Simulating Effects of High-Acceleration Exposure for Mitigation of Cervical Spine Injury in Military Pilots

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Disclosures

- Nathan Pickle, PhD, has no conflicts to report.
- Ryan Middle, BS, has no conflicts to report.
- Paulien Roos, PhD, has no conflicts to report.
- Felicia Davenport, PhD, has no conflicts to report.
- Peter Le, PhD, has no conflicts to report.

Disclaimer

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Neck injury in military pilots

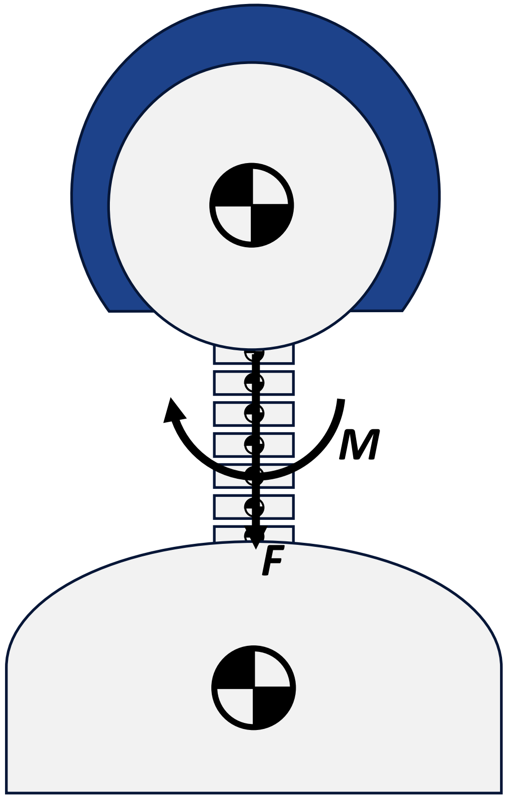
- Neck (cervical spine) injury is a threat to military pilots[1]
- Contributing factors
  - Head-worn equipment
  - Posture
  - G-forces
- In-flight biomechanical data are expensive and difficult to collect
- Computational models can aid in injury mitigation
  - Estimate forces in muscles, joints, ligaments, and discs
  - Supplement experimental (*in vivo*, cadaver, manikin) data

Photos courtesy of DVIDS. The appearance of U.S. Department of Defense (DoD) visual information does not imply or constitute DoD endorsement.

[1] Rumaithi M. Al., et al., Occupational Medicine, Vol. 73, No. 5, June 2023, Pages 236–242.

Why musculoskeletal simulation?

- Net force and moment
  - Simple, only depends on mass of head and helmet
  - Neglects effects on cervical spine



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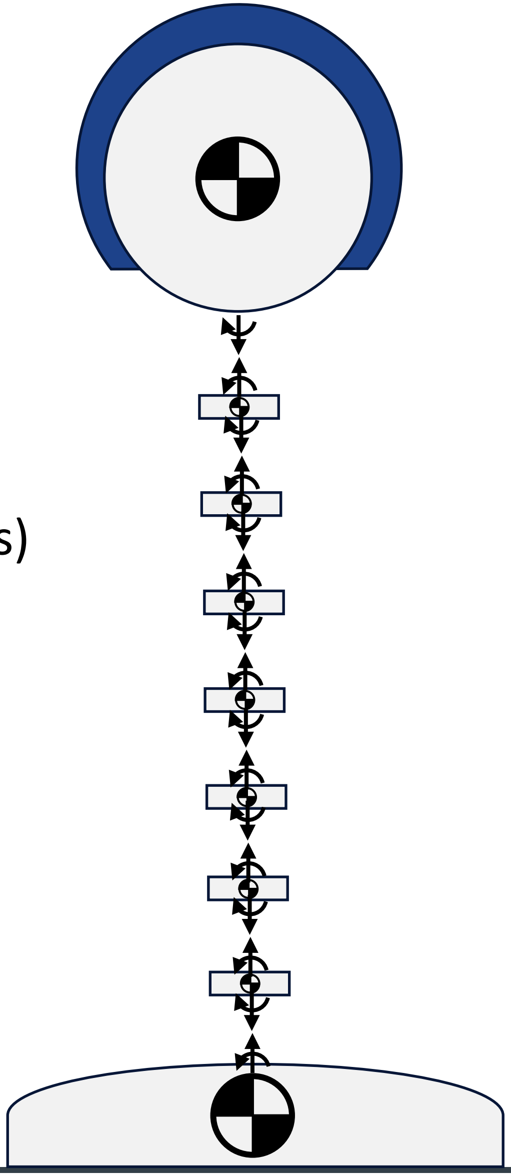
- Inverse dynamics
  - Can be calculated from experimental data (with some assumptions)
  - Neglects contributions from muscles



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- Net force and moment
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- Inverse dynamics
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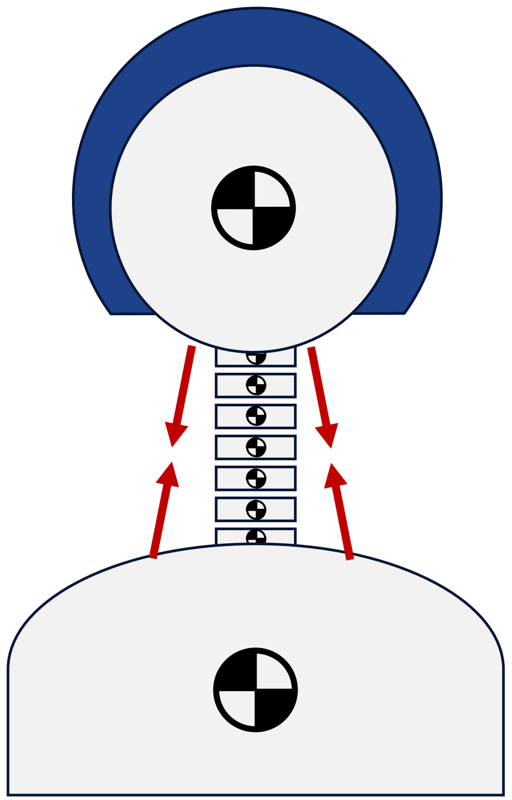
  - Neglects contributions from muscles
- Musculoskeletal simulation
  - Accounts for muscle contributions to joint loading
  - Resolves muscle redundancy
  - Incorporates anatomy of muscles and bones

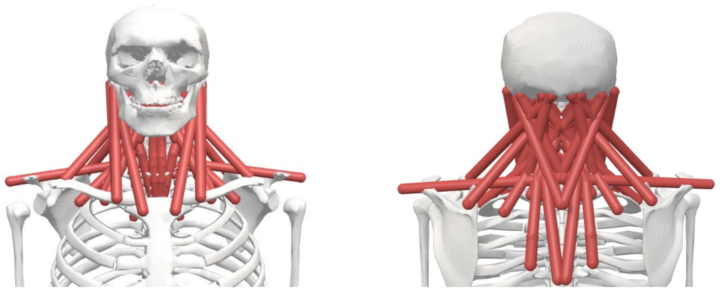


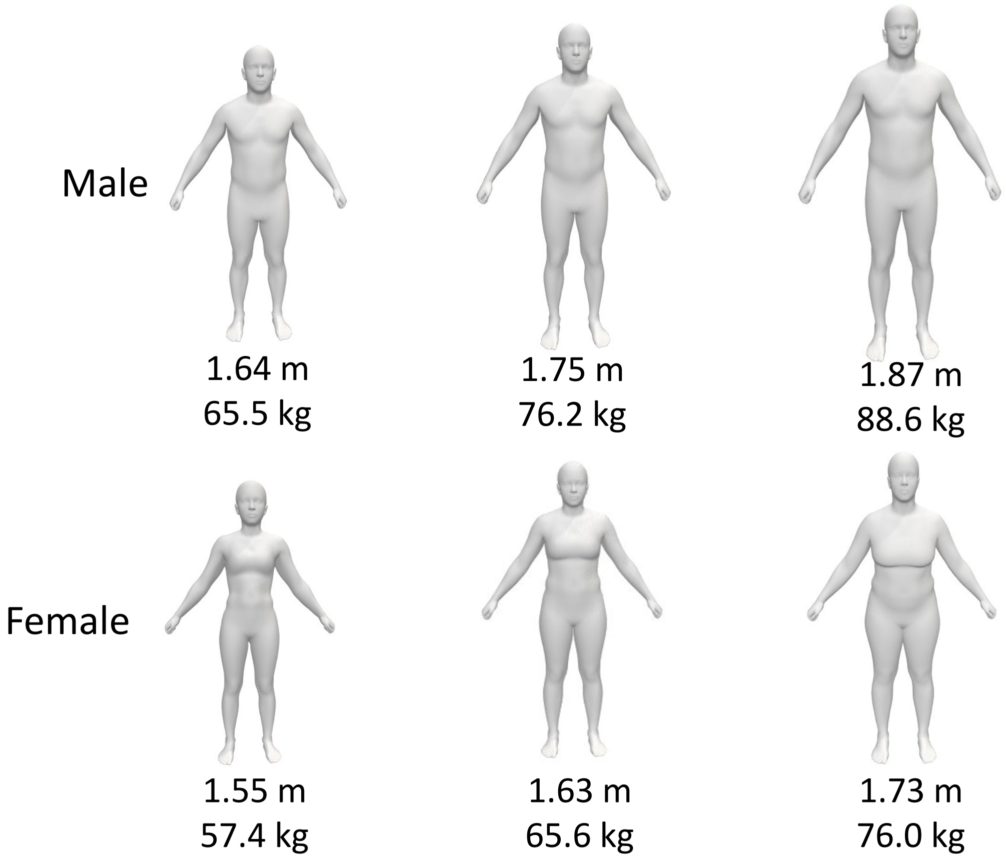
Research Objective

Simulate cervical spine biomechanics during exposure to high acceleration-induced forces representative of flight maneuvers to investigate joint reaction forces across various body sizes and strengths

Methods: Cervical spine model

- Previously published cervical spine model[1]
  - 24 degrees of freedom across 8 joints
  - 84 musculotendon elements
  - Coordinate coupler constraints drive cervical joint angles as a function of head roll/pitch/yaw[2]
- Body size scaling
  - Generated representative “small”, “medium”, and “large” body sizes
  - Based on measurements and 3D body scans from ANSUR-II dataset[3]
- Strength scaled to 50th percentile values for male and female[4]

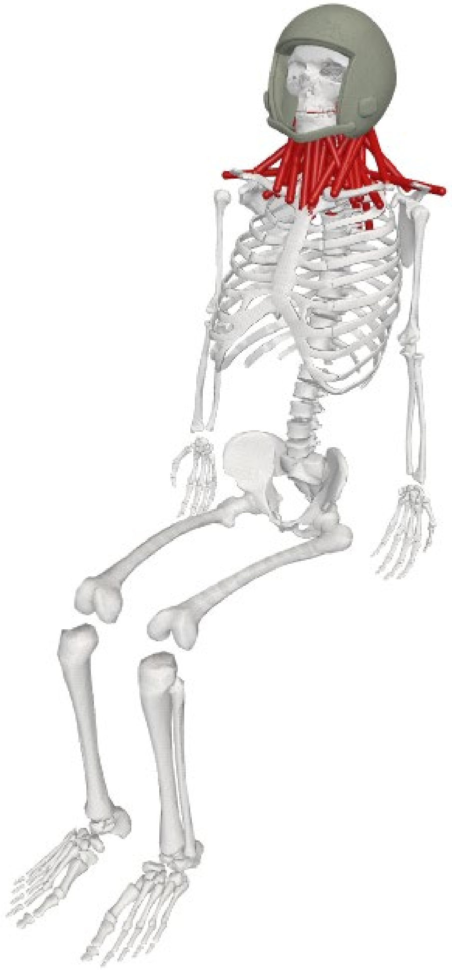




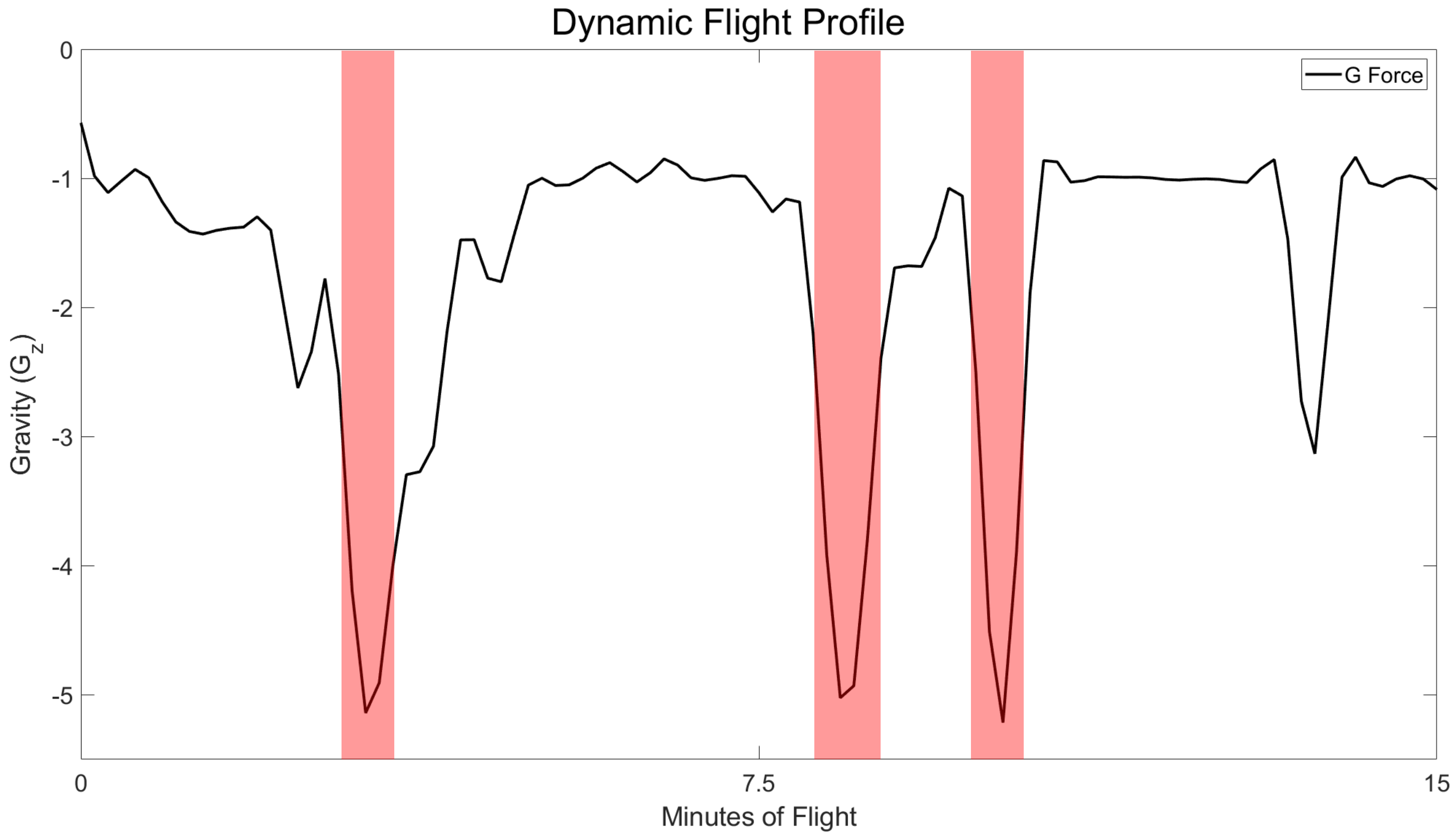
[1] A. Vasavada et al., Spine, vol. 23, no. 4, p. 412, Feb. 1998
[2] A. White and M. Panjabi. Clinical biomechanics of the spine, 1990
[3] C. Gordon et al., 2012 Anthropometric Survey of U.S. Army Personnel, 2016
[4] P. Roos et al., PLoS One, 15(1), 2020

Methods: Simulated flight conditions

- Upright seated posture
- HGU-55/P flight helmet
- G-forces
  - Custom OpenSim plugin dynamically varies the global acceleration vector
  - Dynamic flight acceleration profiles from sensor data
- Simulation
  - Static optimization (independent timesteps) in OpenSim 4.4
  - Data from 15-minute flight
- Assessed maximum magnitude of compressive joint loads
  - Includes contributions from aircraft acceleration and muscle forces
  - Contributions from shear and axial compression
  - Averaged across body sizes



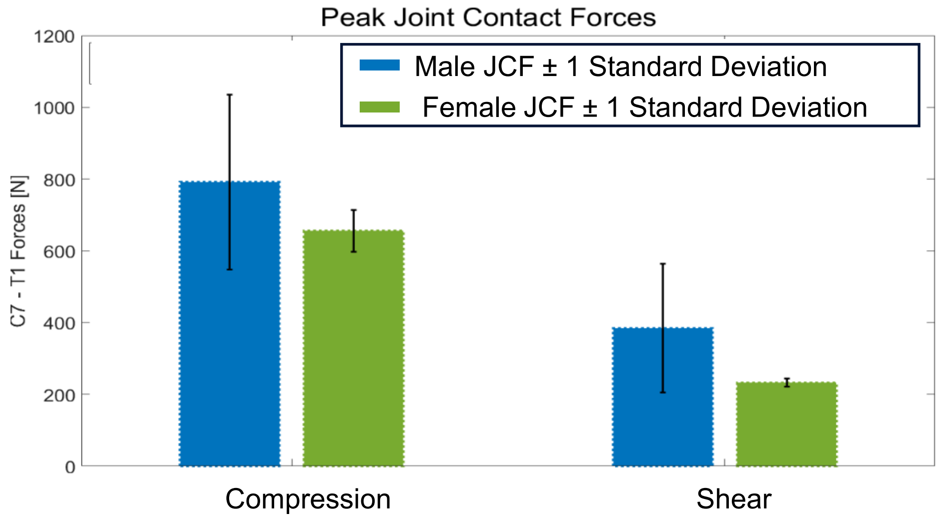
Results: Dynamic acceleration profile

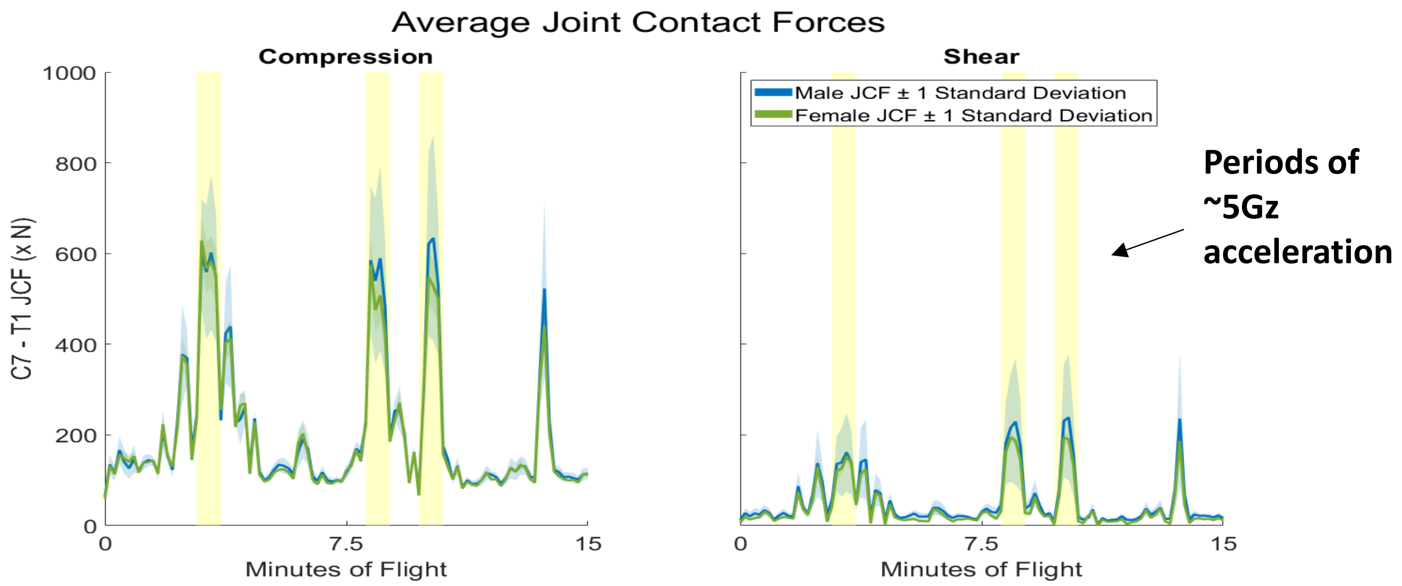


Maximum aircraft acceleration: ~5Gz

Results: Compressive joint loads

- Greatest compressive loads in C7-T1 joint
  - Males experienced higher compressive and shear loads
  - ↑ compressive and shear loads during periods of ↑aircraft accelerations
- Limitations
  - Torso fixed at T1
  - Cervical joint motion driven by constraints
    - Limited information about disc and ligament loading

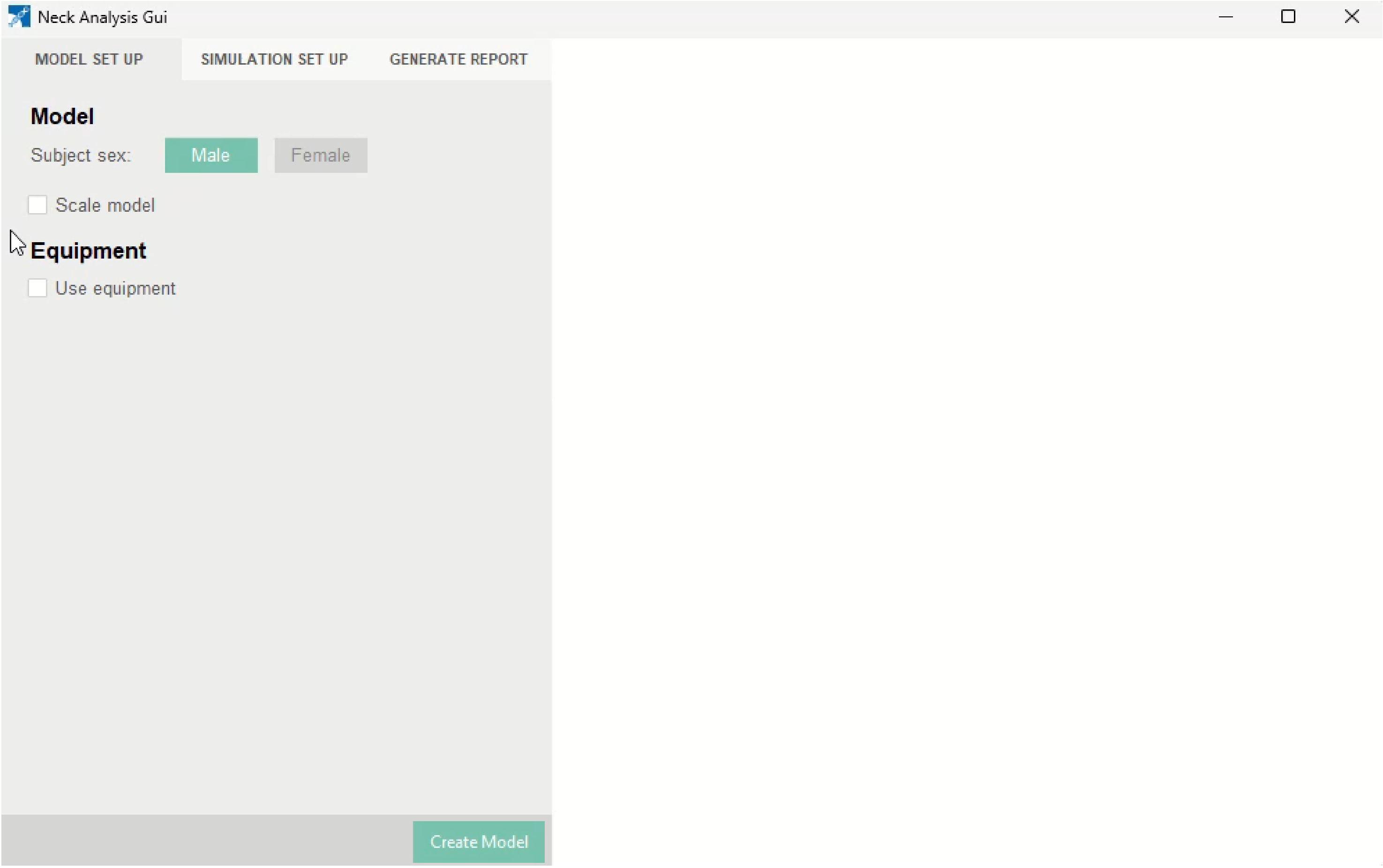




Application

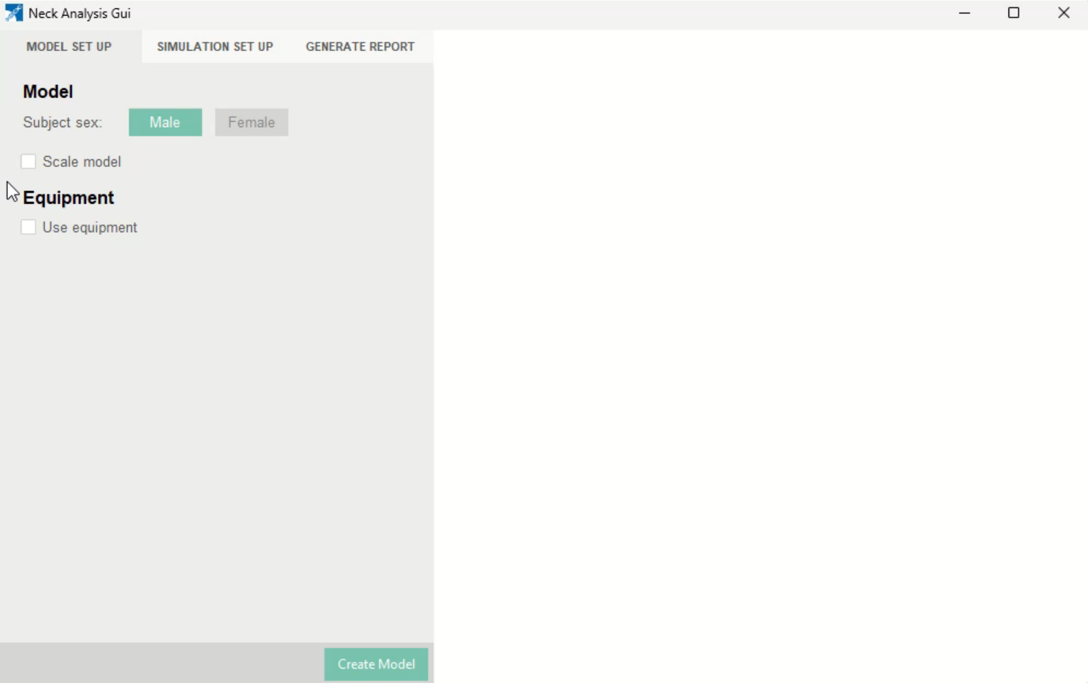
- Software application under development
- Features
  - Cervical spine model
  - Adjustable anthropometry
  - Pre-set or user-defined equipment kits
    - Adjustable mass and inertia
  - Provide acceleration profile as input
  - Specify pilot static posture or dynamic motion

Goal: Make insights from computational models available for decision-making without requiring advanced biomechanics training



Key Takeaways

- Computational models facilitate research into mitigation of neck injury
- Simulations provided estimates of cervical joint loading during a 15-minute dynamic flight
- Greatest influence of Gz acceleration seen at C7-T1
- Software application under development to make this type of analysis more widely available
- *Future*: Validation, assess effects of modeling assumptions, deeper investigation of effects of size and strength



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Sex Differences in Amplification of Head-Coupled Vibration

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Background

MIL-STD-1472H

ISO 2631-1

CANADA

Neck pain a debilitating problem for RCAF helicopter pilots

The Canadian military is looking for ways to reduce the number of neck injuries seen in helicopter pilots, which is attributed partly to heavy equipment. But there is no quick fix for the costly concern.

May 6, 2018 | 4 min read

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Assessing Education and Exercise as Solutions for Aircrew Neck-trouble

Background

20.2% of RCAF members are female

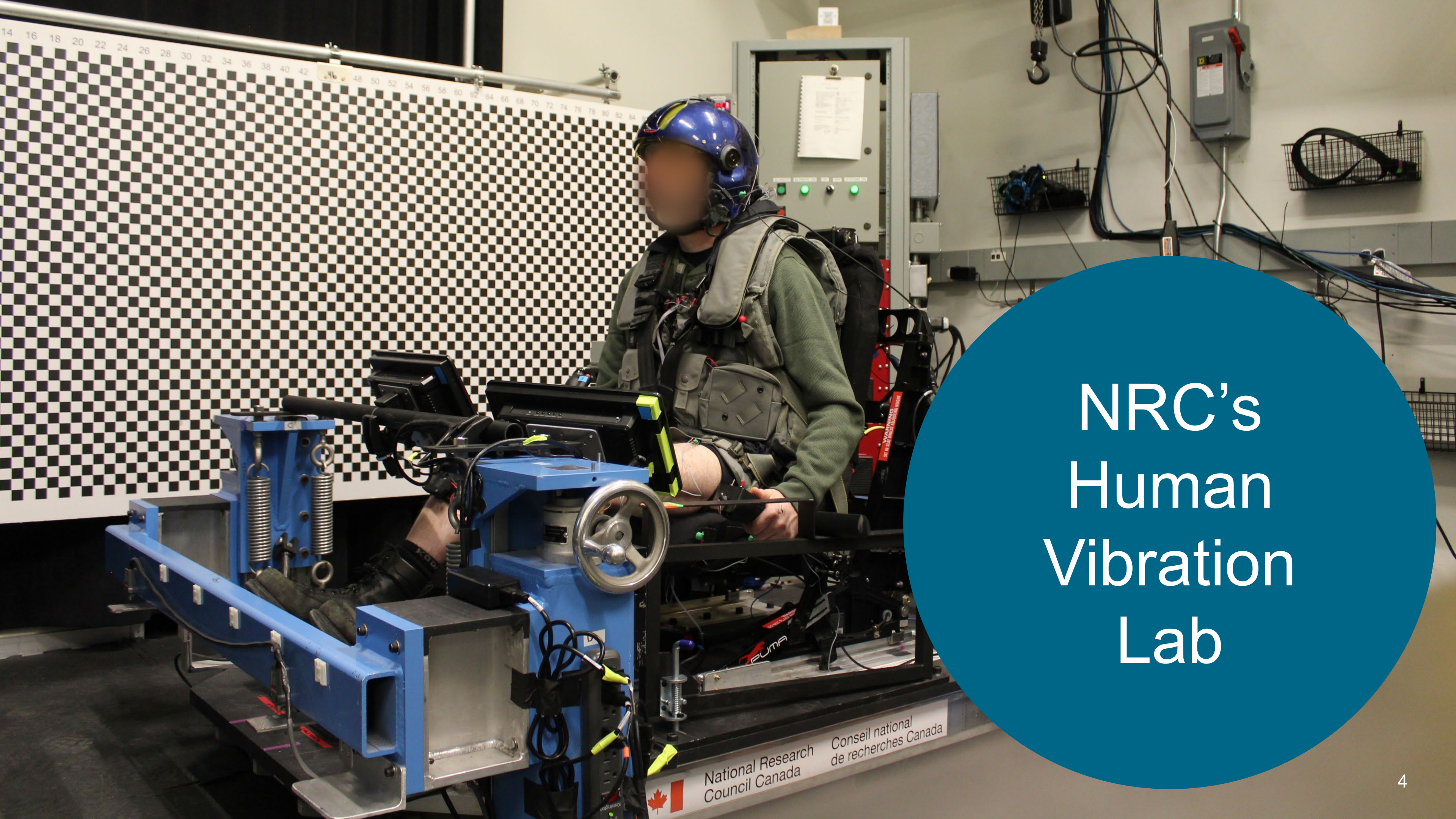
<6% of CAF operational pilots are female

At least one piece of ALSE did not fit properly in 82% of female CAF pilots (Thorgrimson and Breeck, 2025)

Potential factors:

- Pelvis anthropometry
- Adipose tissue
- Spinal flexibility
- Musculature difference
- Mass differences

NRC's Human Vibration Lab



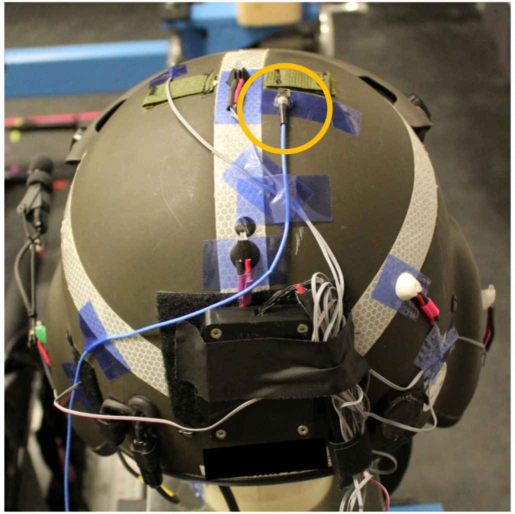
Methods

CH-146 Griffon - Bell 412 helicopter vibration profile

https://www.canada.ca/en/air-force/services/aircraft/ch-146.html

Accelerometers

- Platform
- Seat Pan
- Seat Pad
- Helmet



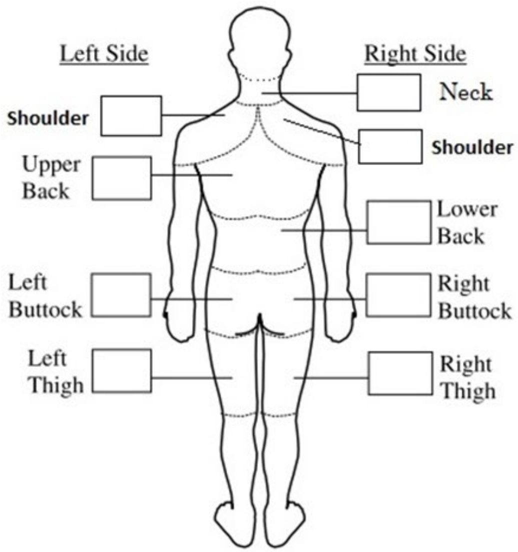
Methods

Participant	Age	Sex	Weight (lbs)	Height (cm)	Seated Height (cm)
P1	23	F	173.2	164.7	127.4
P2	41	M	195.6	173.8	127.1
P3	-	M	166.4	175.5	127.7
P4	35	M	205.8	178.0	126.3
P5	29	F	164.6	167.7	124.5
P6	21	F	188.8	164.5	127.1
P7	55	M	215.0	177.5	130.7
P8	29	M	149.4	183.4	131.4
P9	-	F	115.0	159.8	119.0
P10	21	M	193.6	183.4	133.6
Mean	-	-	F=160.4, M=187.6	F=164.2, M=178.6	F=124.5, M=129.5

Methods

Subjective ratings

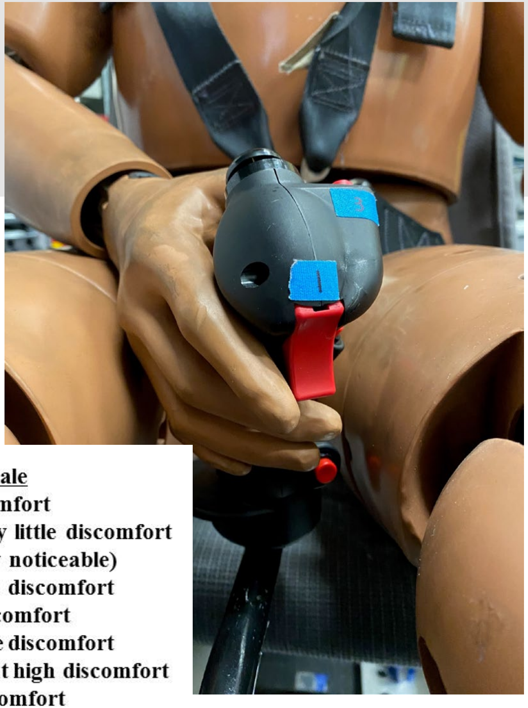
- localized discomfort



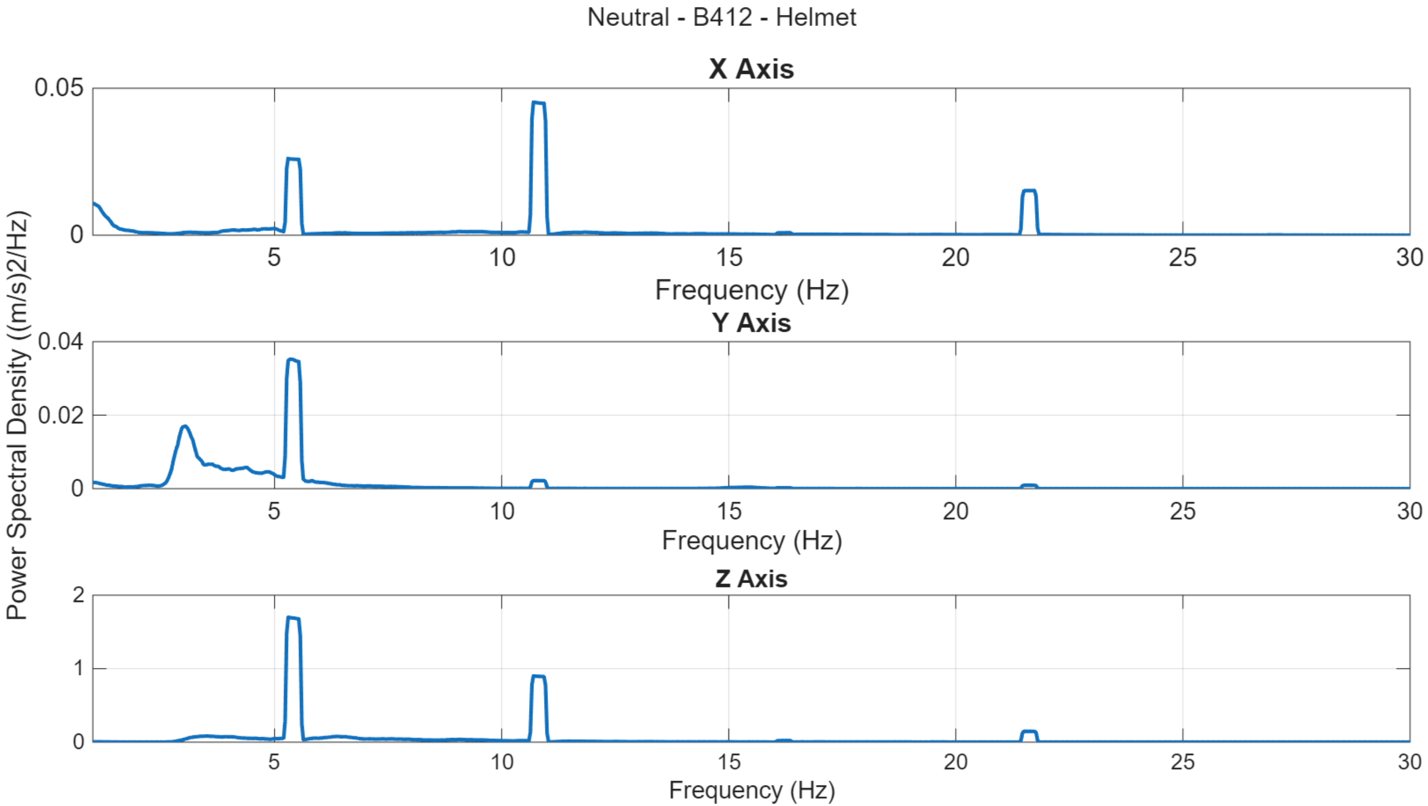
Discomfort Scale

0	No Discomfort
0.5	Extremely little discomfort (hardly noticeable)
1	Very little discomfort
2	Little discomfort
3	Moderate discomfort
4	Somewhat high discomfort
5	High discomfort
6	
7	Very high discomfort
8	
9	
10	Extreme discomfort (almost maximum)

Target tracking task using cyclic



Power Spectral Density



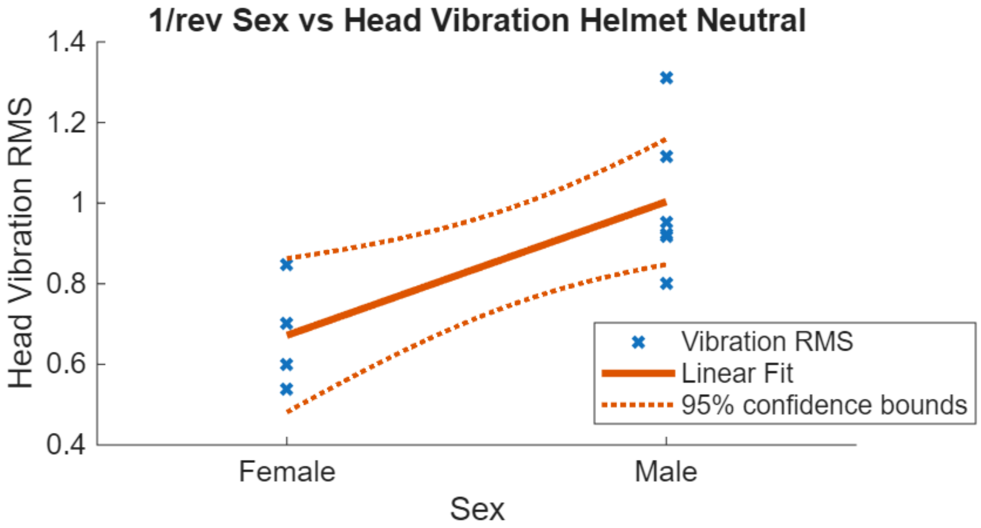
Results – Vibration

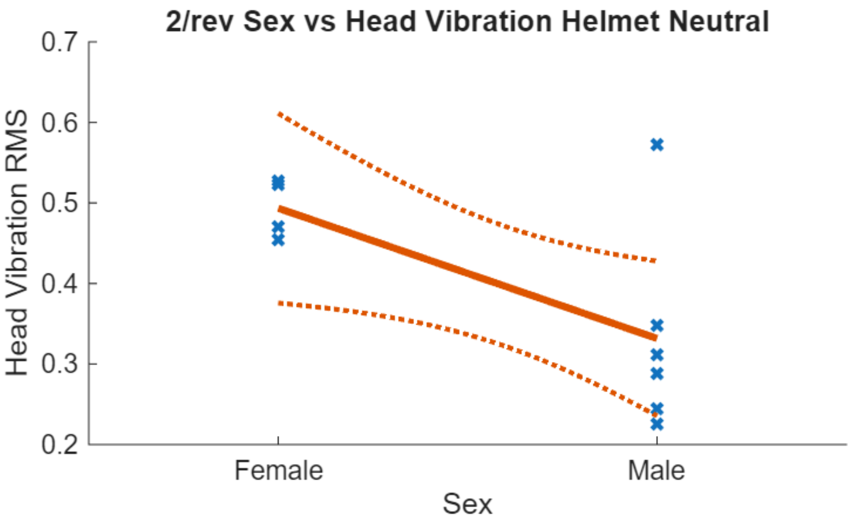
Linear correlation coefficients with vibration and sex

Accel. Location	Platform		Seat Pan	
Harmonic	1	2	1	2
R^2 - Neutral	0.32	0.23	0.04	0.05
R^2 - Hover	0.002	0.04	0.12	0.02

Accel. Location	Seat Pad		Helmet	
Harmonic	1	2	1	2
R^2 - Neutral	0.16	0.09	0.55	0.43
R^2 - Hover	0.15	0.09	0.48	0.46

Results – Vibration





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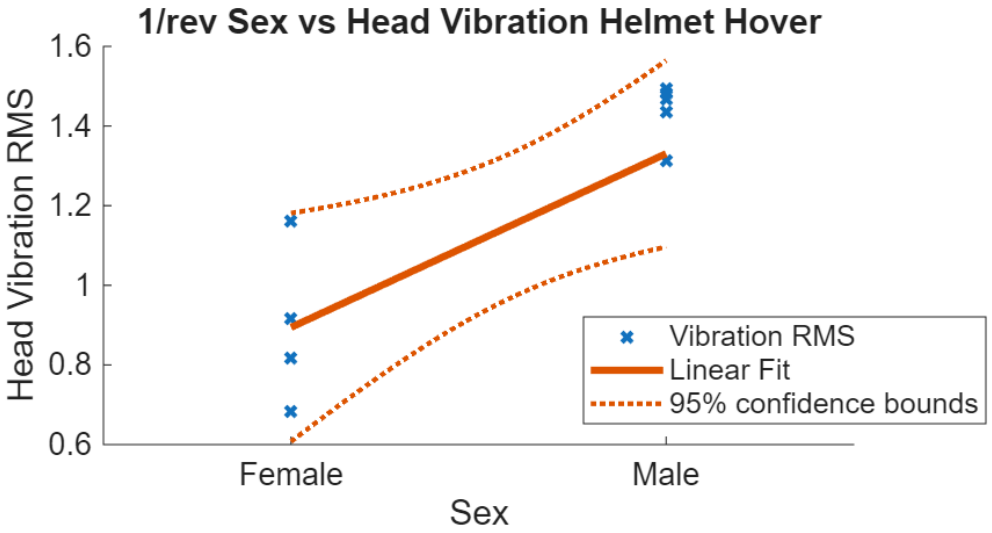
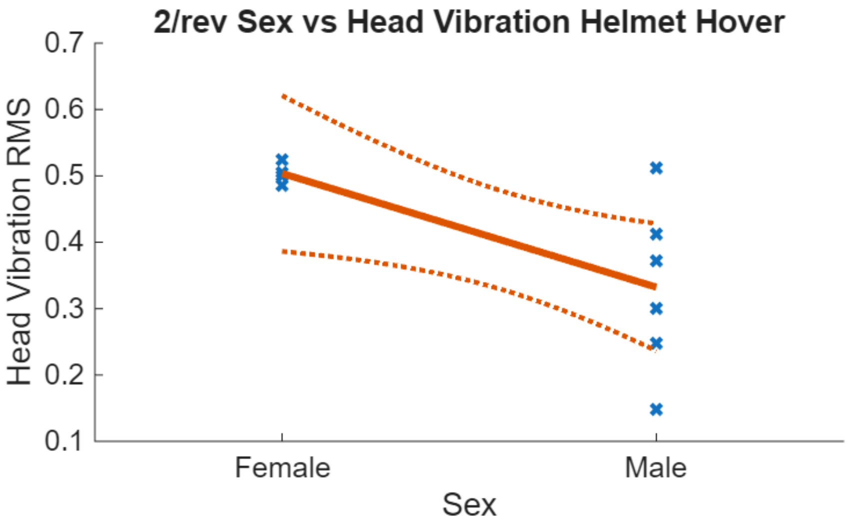
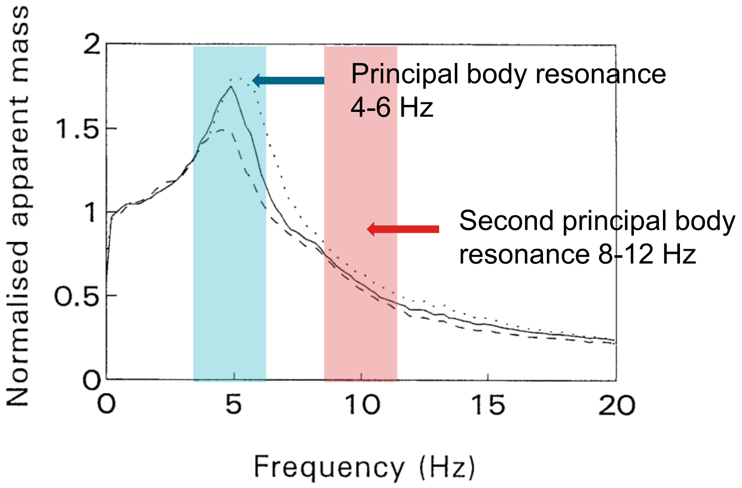




Results - Vibration

Bell 412 Harmonics of the main rotor

Harmonic	Frequency
1	5.4 Hz
2	10.8 Hz
3	16.2 Hz
4	21.6 Hz



Kitazaki and Griffin, 1998

Results - Discomfort

Change in discomfort before and after vibration exposure

Location	P1 (F)	P2 (M)	P3 (M)	P4 (M)	P5 (F)	P6 (F)	P7 (M)	P8 (M)	P9 (F)	P10 (M)
Neck	-	-	-	-	↑	↑	-	-	-	-
Shoulder	-	-	-	-	↑	↑	-	-	-	-
Upper back	-	-	-	-	-	-	-	-	-	-
Lower back	-	-	-	-	↑	↑	-	-	↓	-
Buttock	-	-	↑	-	-	-	-	-	↓	-
Thigh	-	-	-	-	-	-	-	-	-	-

Significance

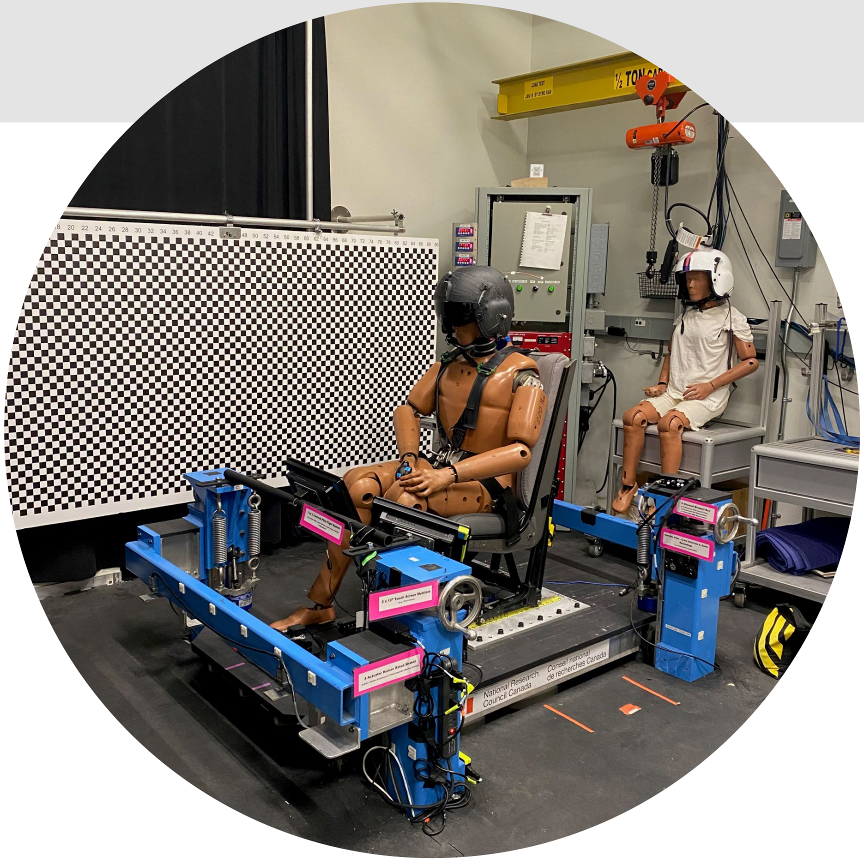
Vibration standards were developed based on data from primarily young male participants and vibration standards refer to only the seat interface.

Design standards around vibration suppression systems and head supported mass may not take into account sex differences, and hence the accommodation of female aircrew.

We need research on what happens from seat to head and this research needs to consider sex differences, for aircrew and other vibration exposure.

Next Steps

- Further evaluation with more test subjects
- Other vibration profiles
- Mitigation



Thank you

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