recent Statistics in the Spec Opps Community
2. Anatomy of a Wave Impact
3. **Inertial Measurement Units (IMU)**
    1. Hull Performance & Side by Side Testing
    2. Human Bio-Mechanic Analysis
    3. Dynamic Digital Twin Analysis Tool
4. Questions

The **Problem?**

Statistics - Special Operations Boating Community

1. Current trends are showing injury rates in this community are reaching upwards of **100%** (6X greater than gen population).
2. Cervical (neck) impact ranges on high-speed assault combatant craft range from 2g to **125g's**.
3. Mathematical models show that forces applied to the Pelvic region resulted in head responses at **5X** magnification. *See Figure 1*.

Source: Naval Special Warfare Group Four Medical letter entitled "Chronic Orthopedic/mTBI Problems in Selected Navy Ratings"

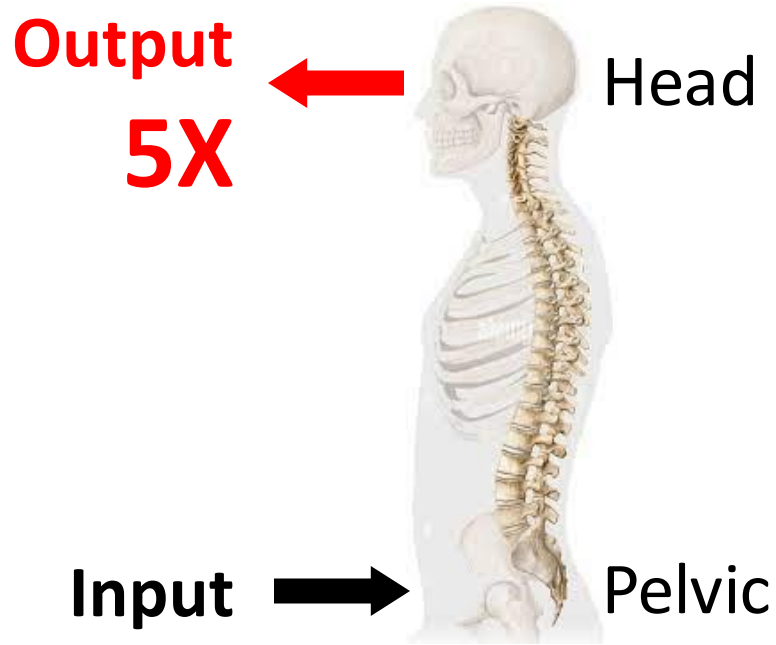
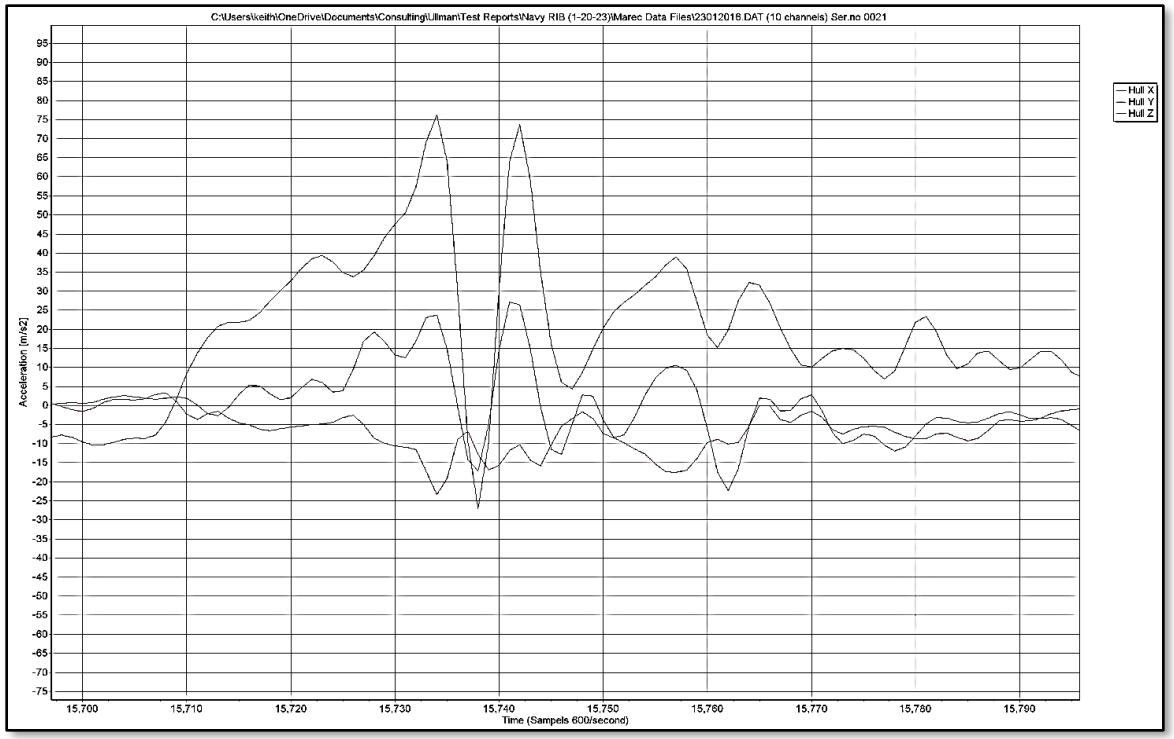


Figure 1

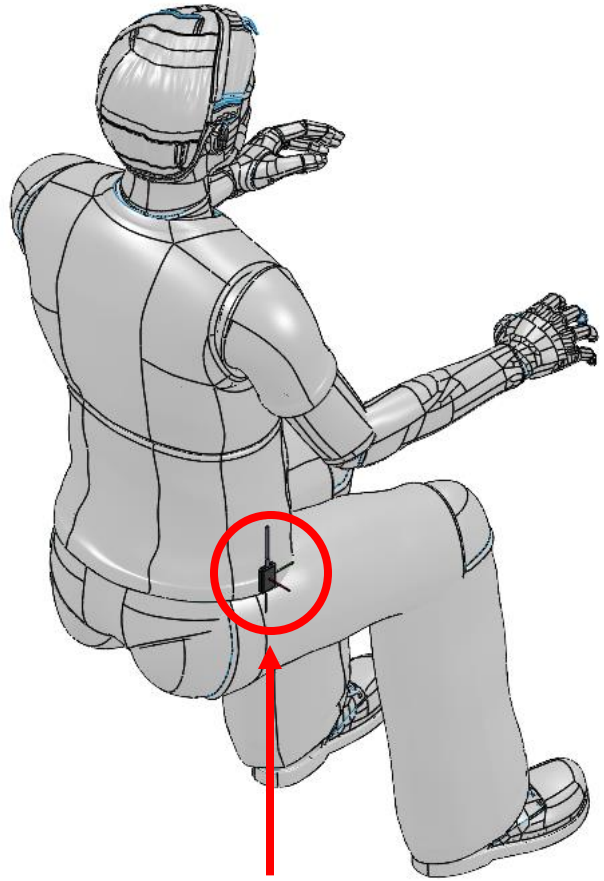
Anatomy of a **Wave Impact**

Conditions: Seas ≈ 1m, Speed = 35 Knots



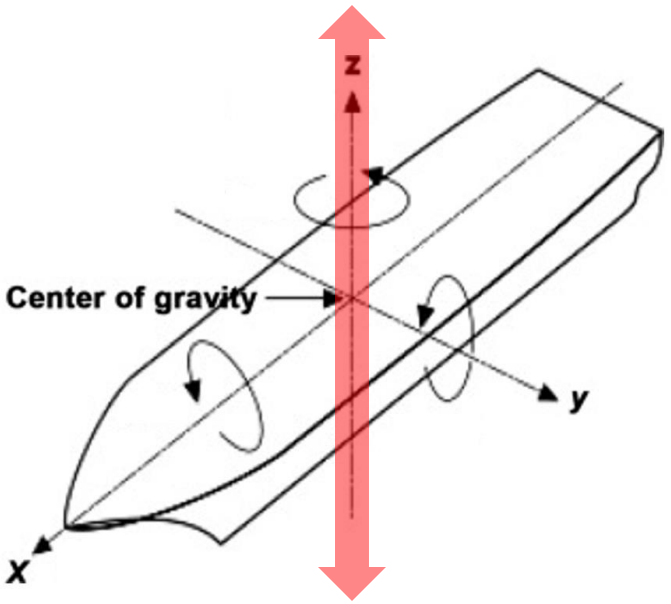
Typical Wave Impact

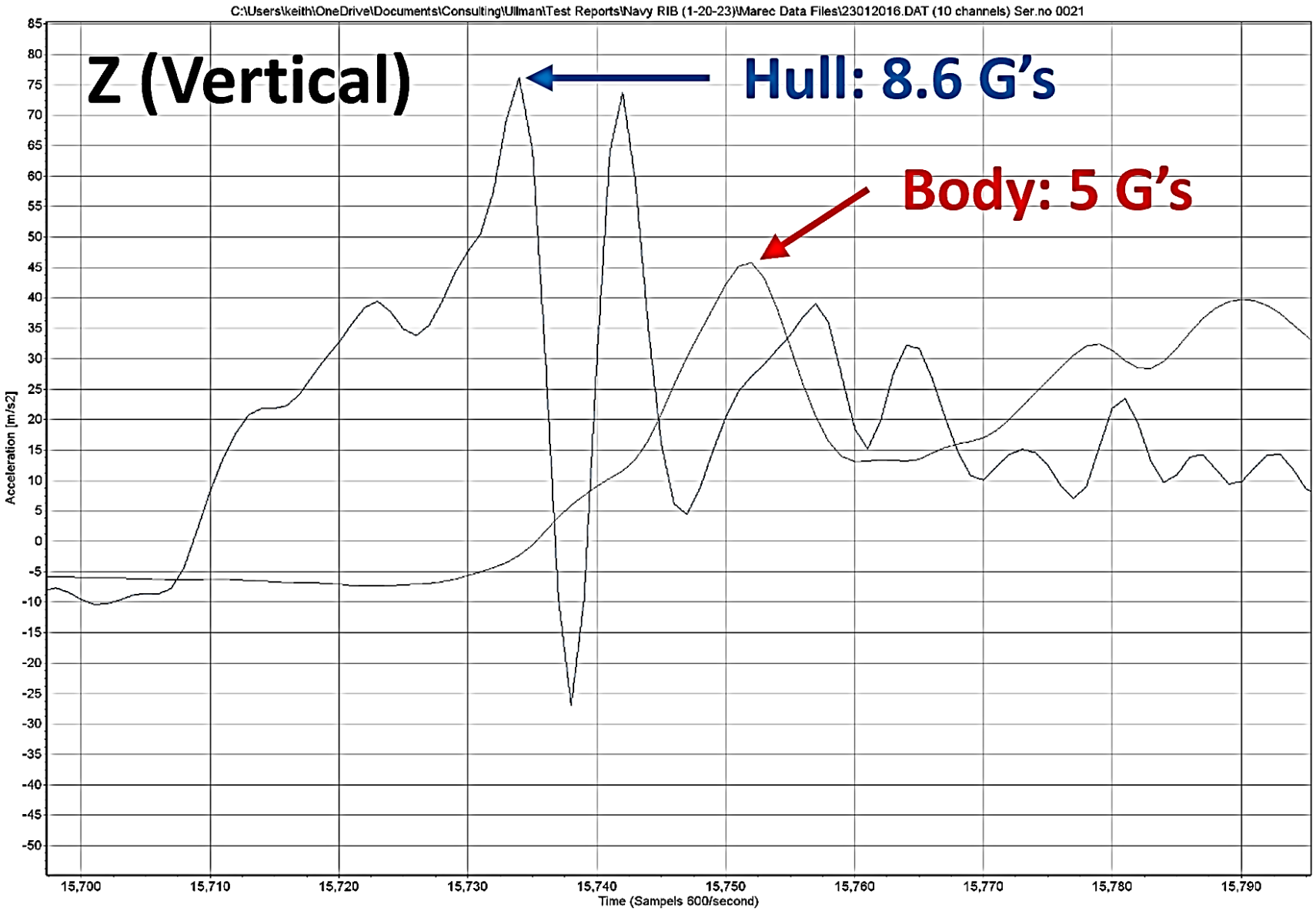
Hull Sensor (Seat Base)
Triac Accelerometer



Body Response
Triac Accelerometer

Vertical Direction (1m seas @ 35 knots)





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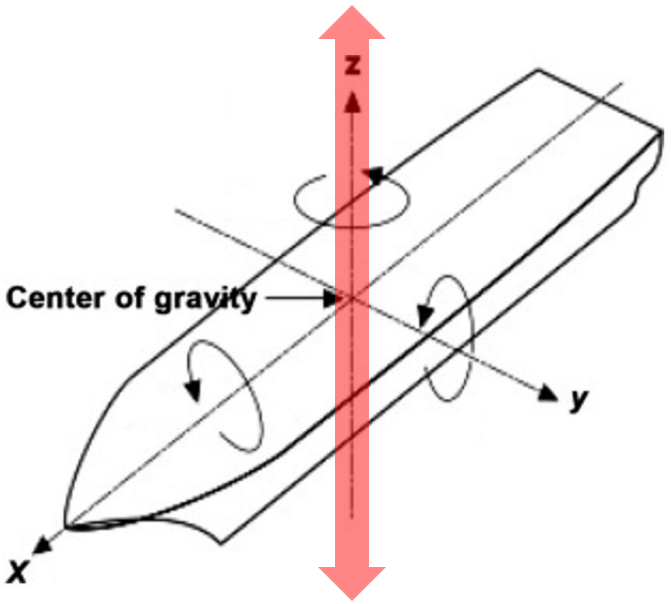
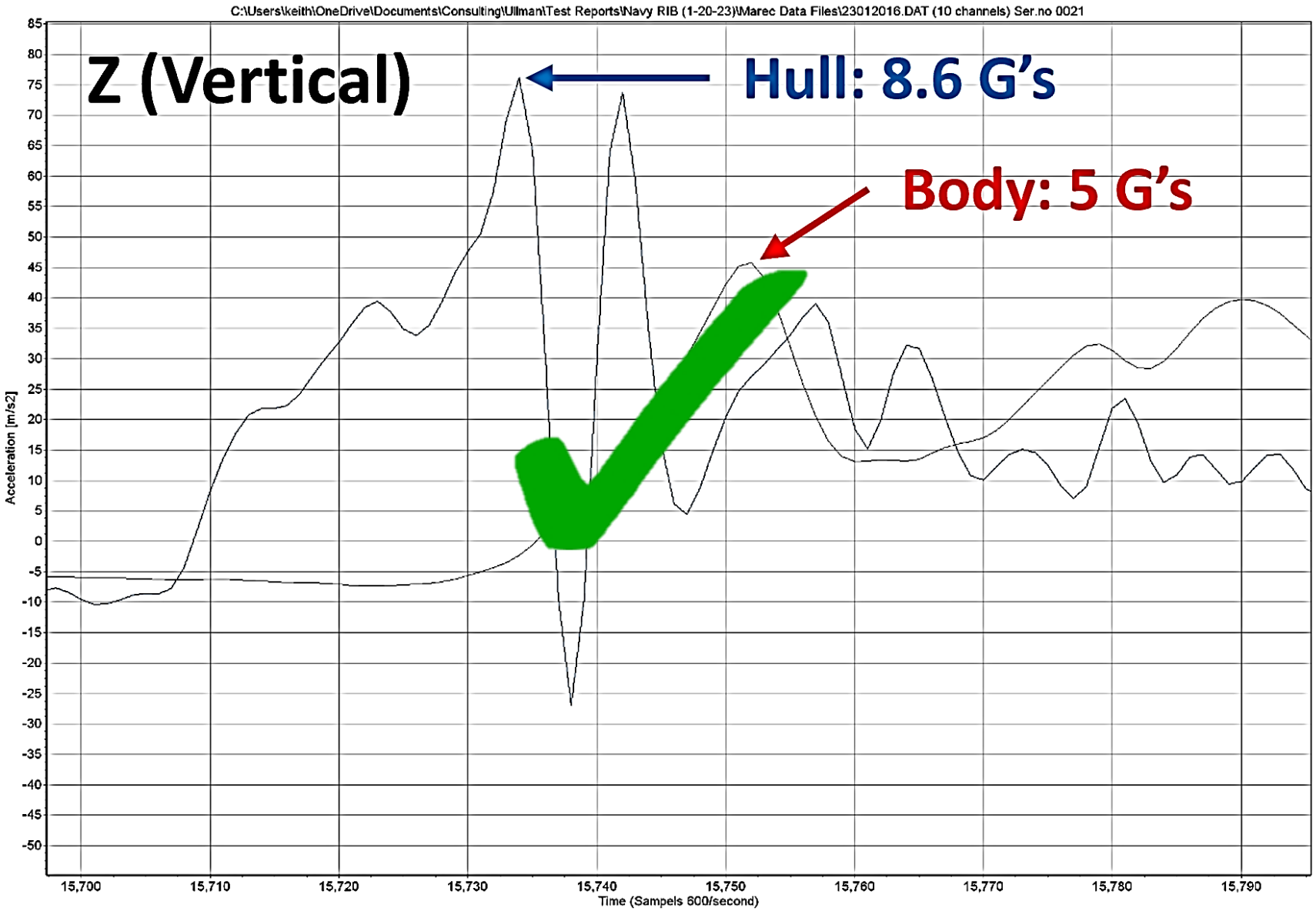
Vertical Direction (1m seas @ 35 knots)

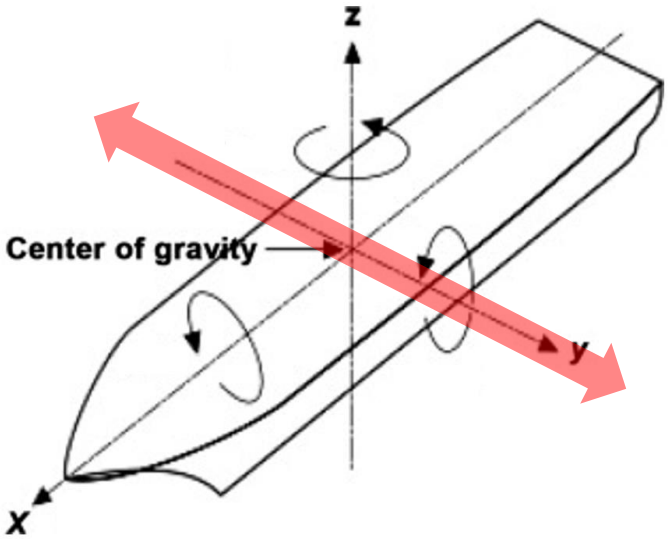


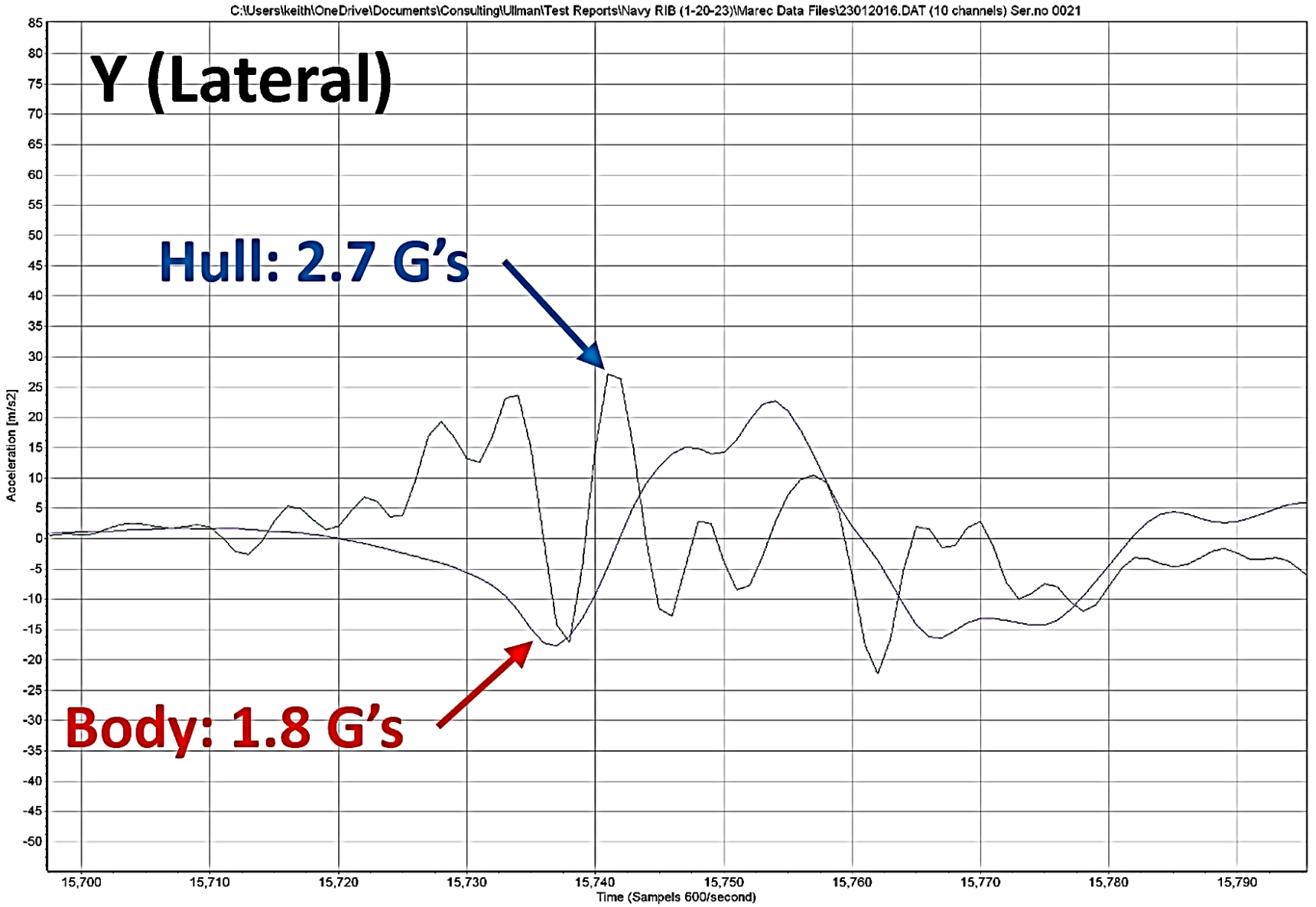
Reduction

≈ 40%

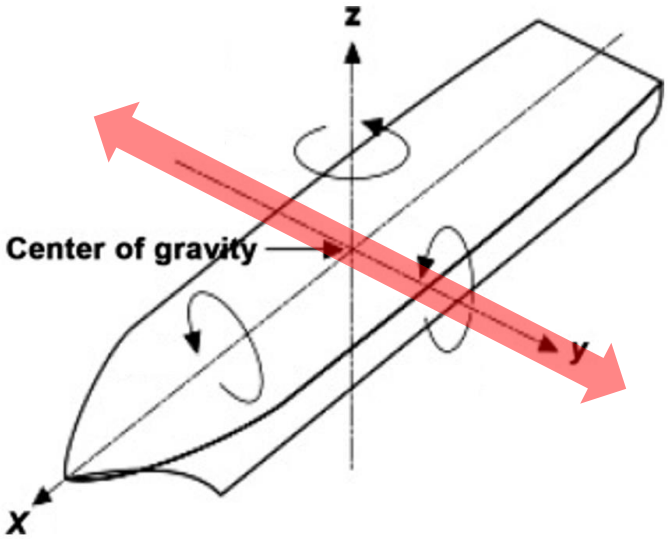


Lateral Direction (1m seas @ 35 knots)

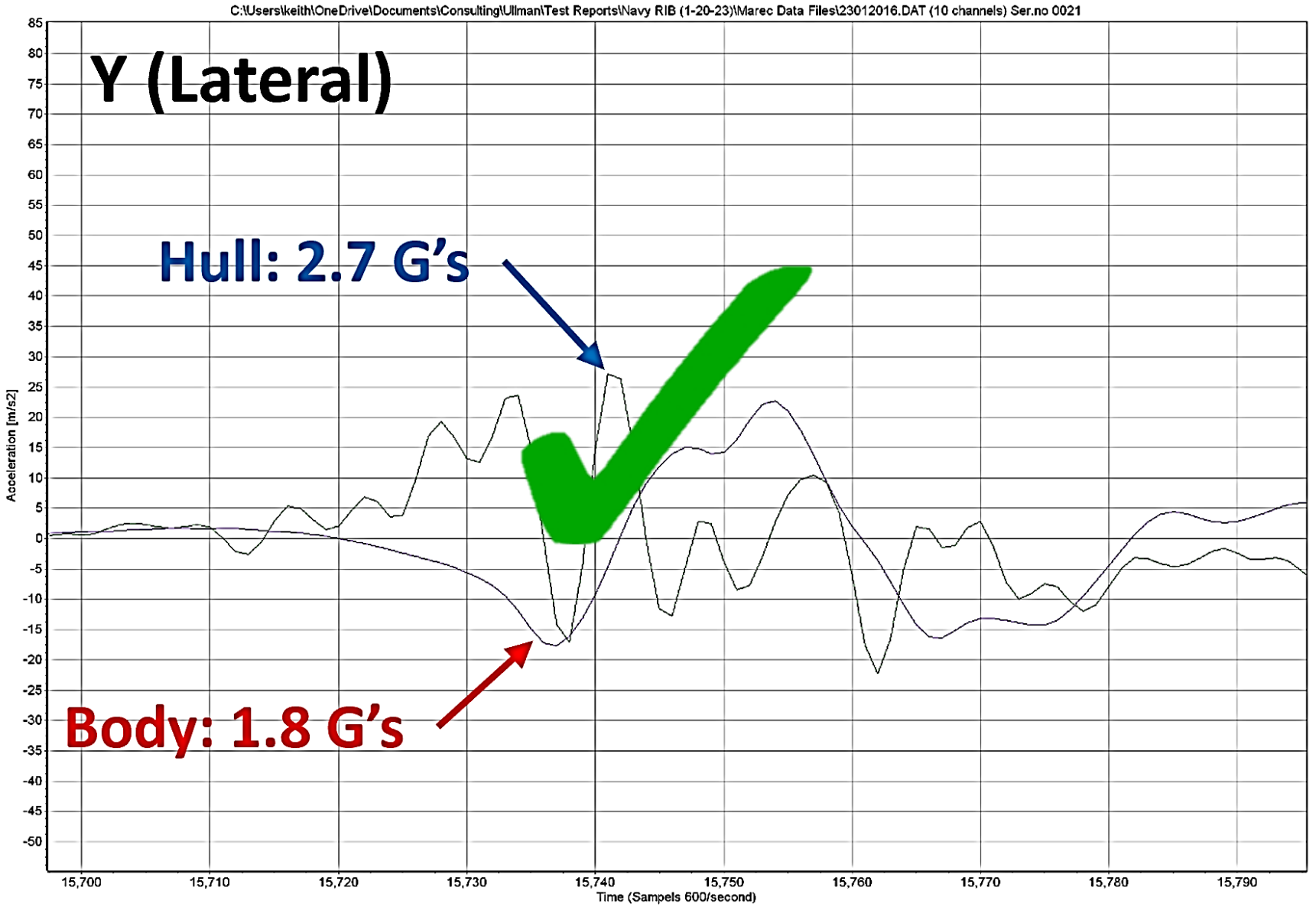




Lateral Direction (1m seas @ 35 knots)



Reduction ≈ 30%



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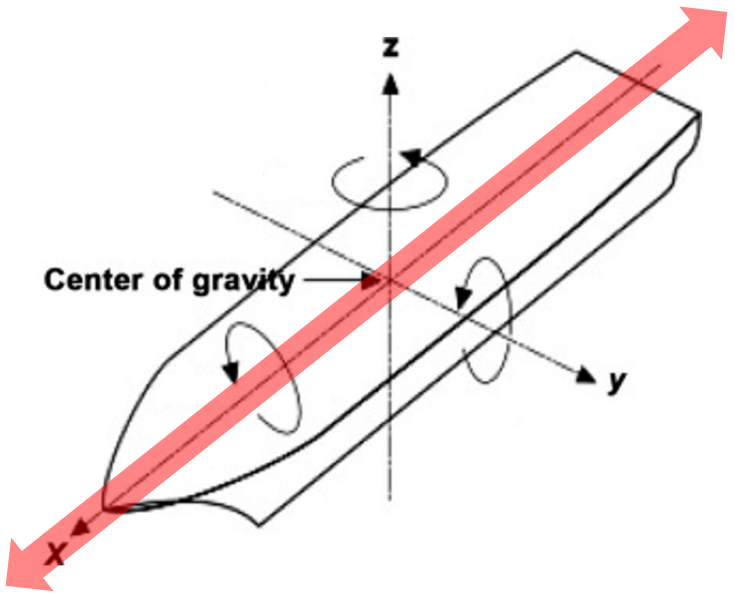
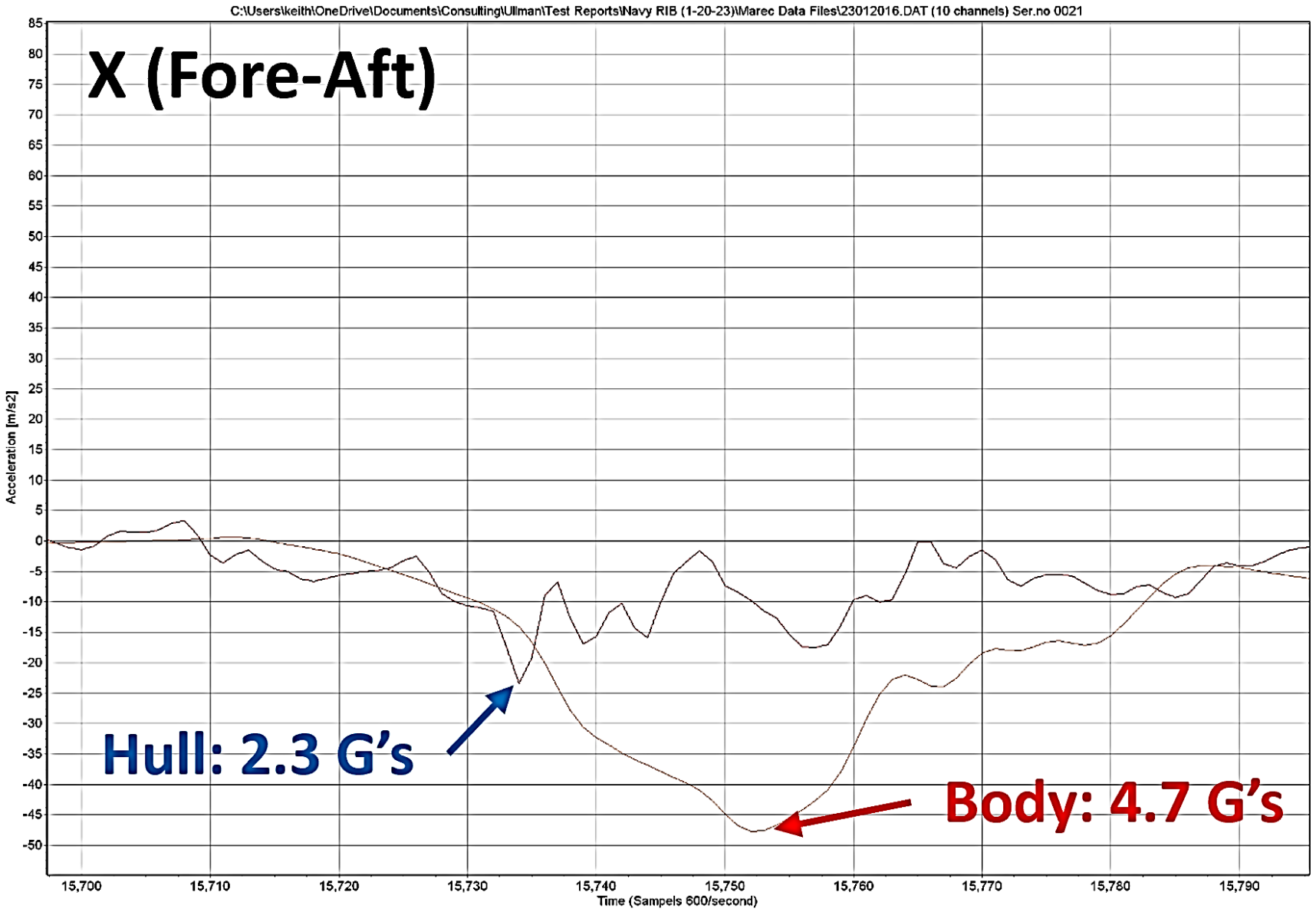
Fore-Aft Direction (1m seas @ 35 knots)





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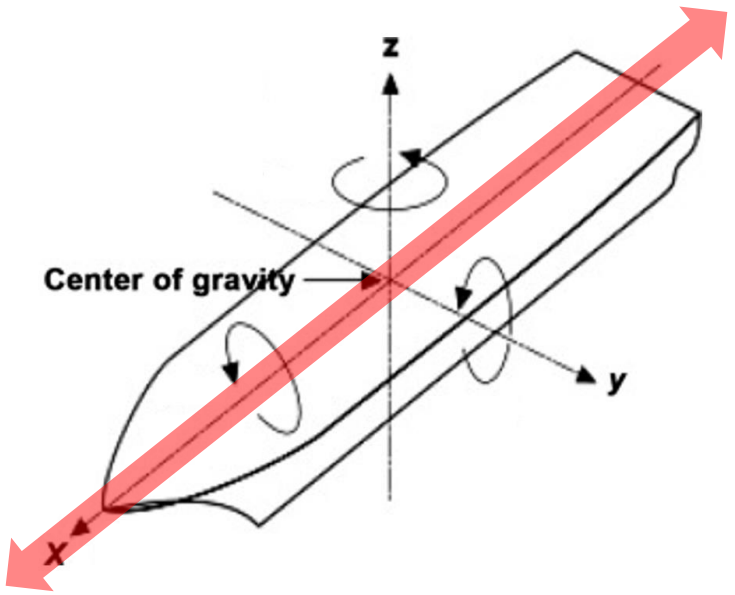
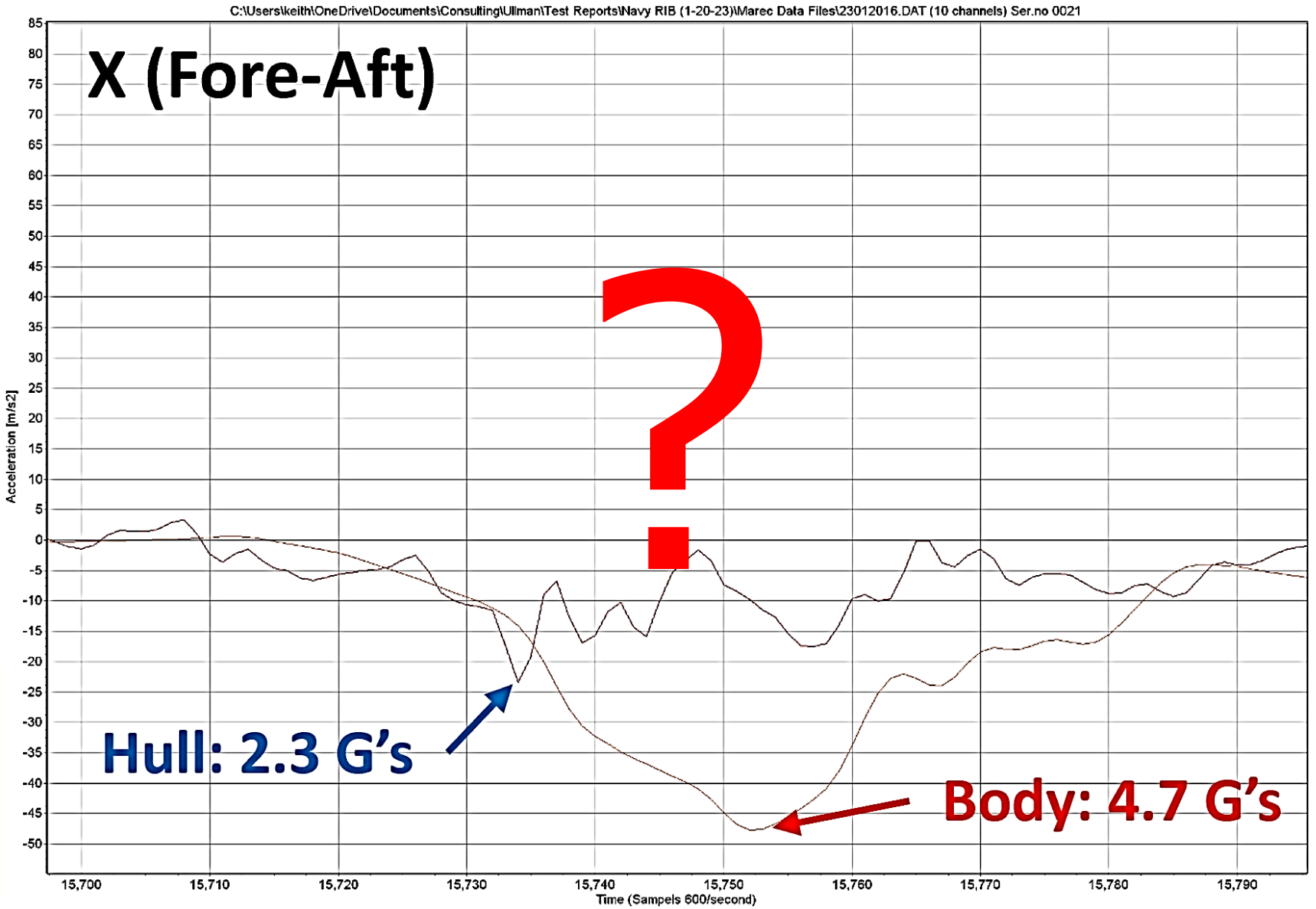
Fore-Aft Direction (1m seas @ 35 knots)



Magnification ≈ 2X



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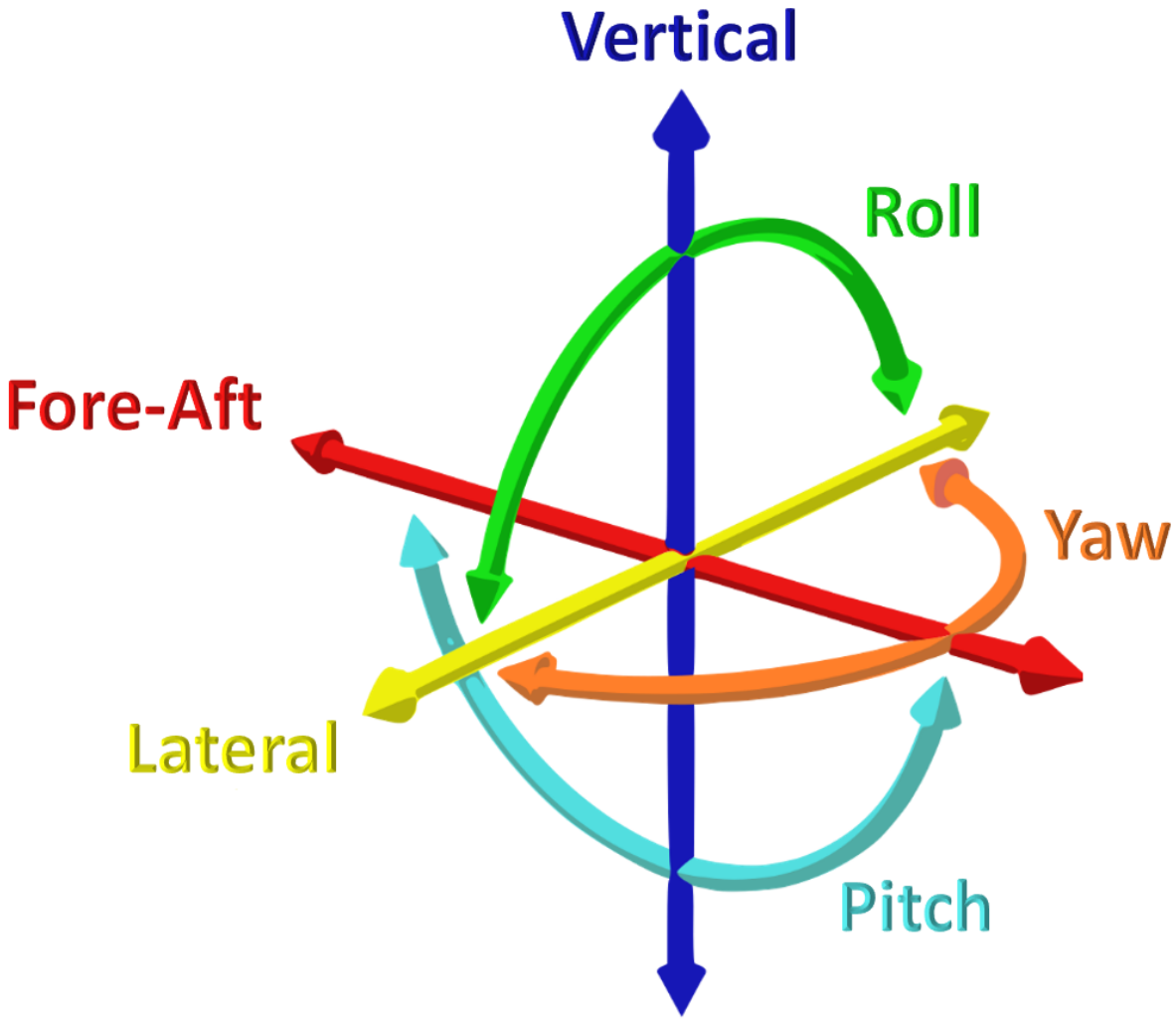
Need for More Information

- Waves produce stochastic or somewhat unpredictable forces.
- Seldom does anything move in pure planar motion
- **Therefore**, for more in depth analysis and design, we need to measure events in **6 Degrees of Freedom**

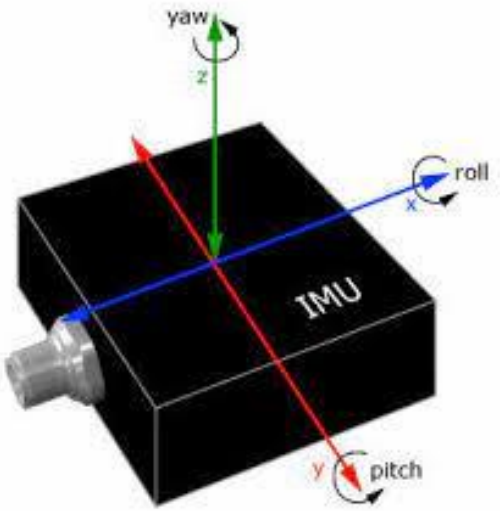


6 Degrees of Freedom

Inertial Measurement Unit (IMU)

Modern IMU's Can Wirelessly Measure:

- Accelerations (up 200 G's at 1,600Hz)
- Rotations, Position
- Temperature
- Humidity
- GPS Location
- Speed
- Electromyography (EMG)
- IP67 w/ 4+ Hours Run Time



Hull Performance

Side by Side Testing

Hull Performance – Side by Side Testing

Item	NAVY BOAT	RAFNAR BOAT
Manufacturer	USMI, Gulfport Mississippit	Rafnar, Reykjavik Iceland
Size (LOA, Beam)	11m, 3.2m	11m, 3.2m
Displacement	≈ 18,000 Lbs	≈ 9,000 Lbs
Hull Type	Deep-V (GRP)	Semi-Displacement & Deep-V (GRP)
Engines	(2) Inboard Diesel Engines, Water Jet	(2) Outboard Gasoline Engines
Picture		

Not a Perfect Apples to Apples Comparison

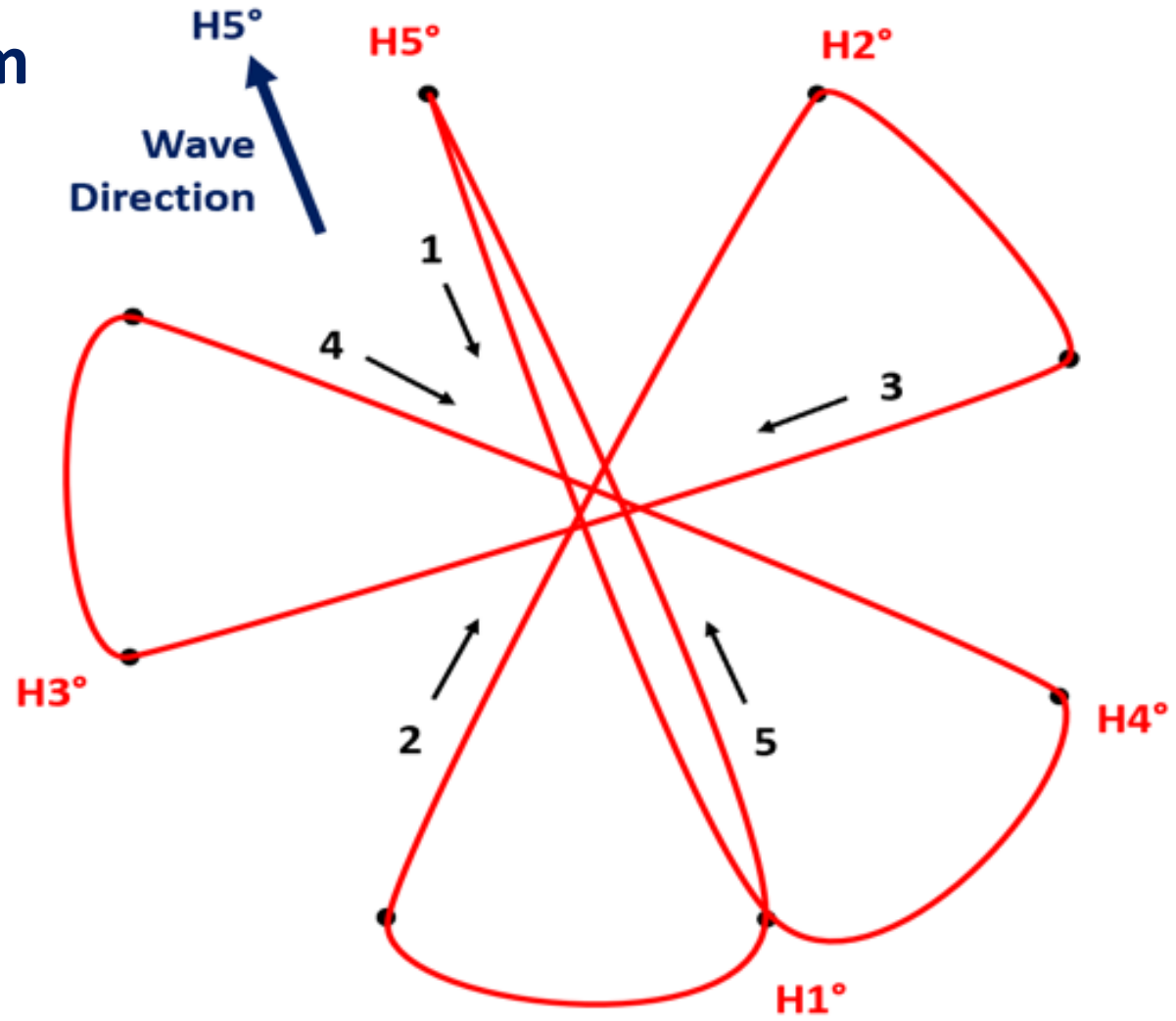
1. The **LCG** is unknown for the Navy Boat
2. Navy Boat is **2X** the Displacement of the Rafnar Boat
3. Rafnar Boat's IMU is **1m** Closer to Transom

The **Overall Advantage** is on the Side of the Navy Boat

Side by Side Test Pattern

- Both boats running **30 knots**, **same direction** at the **same time**

Waves ≈ 1m

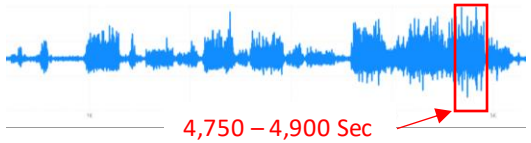


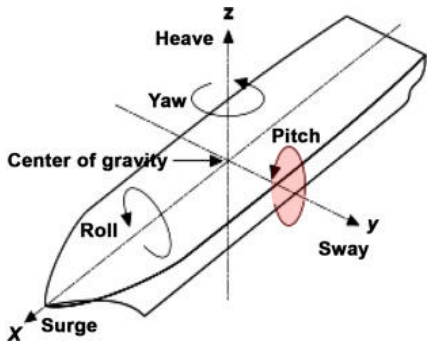
5 Ways to the Seas

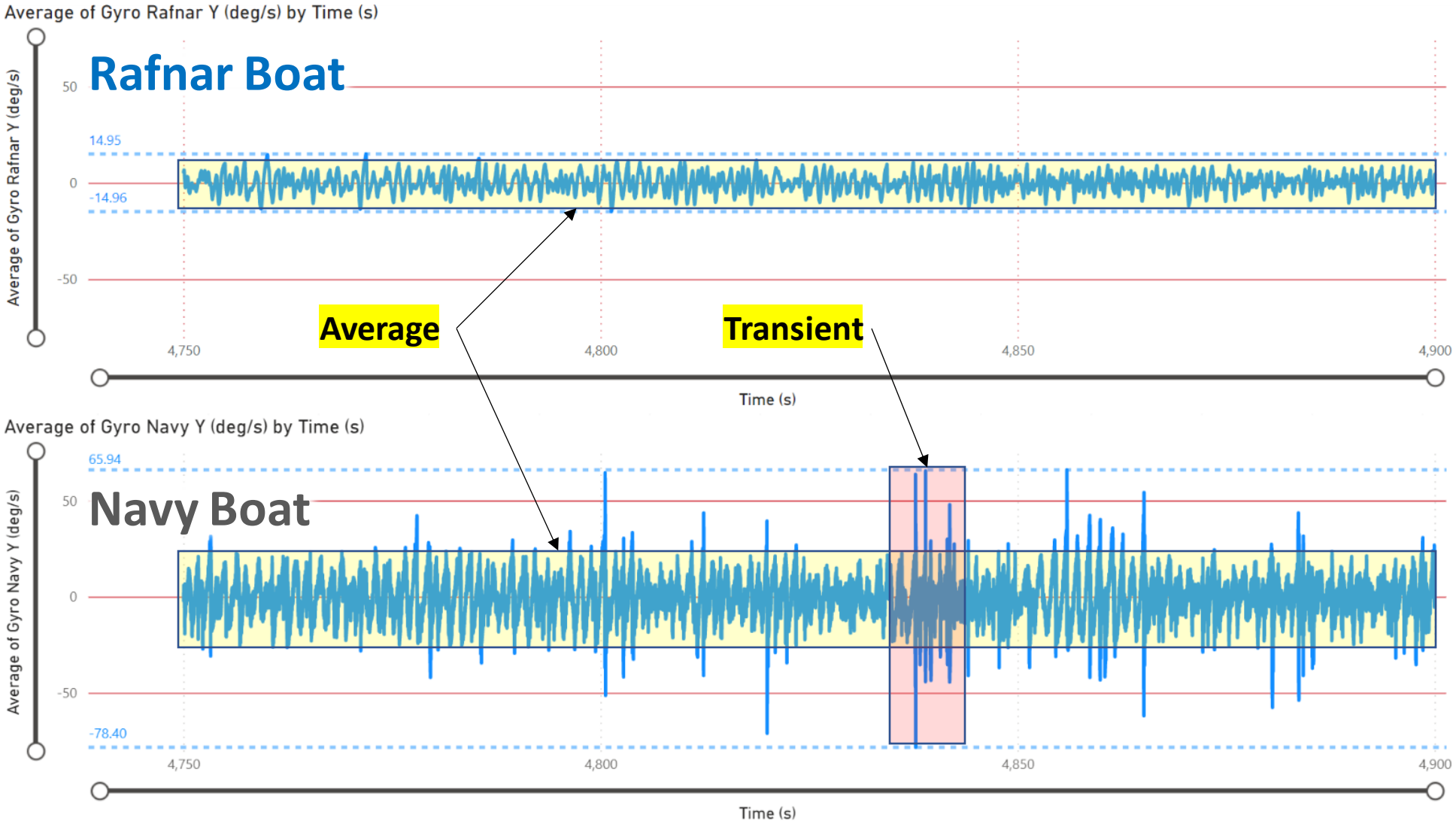
1. On the bow
2. On the starboard stern
3. On the port beam
4. On the starboard bow
5. Following Sea

Side by Side Data – How to Read the Chart

- X Axis = Time, Y Axis = Angular Velocity, Both Graphs at Equal Scale

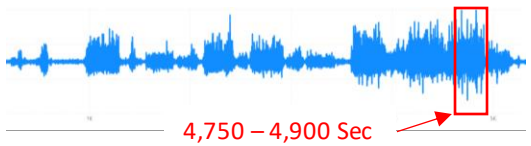


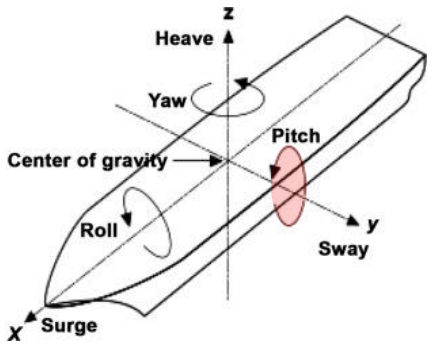


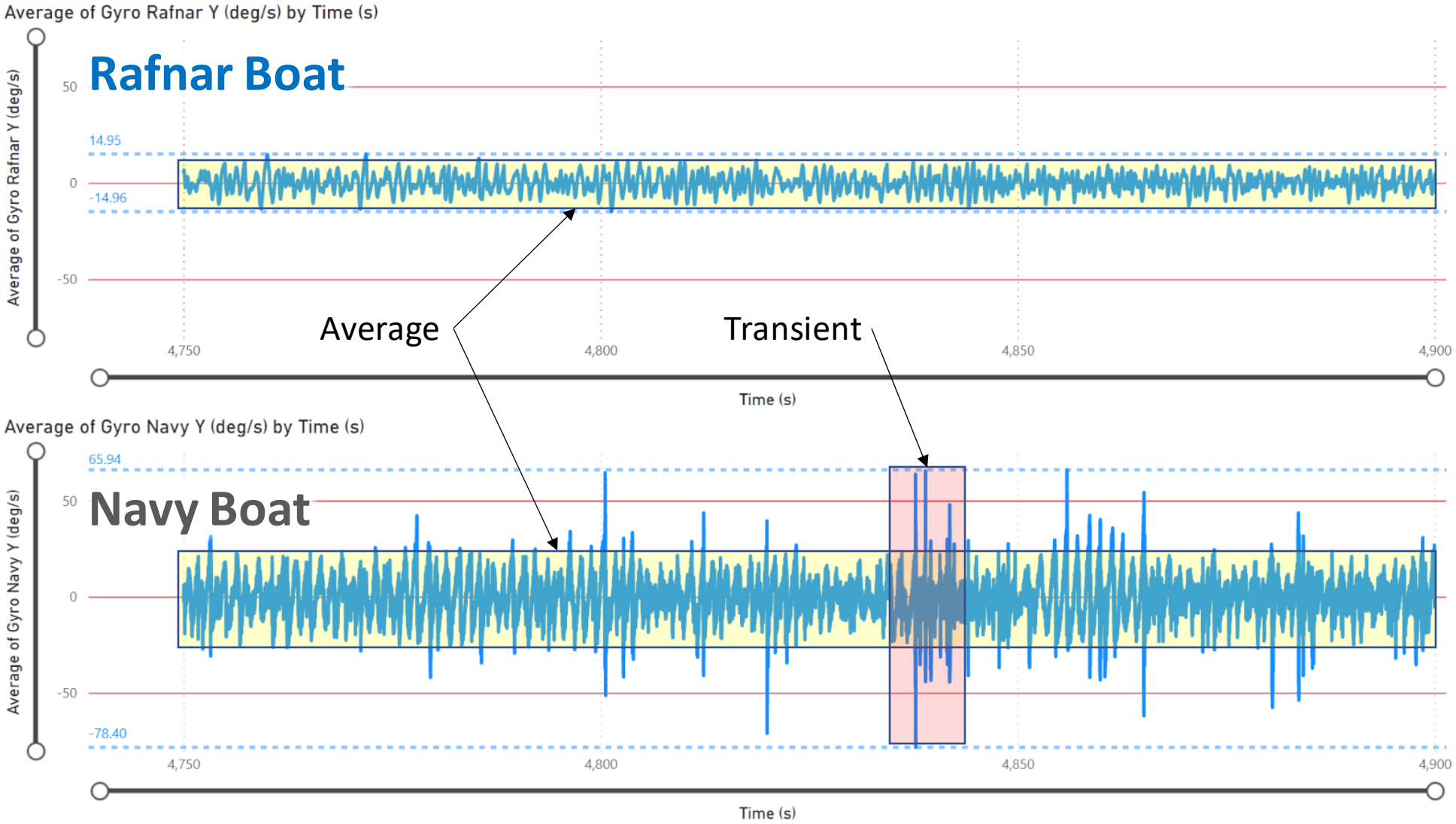


Angular Velocity – Pitch Direction (Degrees/s)

➢ **Navy Boat** experienced **2X** - **5.5X** greater <u>angular velocities</u> than the **Rafnar Boat**

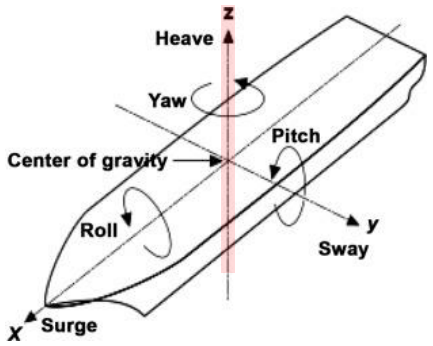


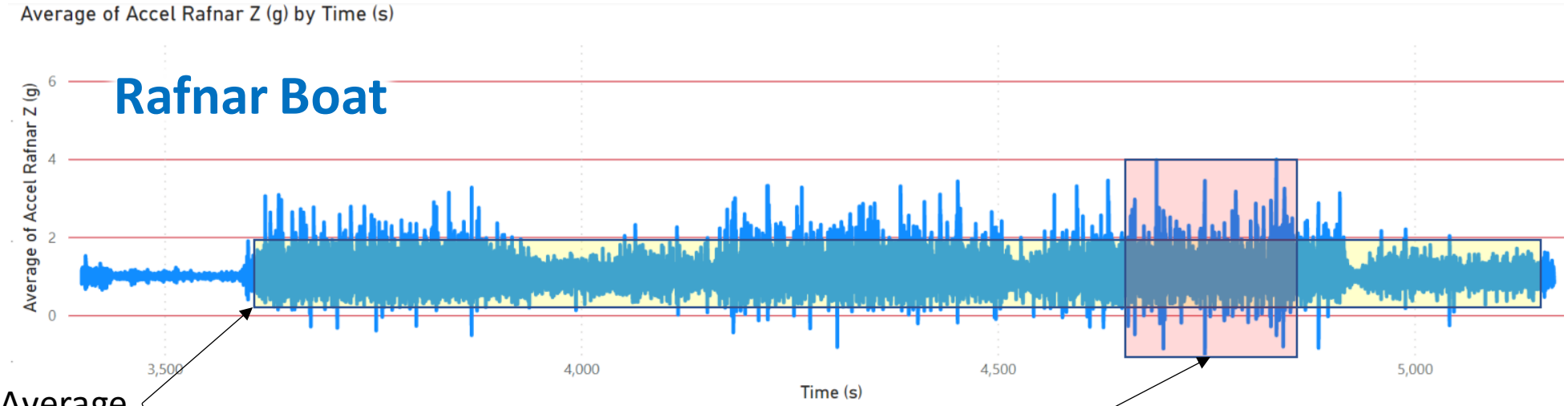




Vertical Acceleration, Z Direction (G's)

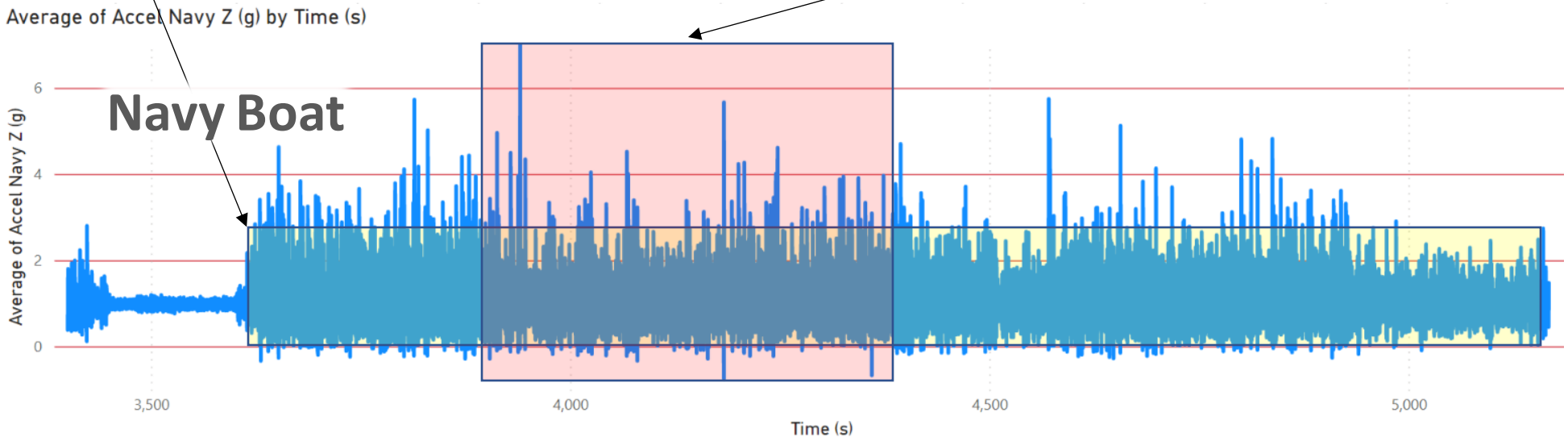
➢ **Navy Boat** experienced **1.7X** greater vertical accelerations than the **Rafnar Boat**





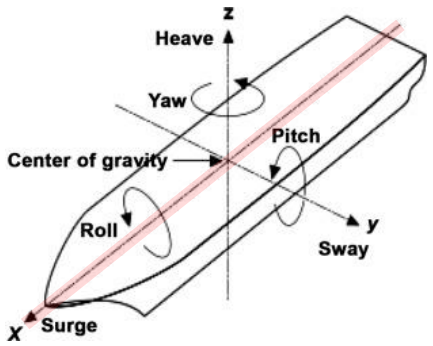
Average

Transient



Fore-Aft Acceleration, X Direction (G's)

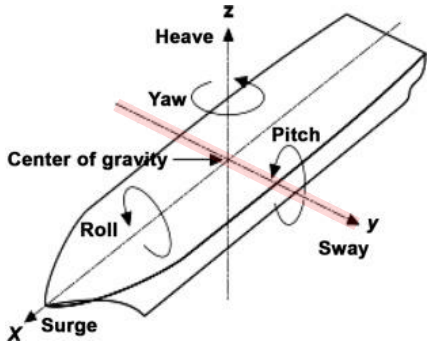
➢ **Navy Boat** experienced **2X** - **3.5X** greater <u>fore-aft accelerations</u> than the **Rafnar Boat**

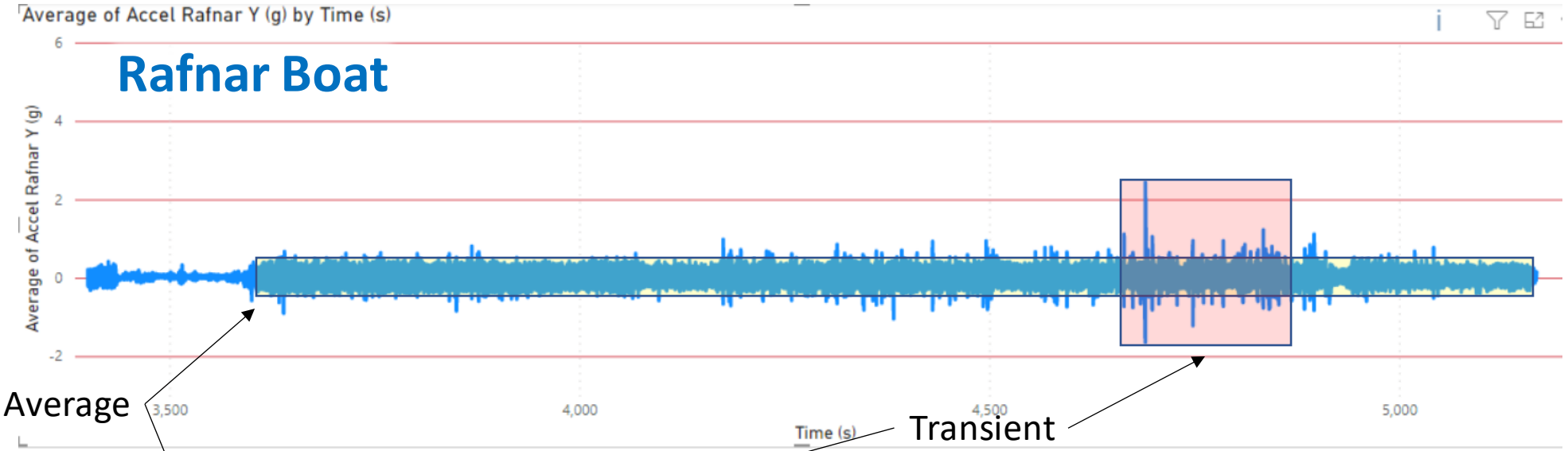


Lateral Acceleration, Y Direction (G's)

HighSpeedBoat OperationsForum

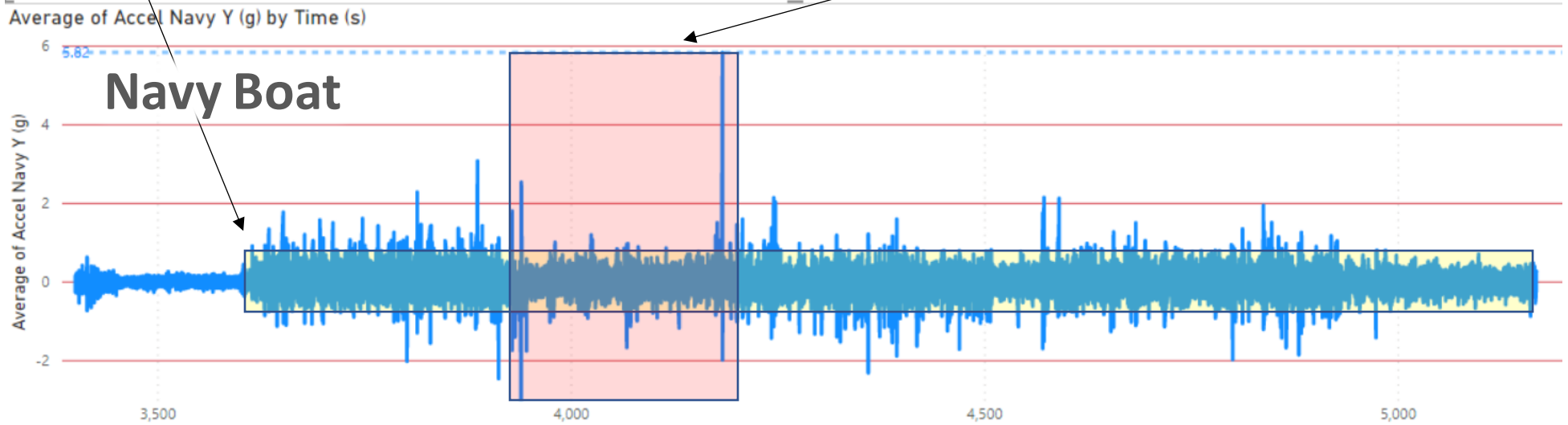
➢ **Navy Boat** experienced **1.6X – 2.1X** greater <u>lateral accelerations</u> than the **Rafnar Boat**





Average

Transient



Summary Slide (Normalized to one Another)

Boat	Navy Boat		Rafnar Boat	
				
Data Type	**Average**	**Transient**	**Average**	**Transient**
Angular Velocity (Pitch Direction)	**2.0X**	**5.5X**	1.0	1.0
Acceleration (Vertical)	**1.7X**	**1.7X**	1.0	1.0
Acceleration (Fore-Aft)	**2.0X**	**3.5X**	1.0	1.0
Acceleration (Lateral)	**1.6X**	**2.1X**	1.0	1.0
Rotation (Pitch Direction)	**1.5X**	**1.5X**	1.0	1.0
Rotation (Roll Direction)	**1.5X**	**1.5X**	1.0	1.0

Dynamic Digital Twin

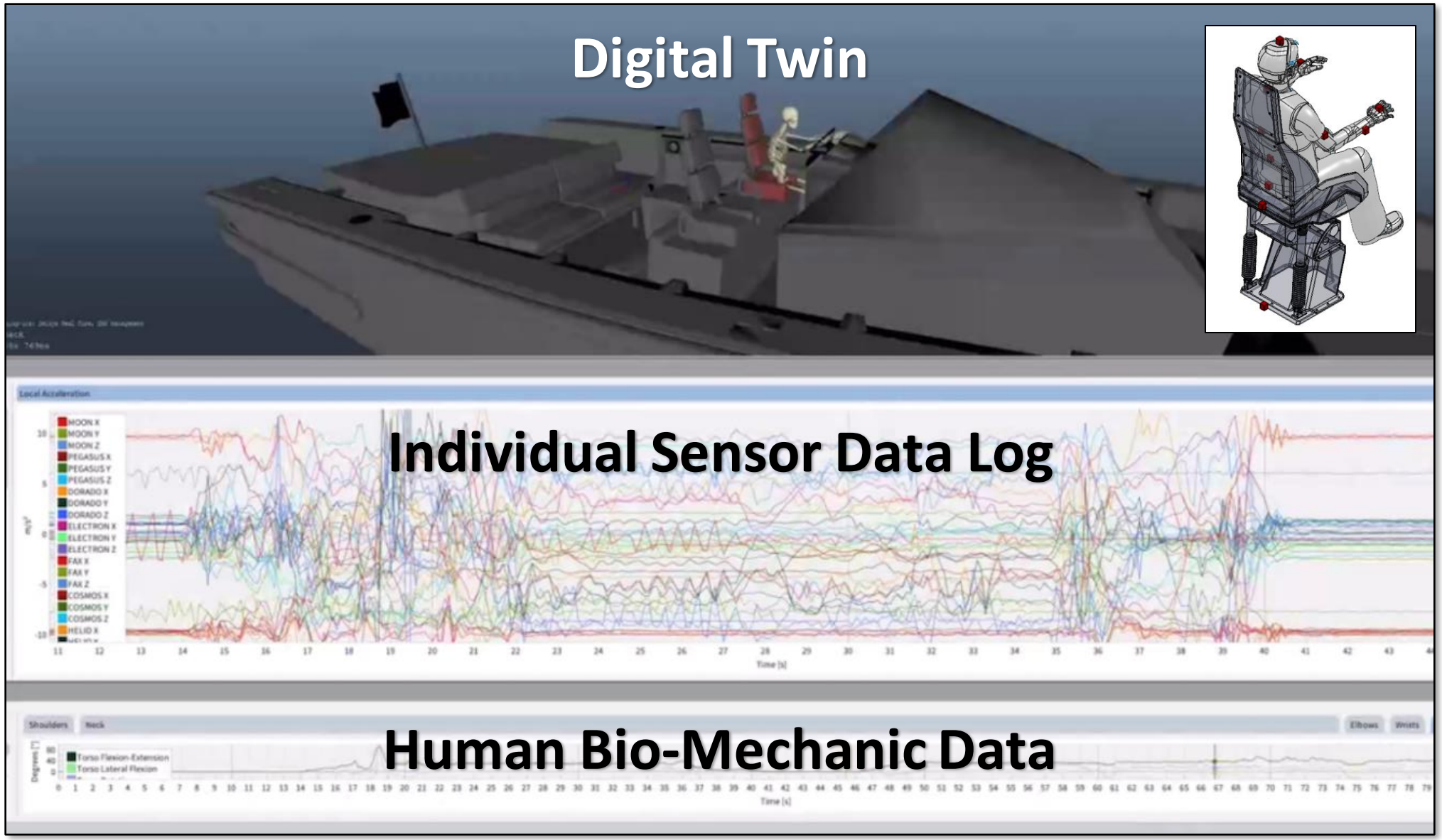
Using (13) IMU’s

Overview of the Dynamic Digital Twin *(Beta Release)*

HighSpeedBoat OperationsForum

3D animation showing both **real time** and **recorded playback** of all modeled elements within the test protocol.

Up to (18) IMU's each recording **acceleration, rotation, and angular velocity** for the boat, and every major portion of the human skeletal systems.



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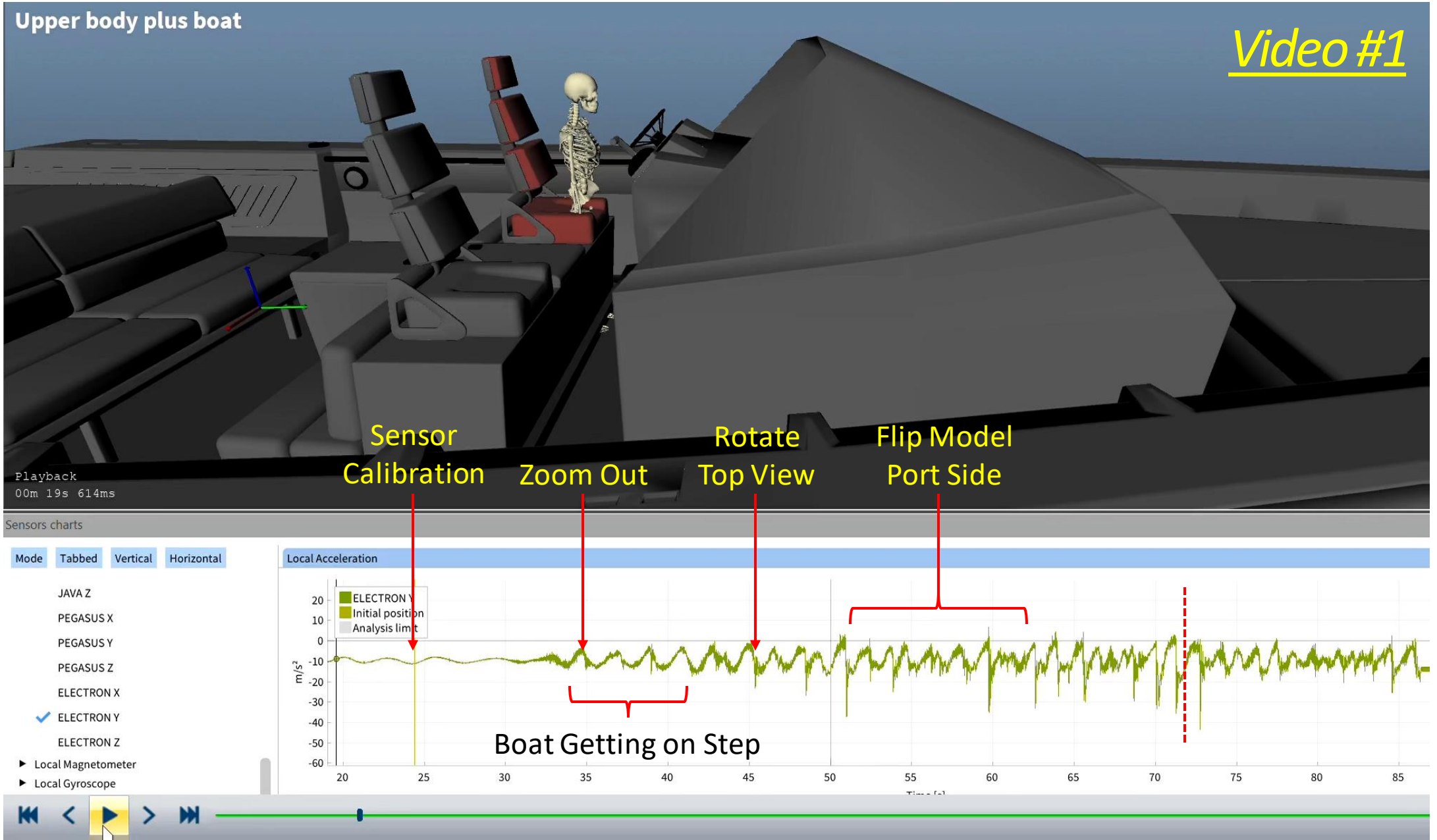
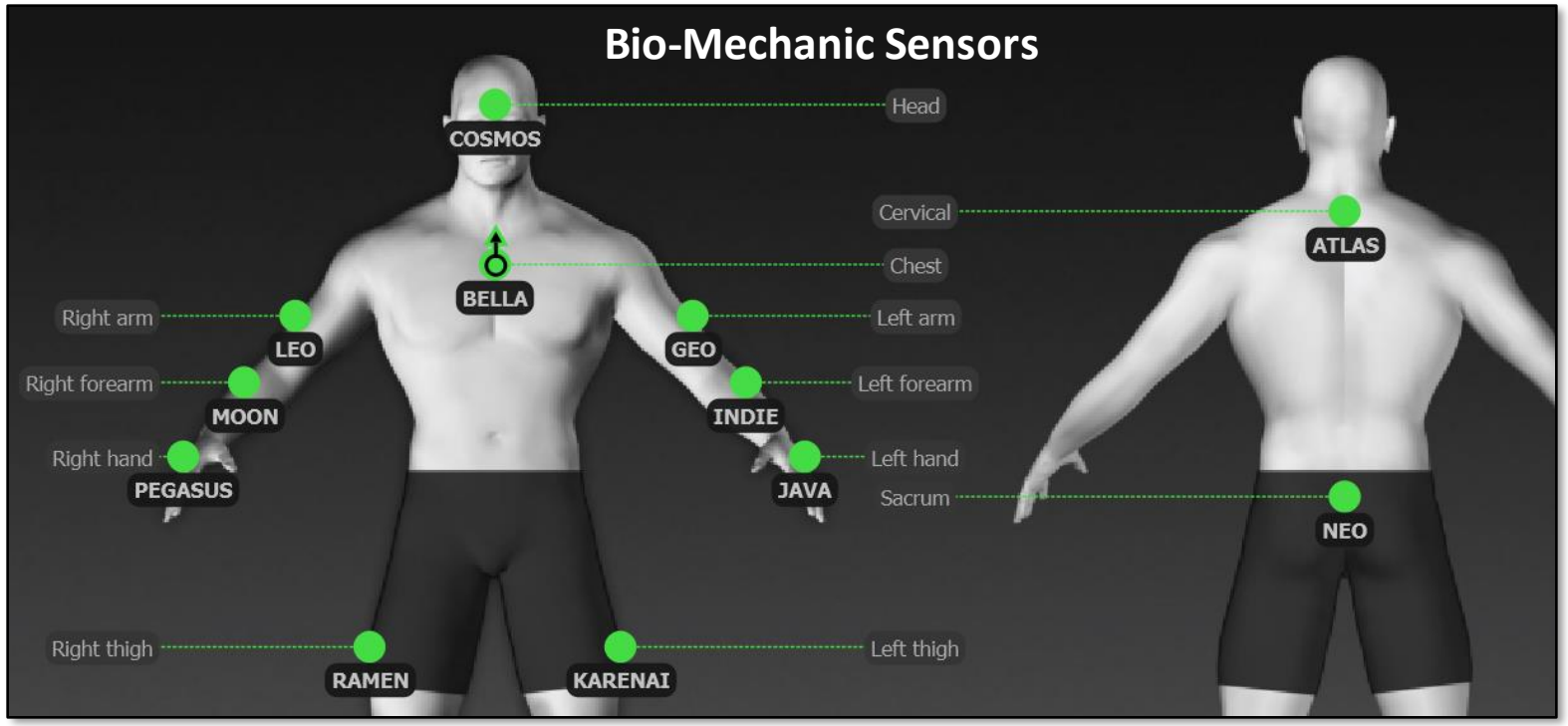
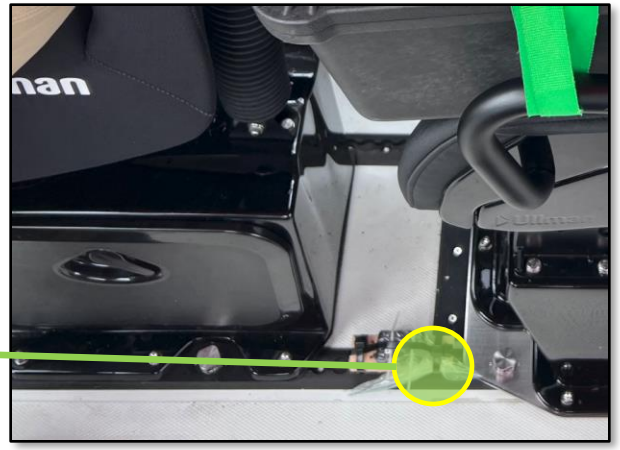
Sea Trials Performed at Trident Spectre (May 23rd, 2023)



Building a Digital Twin - Replicating Boat & Body



- (12) IMU's on the Body
- (1) IMU on the Hull



Hull Sensor

Mounted to Deck Track

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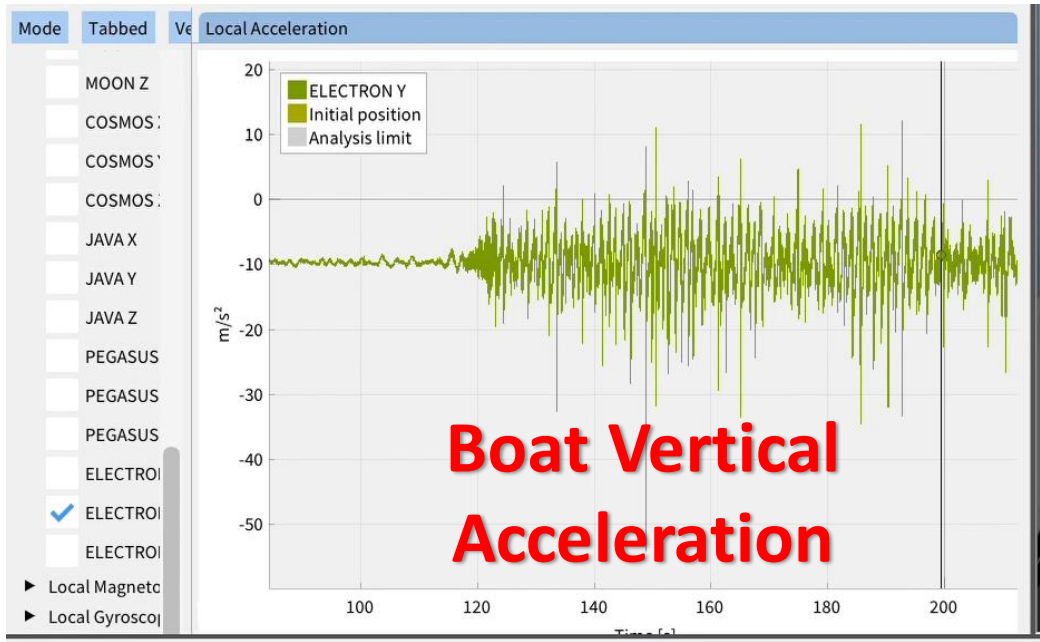
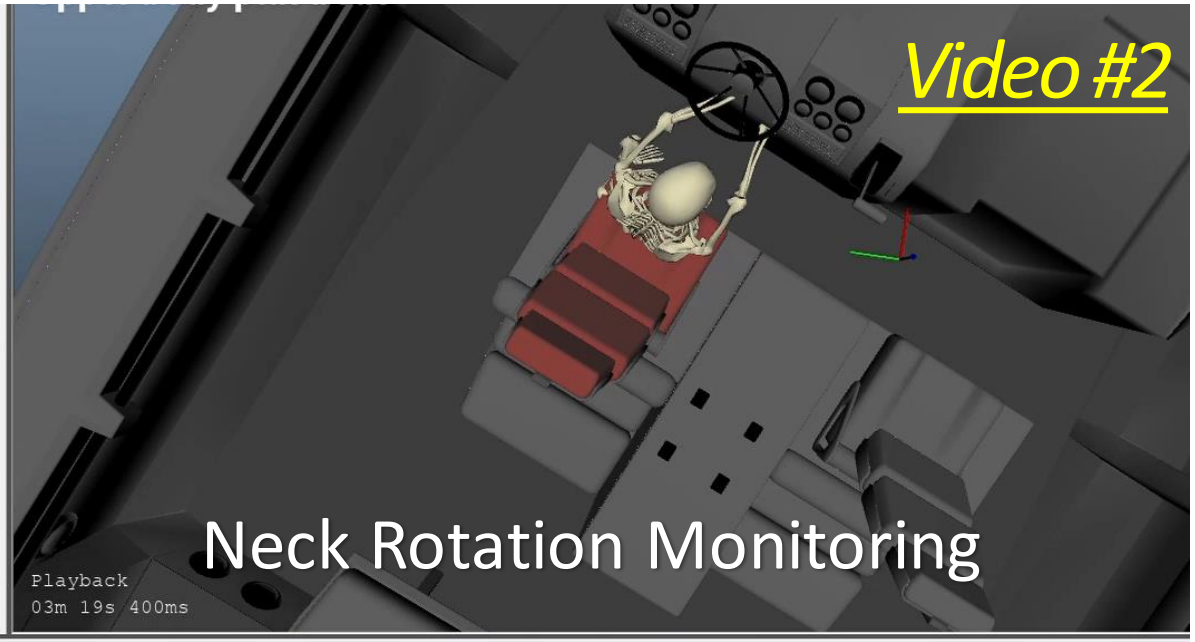
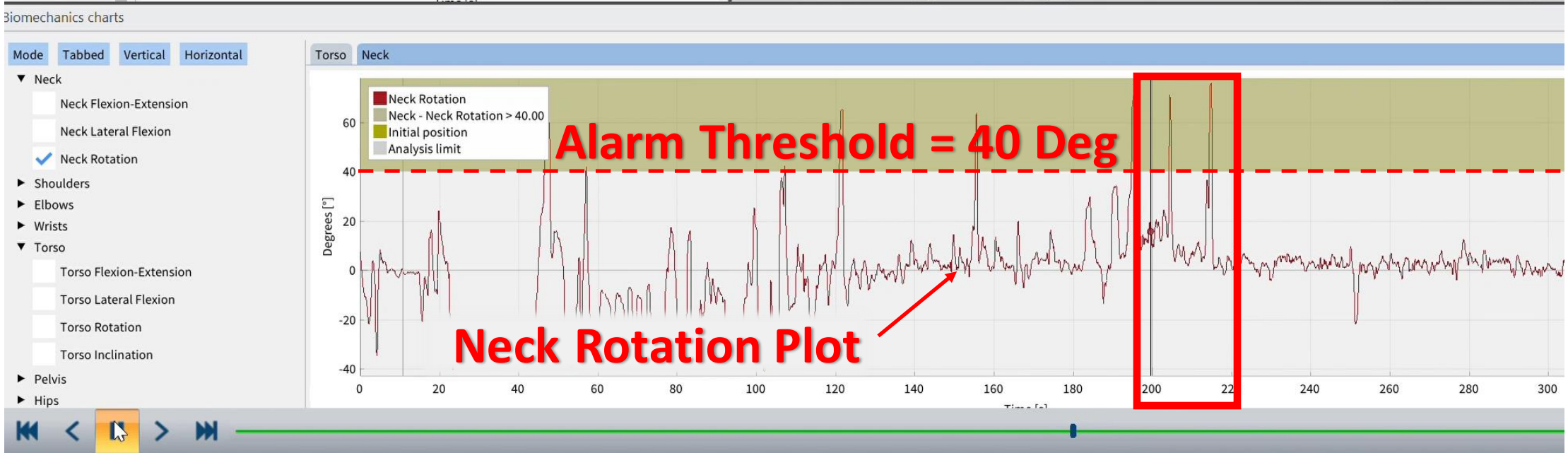
Real Time Bio-Feedback, Alarm / Event Triger





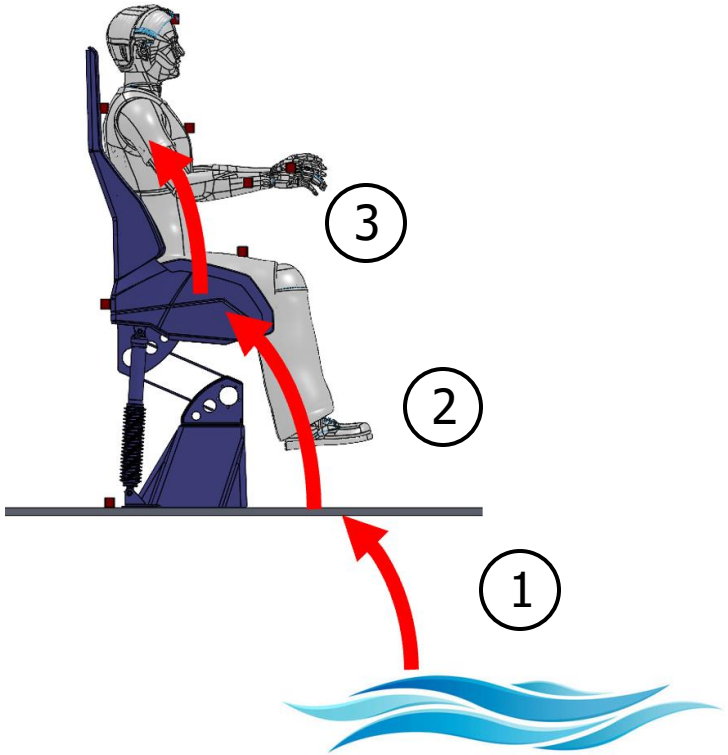


Dynamic Digital Twin

Future Development

Digital Twin (Future Development)

- Add Seat's Dynamic Response



Wave Impulse Movement:

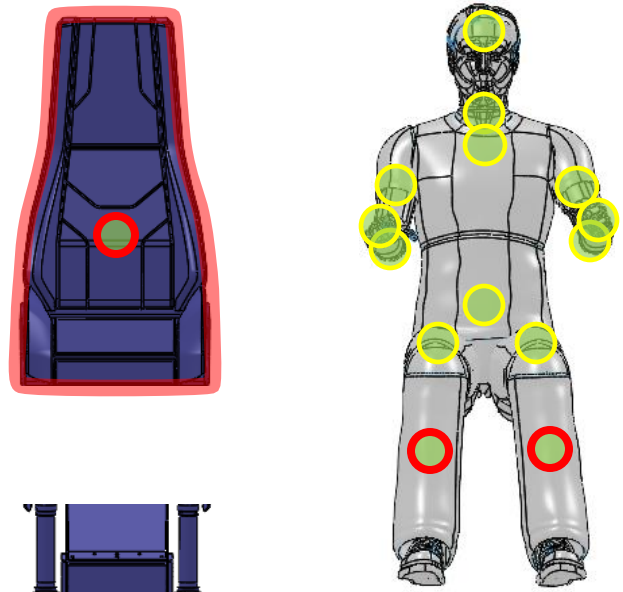
1. Wave to Boat
2. Boat to Seat
3. Seat to Body

Body

(14) Point Bio-Mechanic Model

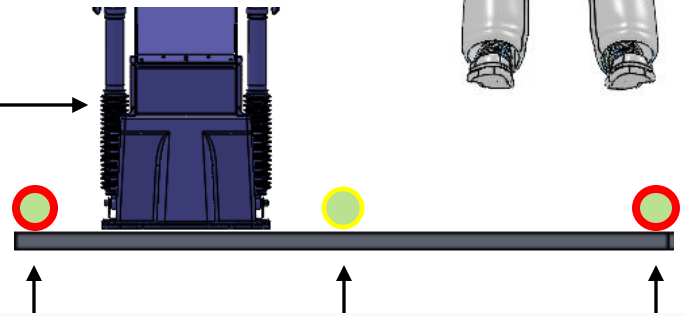
Seat Top

Rigid Body 6DoF



Boat & Seat Base

Rigid Body 6DoF



Tri-Axial Accelerations — Bow — Midship — Stern

Add (5) Sensors

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What are the **Use Cases** for this Technology

1. **Hull Performance** – There are a wide variety of use cases including:
    1. CFD Verification
    2. Measure Bow Rise Over the Entire Speed Range
    3. Roll & Pitch Stability
    4. Wave Impact Exposure Characterization
    5. Side by Side Testing & Down Selection
    6. Trim Tab Performance & Optimization
2. **Human Systems Design/Ergonomics** – Used in the testing of new human systems and interfaces designed to mitigate impact exposure.
3. **Operator Training** – Real time operator training showing users what "RIGHT" posture looks and feels like with live bio-feedback.
4. **Safe Boat Operations** – Tying real time bio-feedback to boat safety operations like kill switch and/or throttles

QUESTIONS?

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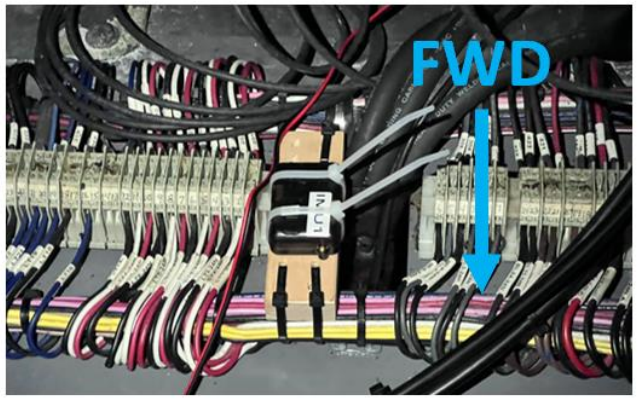
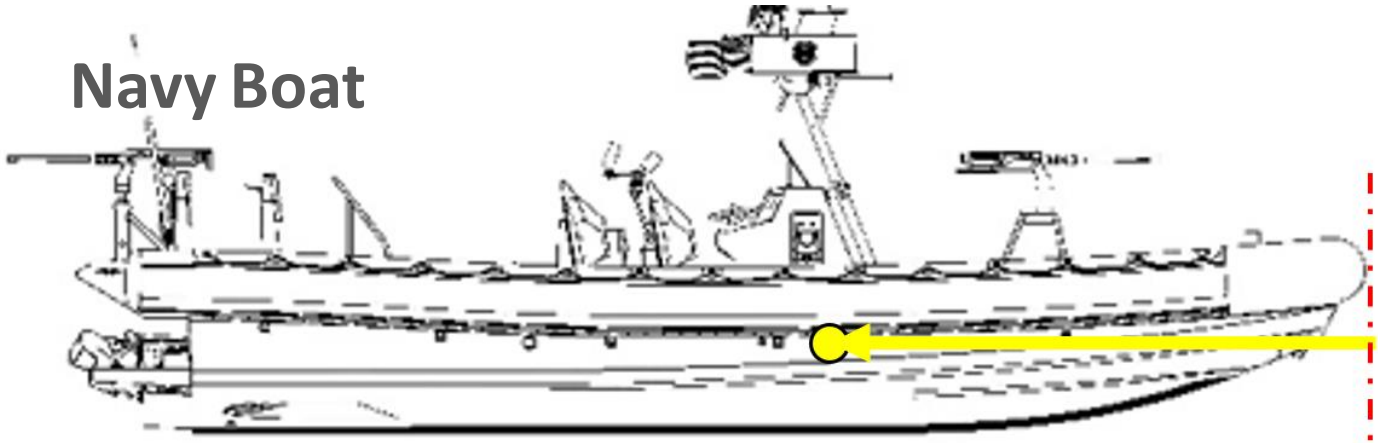
Backup Slides

IMU Location *(1m Difference Between the Boats)*



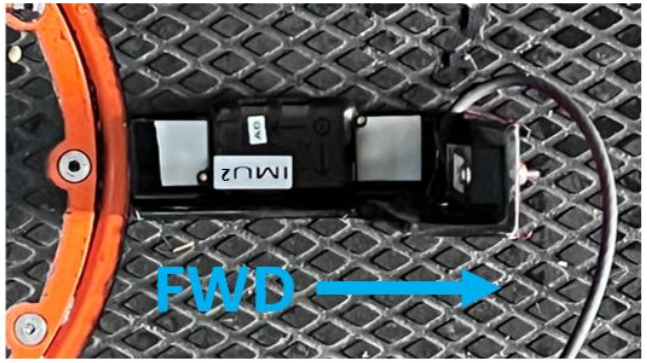
Navy Boat

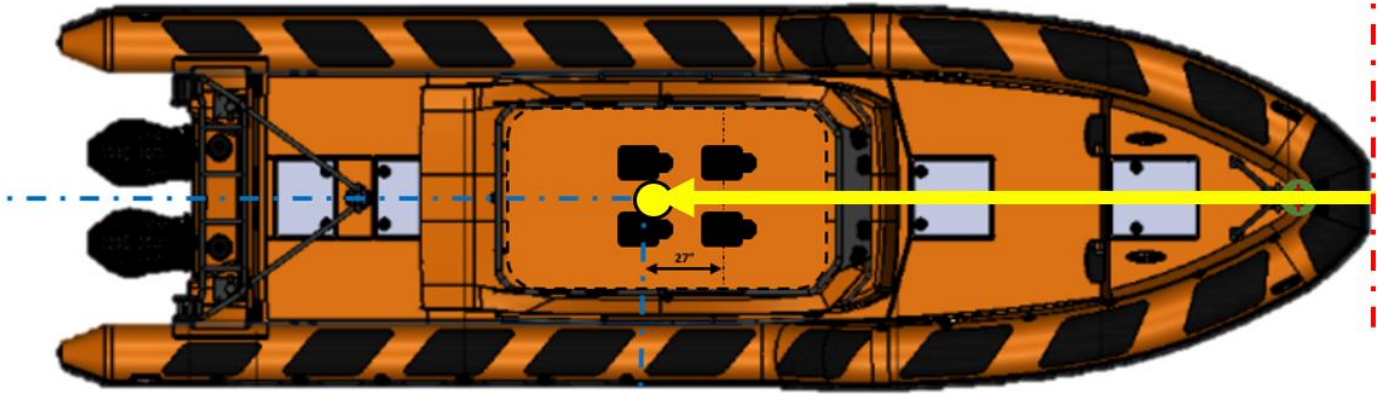


≈ 5m

IMU #1

Rafnar Boat





≈ 6m

IMU #2

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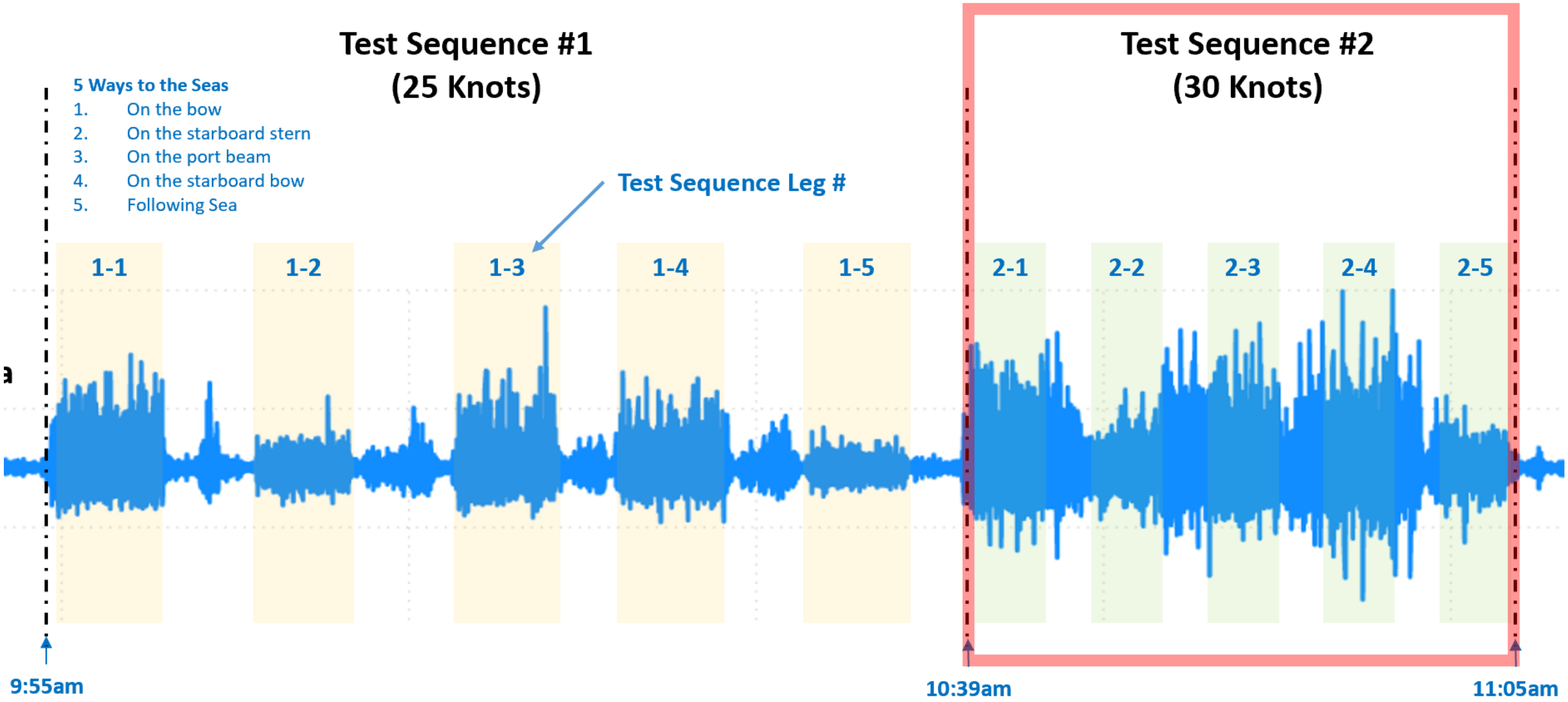
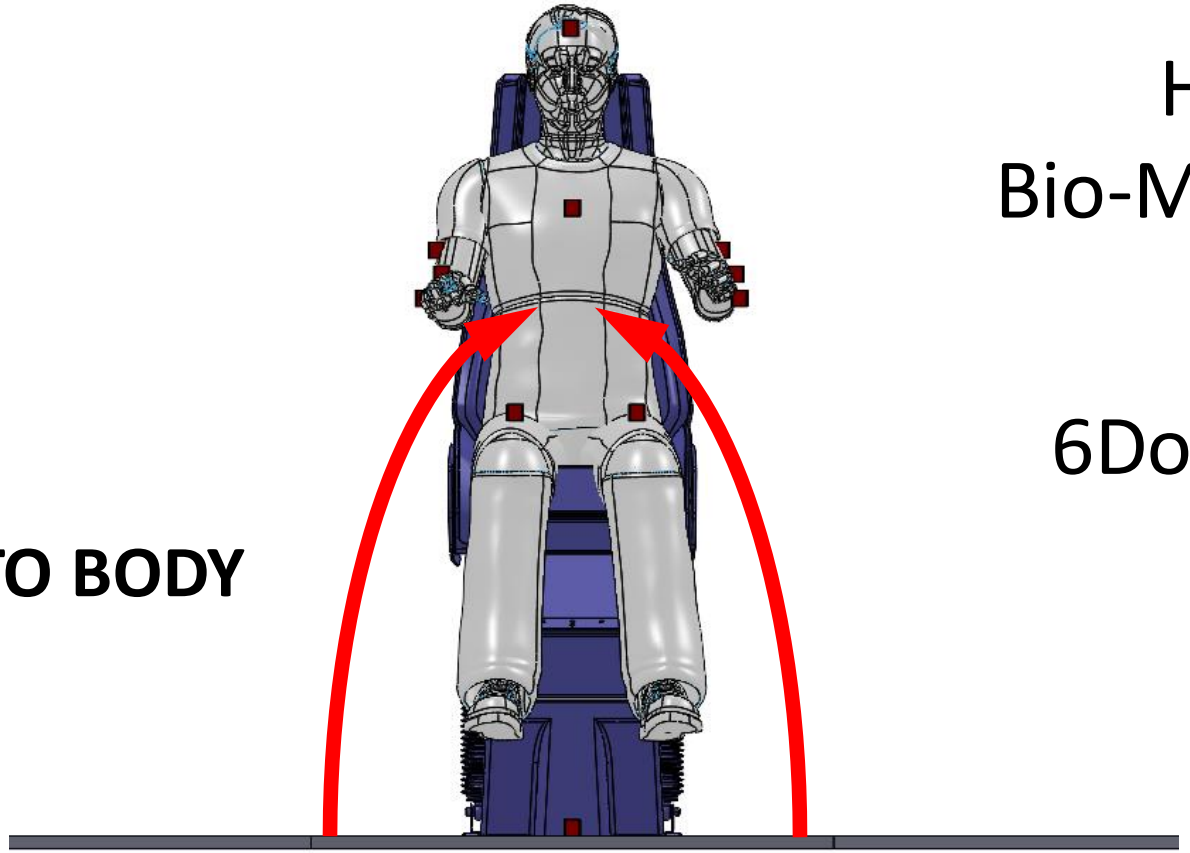
Test Sequences (IMU Accel-Z Data)



Wave to Boat, Boat to Body or WB^3 Analysis

- Currently in Beta Release



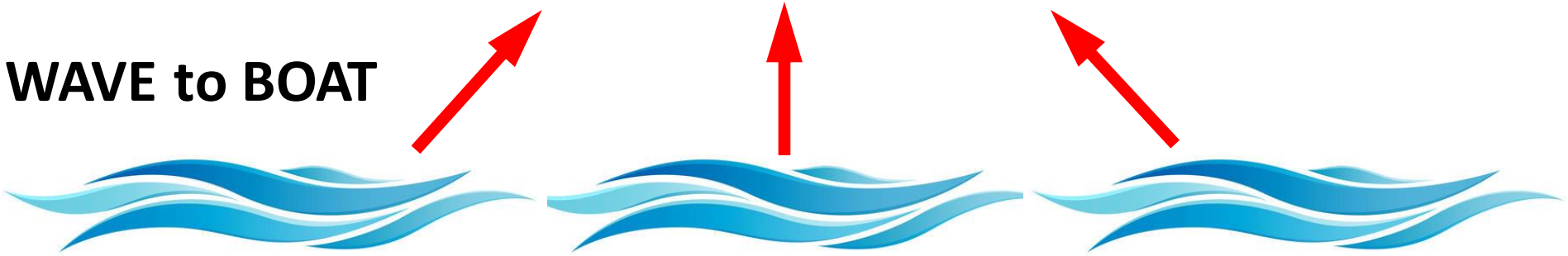
Human Body
Bio-Mechanic Analysis

+

6DoF Boat Analysis

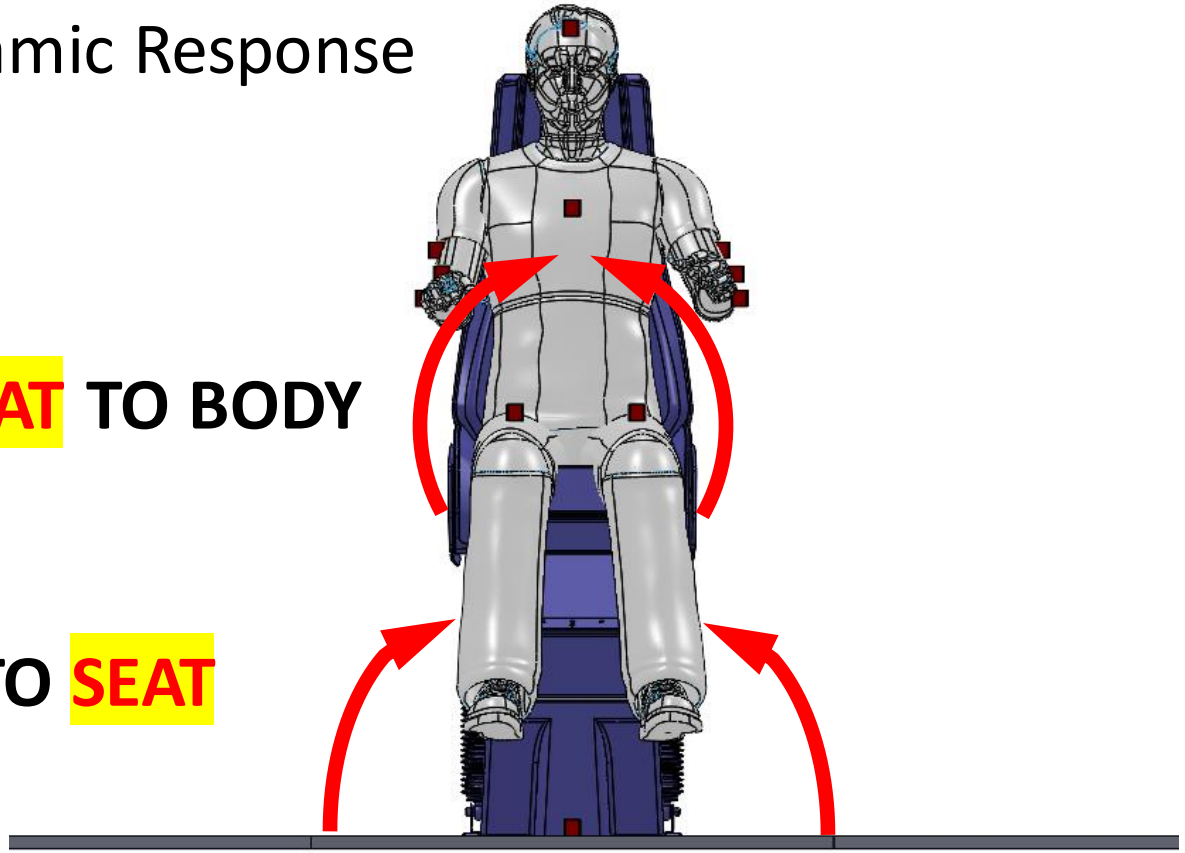
2. BOAT TO BODY

1. WAVE to BOAT



Digital Twin Analysis Tool (Future Development)

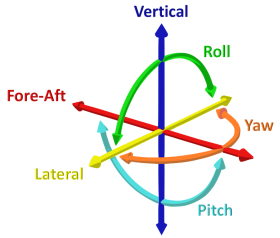
- Add the Seat's Dynamic Response

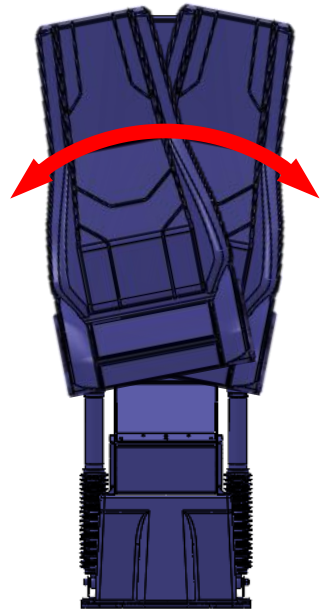


3. SEAT TO BODY

2. BOAT TO SEAT

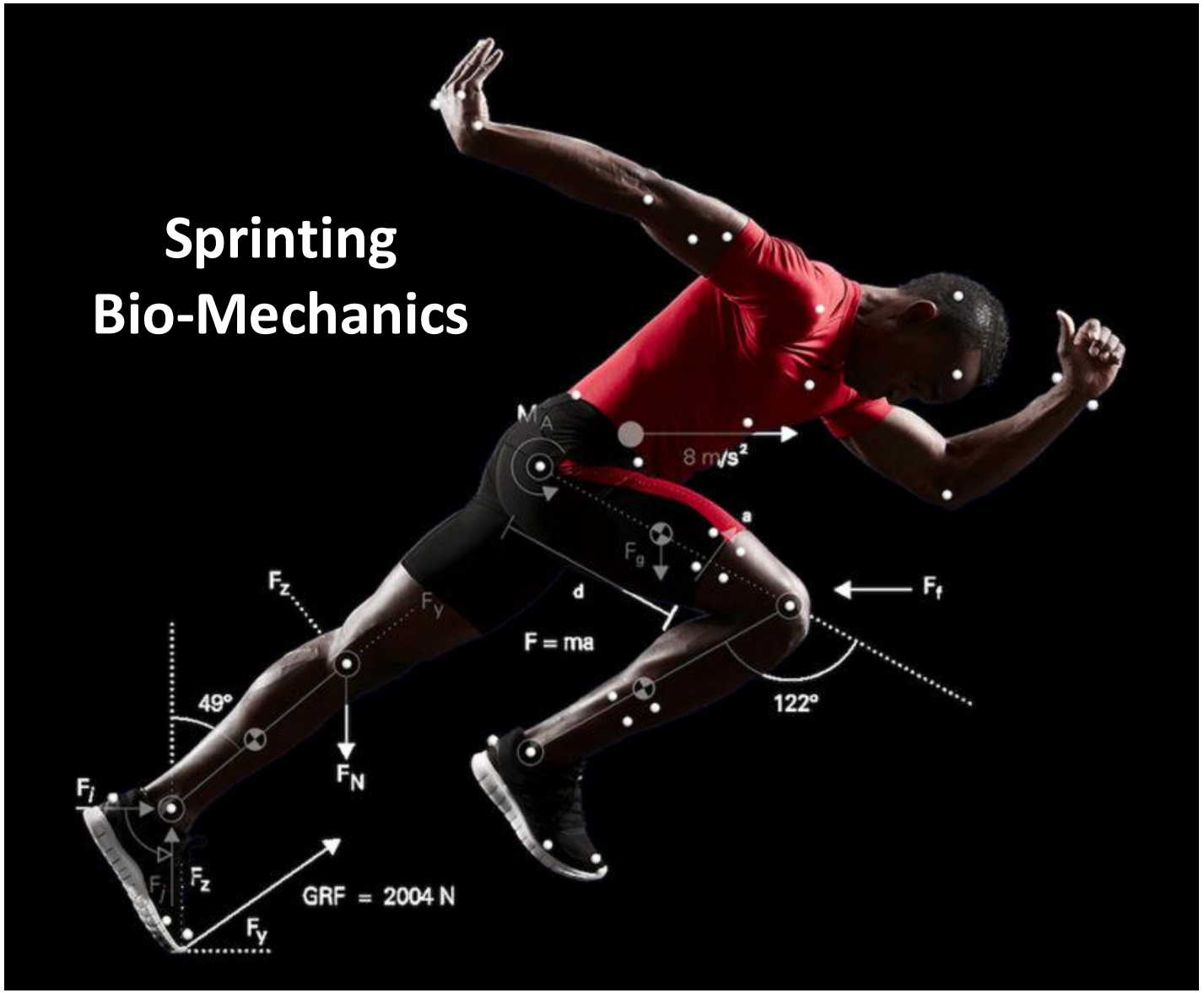
1. WAVE to BOAT





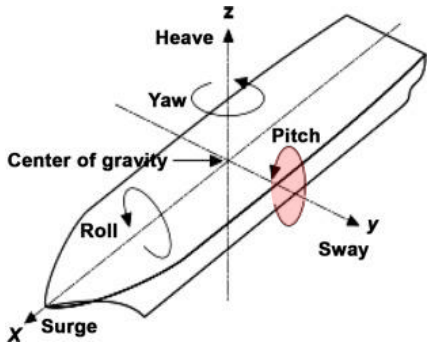
Bio-Mechanic Analysis, What is it?

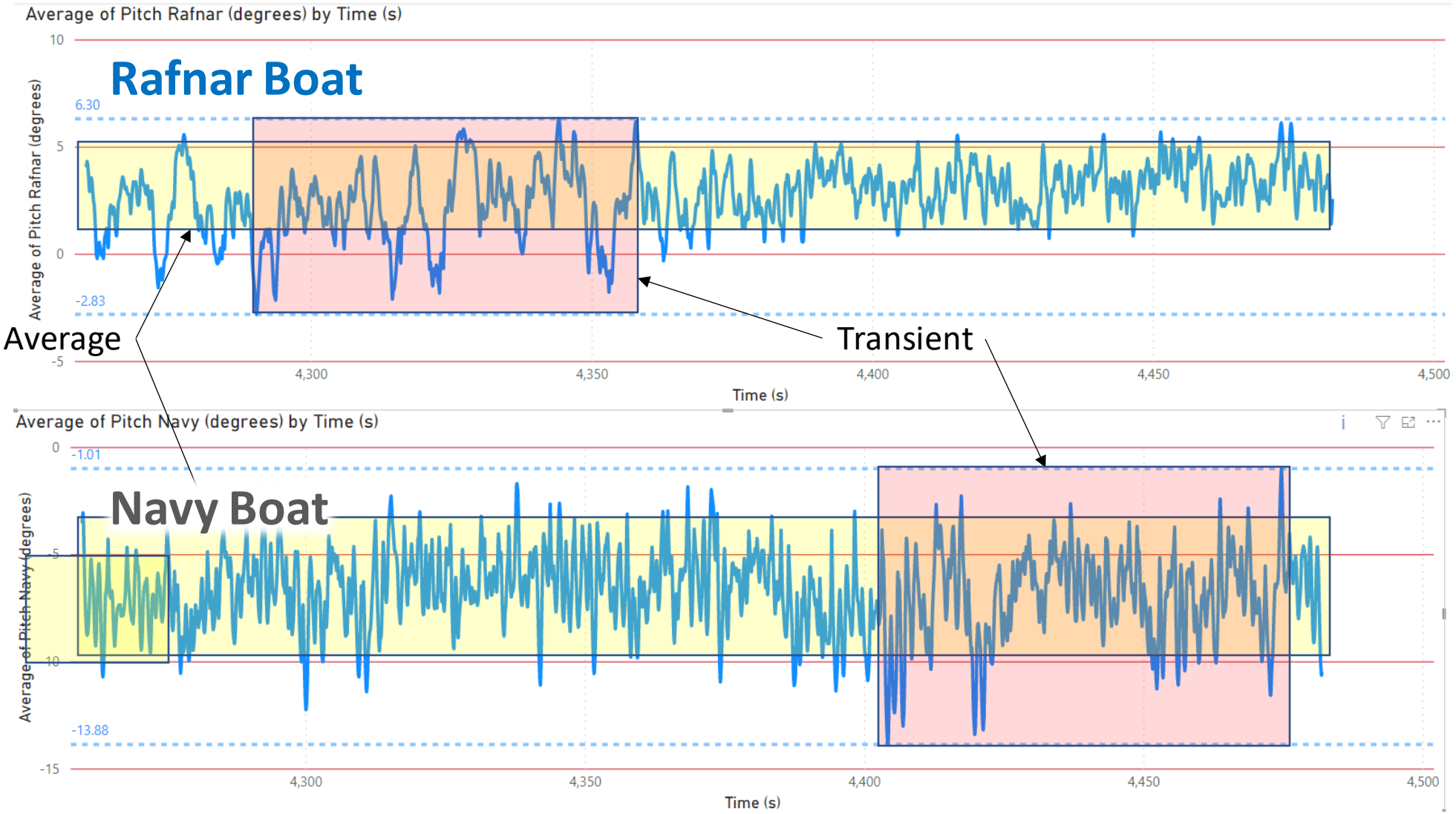
- Study of the Human Musculoskeletal Systems
- Uses a wide variety of sensor types to study human motion, applied forces, and muscle EMG response during strenuous activities.
- Up until now, there are very few, if any, such efforts focused in the maritime industry



Rotation, Pitch Direction (Degrees)

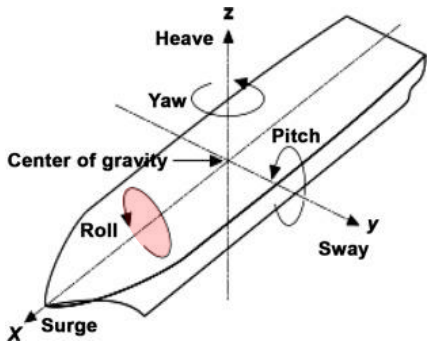
➢ **Navy Boat** experienced **1.5X** greater pitch rotation than the **Rafnar Boat**

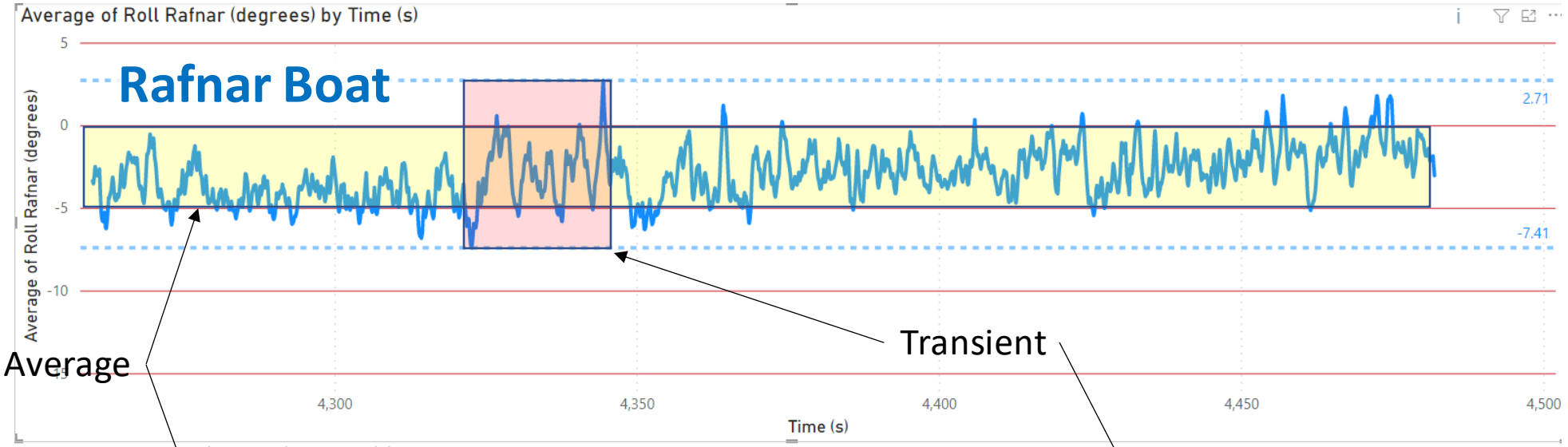


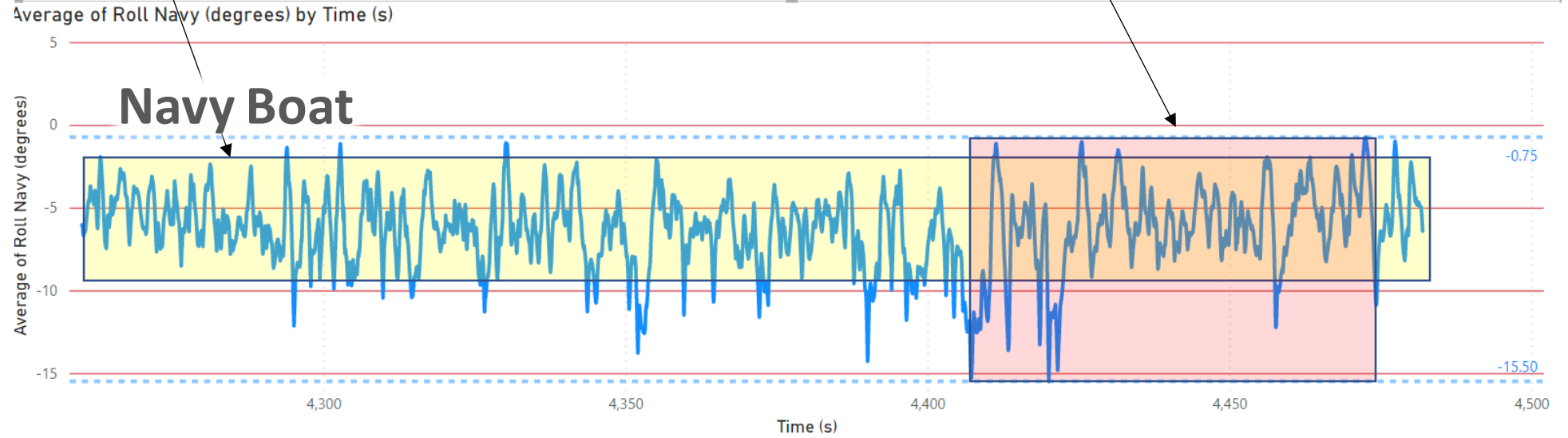


Rotation, Roll Direction (Degrees)

➢ **Navy Boat** experienced **1.5X** greater roll rotation than the **Rafnar Boat**







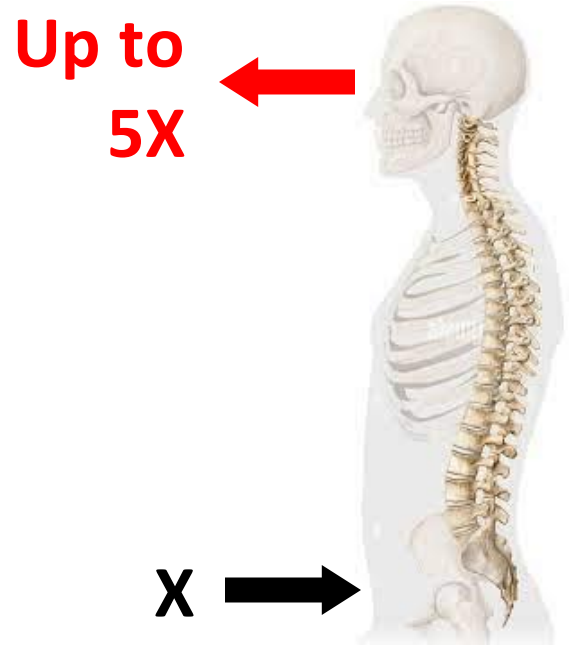
Statistics - Special Operations Boating Community

HighSpeedBoat OperationsForum

1. Current trends are showing injury rates in this community are reaching upwards of **100%** (6X greater than gen population).
2. Cervical (neck) impact ranges on high-speed assault combatant craft range from 2g to **125g's**.
3. Mathematical models show that forces applied to the Pelvic region resulted in Head responses at **5X** magnification.

Source: Naval Special Warfare Group Four Medical letter entitled "Chronic Orthopedic/mTBI Problems in Selected Navy Ratings"

Horizontal Pelvic Acceleration	Resulting Max Head Accelerations
5 G's	**28 G's**
12 G's	**60 G's**



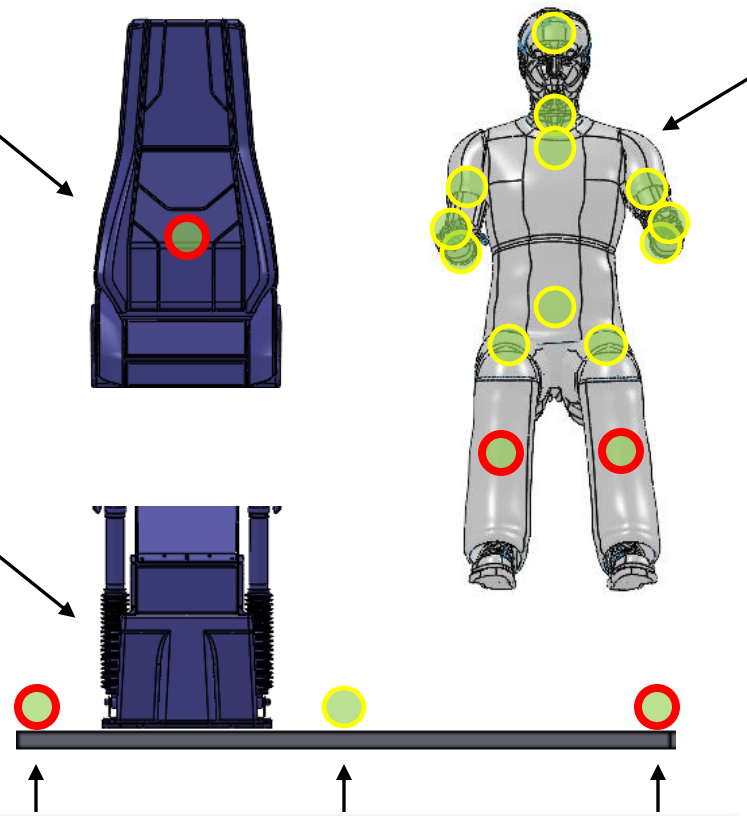
Digital Twin (Future Development)

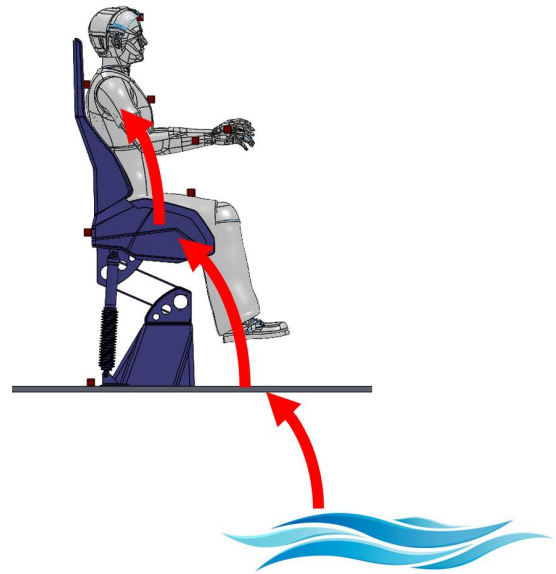
- **Add (5) Sensors**

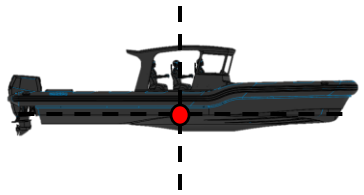
Seat Top
Rigid Body 6DoF

Boat & Seat Base
Rigid Body 6DoF

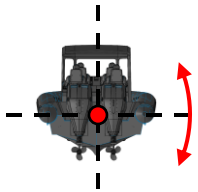
Body
(14) Point
Bio-Mechanic
Model



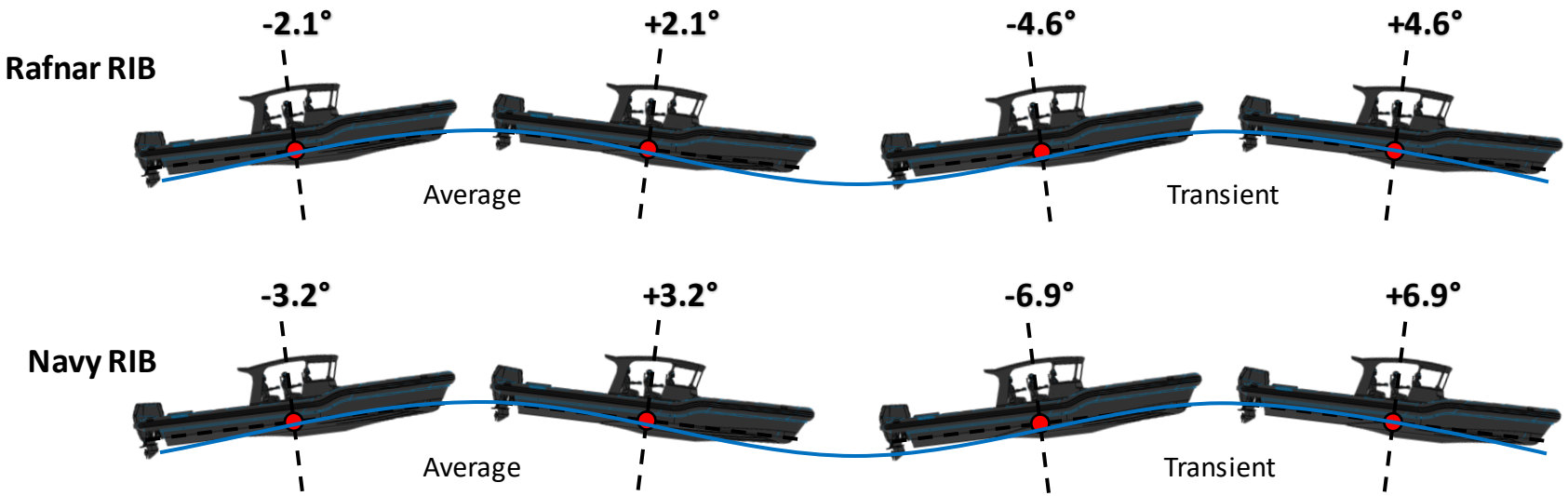


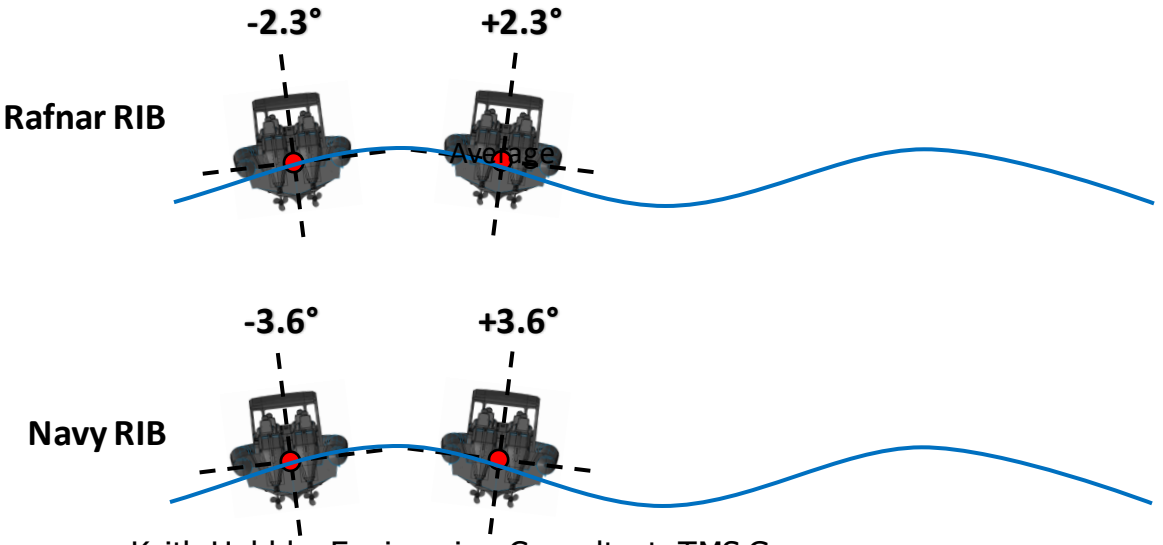


Pitch



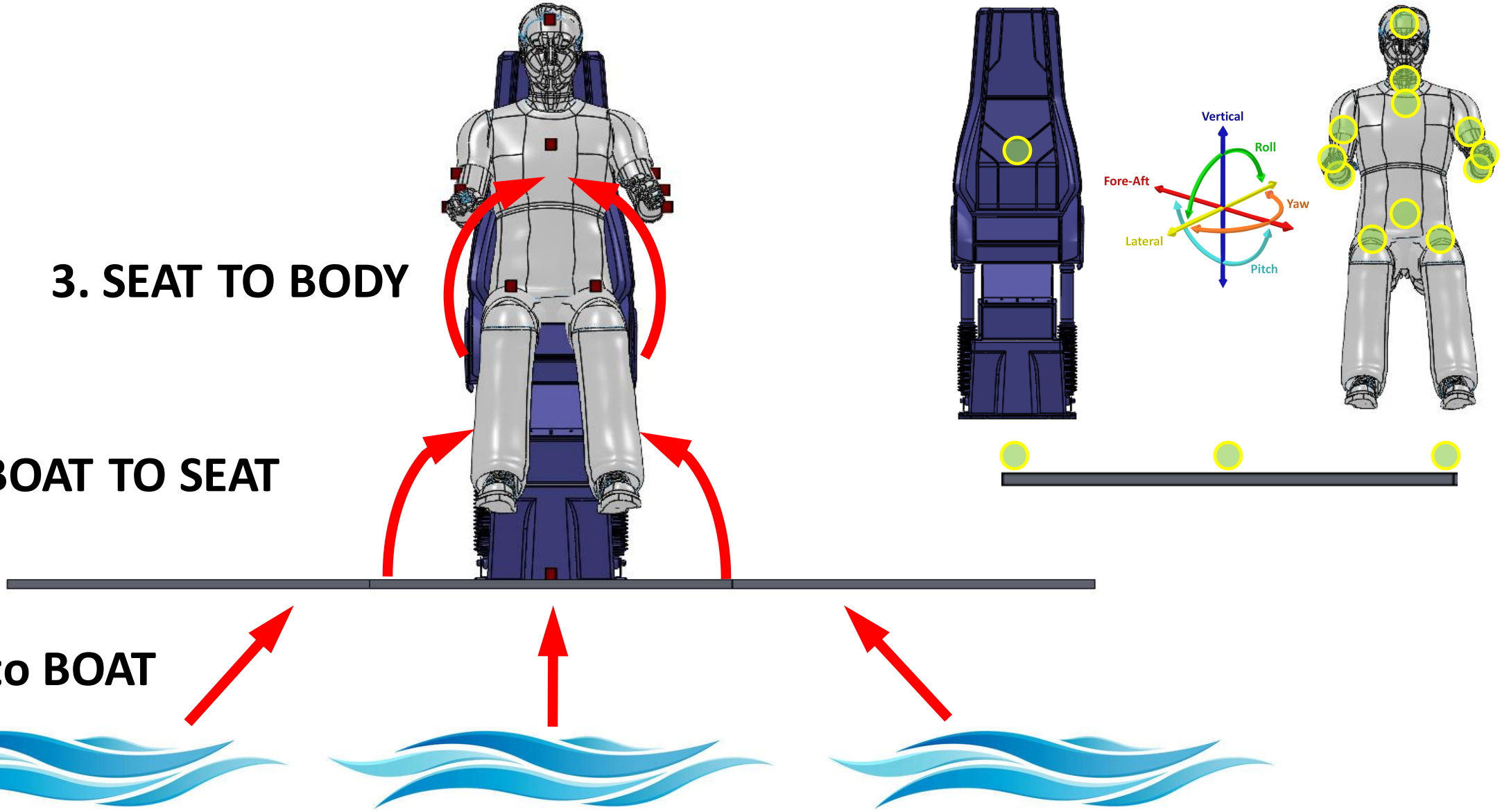
Roll





Keith Hubble, Engineering Consultant, TMS Group

Wave BSB Analysis (Under Development)



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