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Toward Head-Neck Rehabilitation Using Wearable Robots

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Feb 11th 2021

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Problem – Head Drop

http://practicalneurology.com/videos.asp?f=video23

Current Care

Problem – Head Drop

http://practicalneurology.com/videos.asp?f=video23

Unmet Needs

- Improve posture and restore motion
- Enable social participation

Outline

- Design of wearable robots for head drop
  - Engineering developments
  - Clinical evaluations
- New research horizon
  - Converging themes
  - Prior work
  - Potential directions

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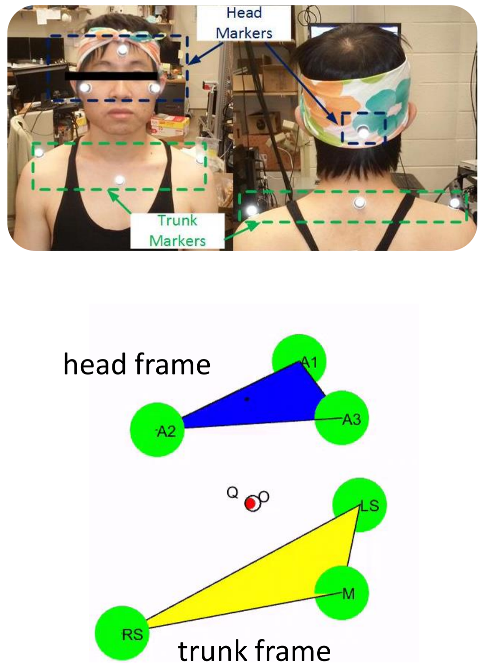
Design Objectives

A wearable machine that is

- Biomechanically compatible
  - Meet structural and motion characteristics
  - Allow large ranges of rotation
- Easy and safe to use
  - Lightweight and easy to don/doff
  - Intuitive and safe control interfaces

Mechanical Design



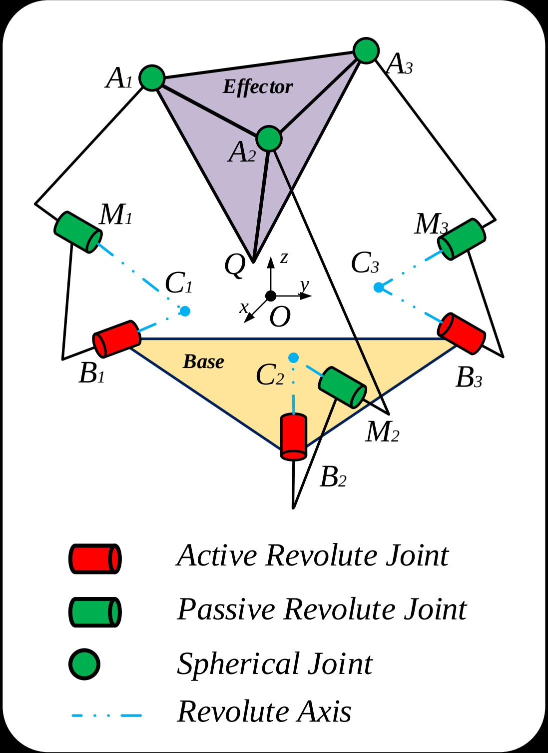
Step 1 – Characterize Head-Neck Motion

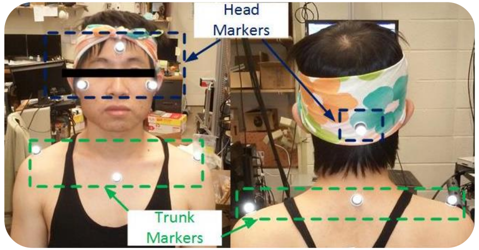
- Vicon MoCap system with 10 cameras
- Measure head rotation relative to shoulders
- Four types of head-neck movements
  - Sagittal plane flexion-extension
  - Frontal plane lateral bending
  - Transverse plane axial rotation
  - Combined motion
- Head-neck motion is predominantly rotations, with small translations.

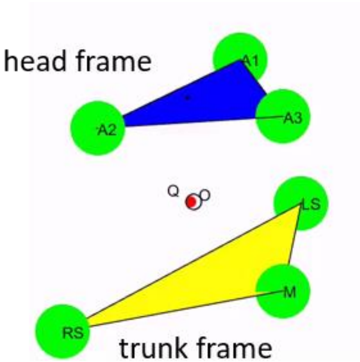
Mechanical Design

Step 2 – Choose a mechanical structure

- 3-DOF closed-chain structure with revolute joints
  - Closed-chain – Low moving inertia
  - 3-DOF – Large rotation with small translation
  - Revolute joints – Easy to fabricate
- 3-RRS mechanism with special axes alignments
  - Revolute joints within a chain intersect at a point
  - Easy to assemble
  - Coupled rotation and translation



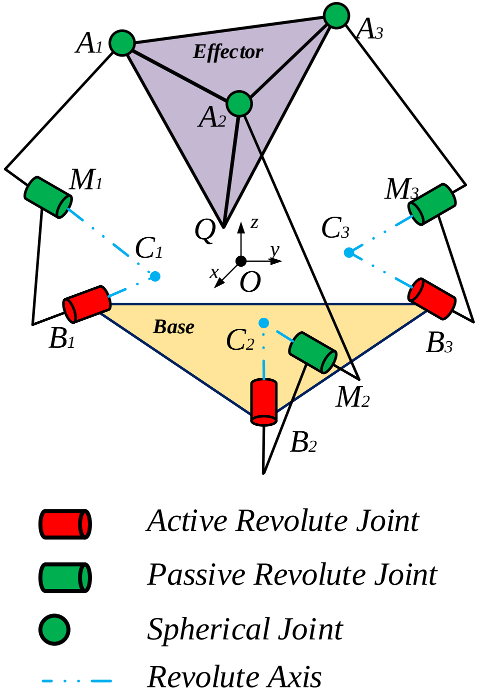




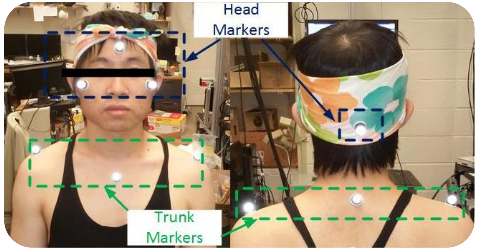
Step 3 – Optimization

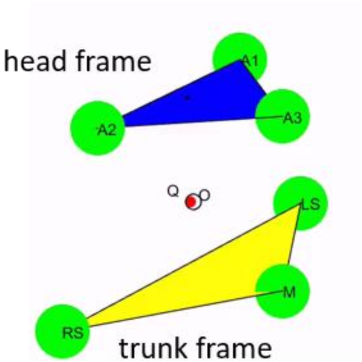
Choose parameters to meet the biomechanical data.

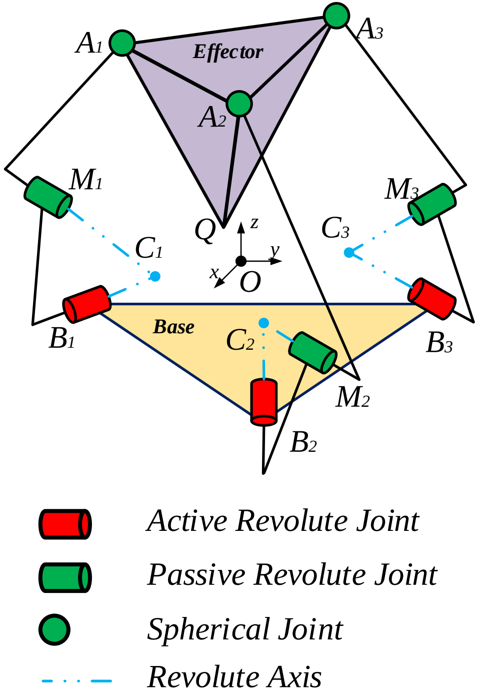
- Hierarchical random search
- Parameter space – geometric parameters of the structure.
- Multiple objectives – Maximize rotational range of motion and minimize error in translation.



Mechanical Design

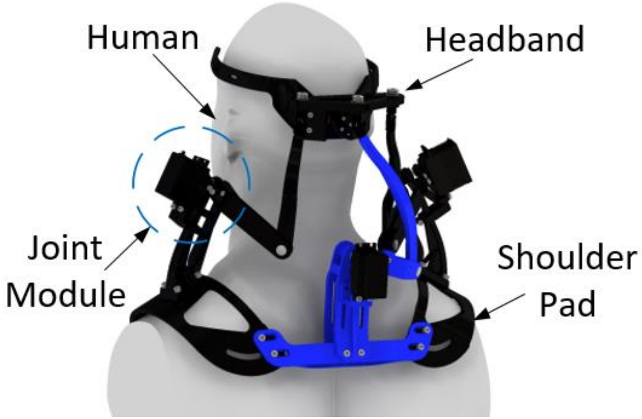






Realization – 1st Generation

- Can be integrated with other sensors, e.g., EMG, virtual reality, eye-tracker, …
- Modular design for different usages
  - Measurement (potentiometers)
  - Passive support (springs)
  - Active intervention (servomotors)



	Measurement Brace	Spring-Loaded Brace	Motorized Brace
Functionality	Measure real-time head angles in three-dimensions	Support the head in various static configurations	Apply controllable force and motion to the head
Key Features	• Spatial angle recording • Large range of motion	• Quick adjustment • Compliance	• Active interaction • Force/position control
Weight	0.5 kg	0.9 kg	1.2 kg

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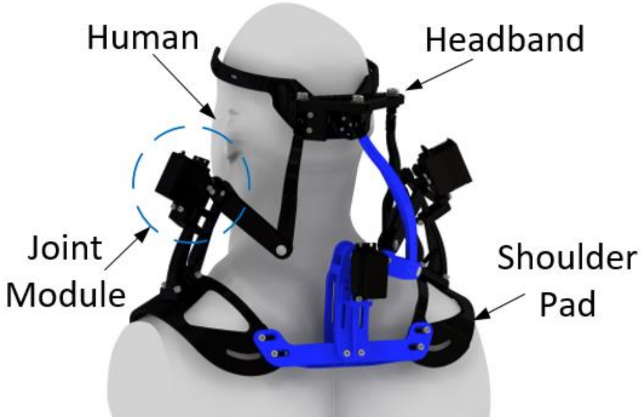
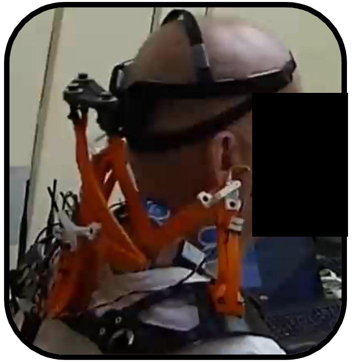
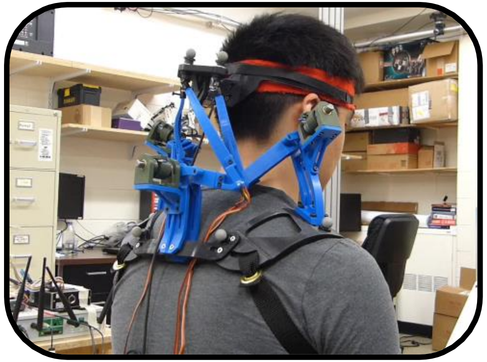


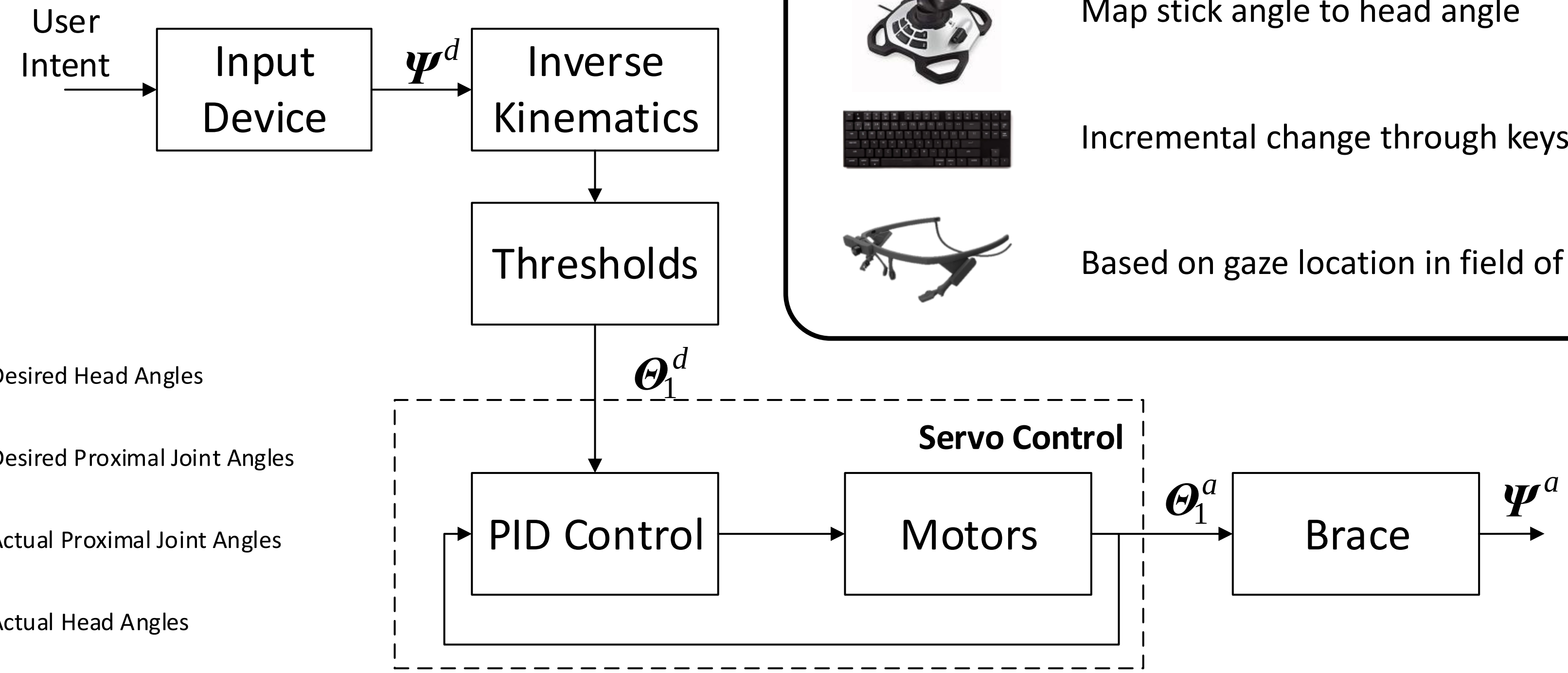




Realization – 2nd Generation

- One joint module – Dynamixel servo units
  - High backdrivability – Transparency
  - Encoders – Position feedback
  - Current sensors – Low-cost force feedback
- Advantages
  - More compact and easier to use
  - Mode change can be achieved in software
  - Can be used for training (force modulation)

Control Interface – Motion Assistance



Map stick angle to head angle

Incremental change through keys

Based on gaze location in field of view

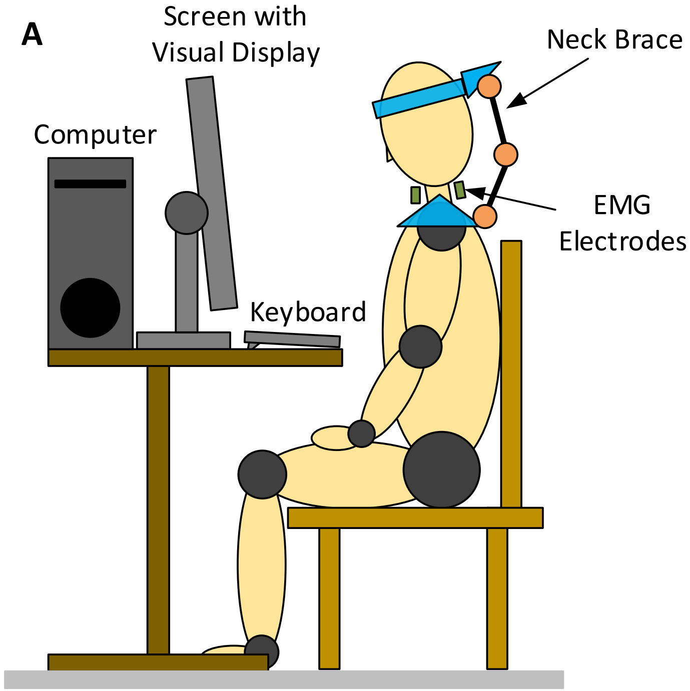
$\boldsymbol{\Psi}^d$ Desired Head Angles

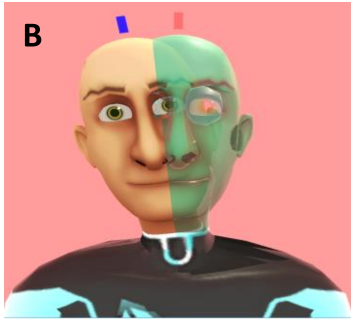
$\boldsymbol{\Theta}_1^d$ Desired Proximal Joint Angles

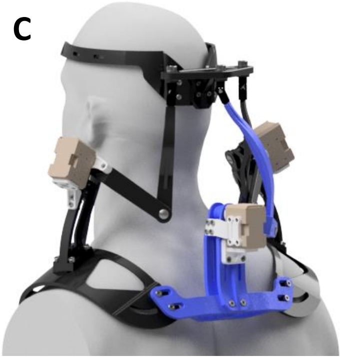
$\boldsymbol{\Theta}_1^a$ Actual Proximal Joint Angles

$\boldsymbol{\Psi}^a$ Actual Head Angles

Evaluation with ALS Patients







Evaluation with ALS Patients

Characteristics of five enrolled subjects

ID	Gender	Age	Height (cm)	Weight (kg)
001	M	55	195	91
002	M	33	185	116
003	F	56	169	73
004	M	76	166	69
005	M	39	183	110

Without Assistance (*Baseline*)

- Static Upright
- Sagittal Plane
- Frontal Plane
- Transverse Plane

With Assistance (*Assist*)

- Static Upright
- Sagittal Plane
- Frontal Plane
- Transverse Plane

Evaluation with ALS Patients

Movement functions with respect to time[1]

Motion Tasks	Functions (Units: SI)
Sagittal Plane Flexion-Extension	$x_{(t)} = 15^\circ \sin(0.2\pi t + 0.73) - 10^\circ$
Coronal Plane Lateral Bending	$x_{(t)} = 20^\circ \sin(0.2\pi t)$
Transversal Plane Axial Rotation	$x_{(t)} = 25^\circ \sin(0.2\pi t)$

Notes: 1 – Each motion is repeated 5 times, with the middle three cycles recorded for data analysis.

Without Assistance (*Baseline*)

With Assistance (*Assist*)

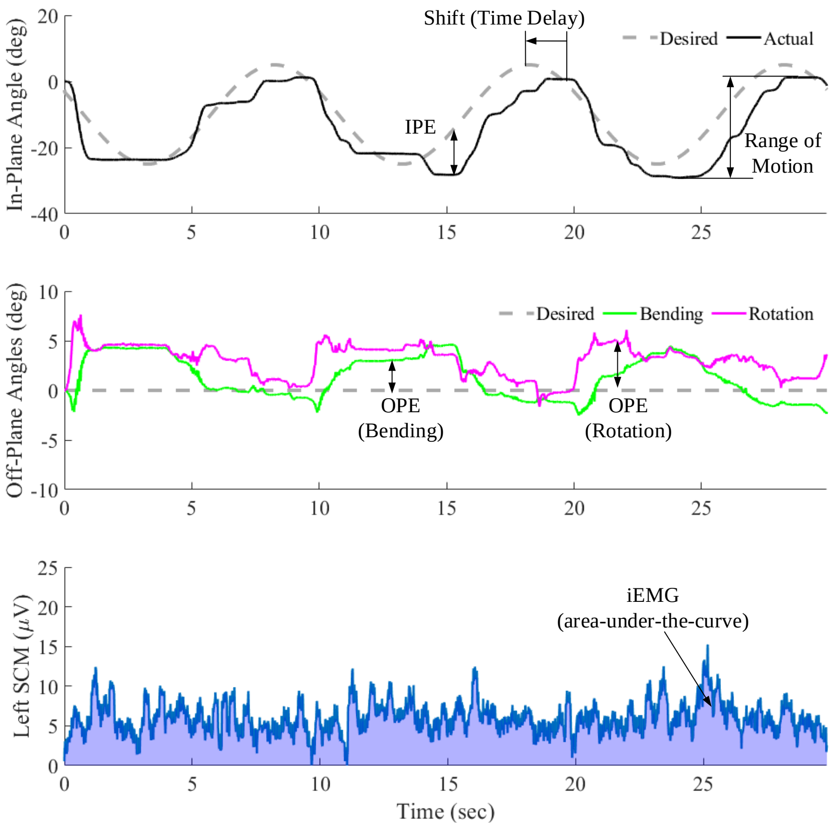
Evaluation with ALS Patients

Independent Variables

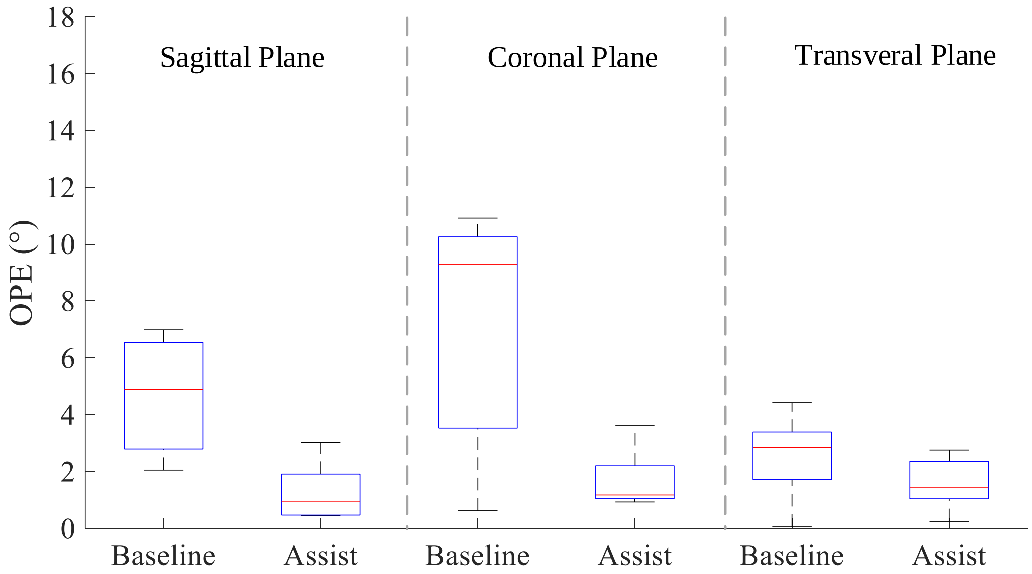
- Experimental Conditions: *without assistance* vs. *with assistance*
- Movement Planes: *Sagittal*, *Frontal*, and *Transverse*
- Muscle sites: *left / right SCM* and *SC*

Dependent Variables

- In-plane tracking error (*IPE*)
- Out-of-plane error (*OPE*)
- Range-of-motion error (*RME*)
- Integrated EMG (*iEMG*)

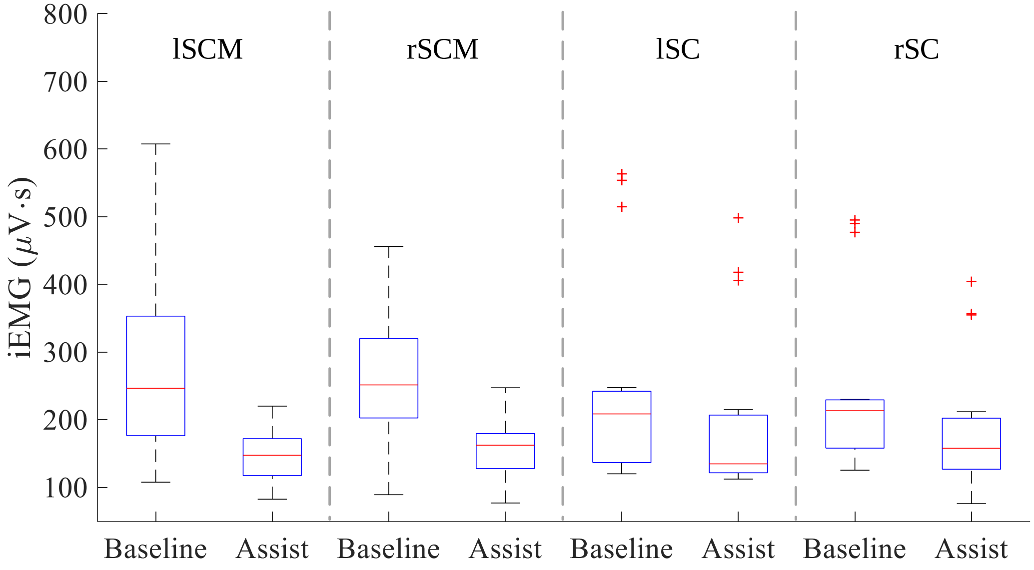


Key Results – Movement Accuracy



- *Without Assistance* the error is higher than *With Assistance*
- Movement planes do not influence the result of *OPE*

Key Results – Muscle Activity



- *Without Assistance* the muscle activation is higher than *With Assistance*
- Different muscles have a similar effect on *iEMG*

Conclusions

- The powered robotic brace
  - Is wearable and safe to use
  - Improves the movement quality
  - Reduces the muscle activation
- The user interface may be upgraded to accommodate more users, especially those with low upper limb strength and poor finger control.

Outline

- Design of wearable robots for head drop
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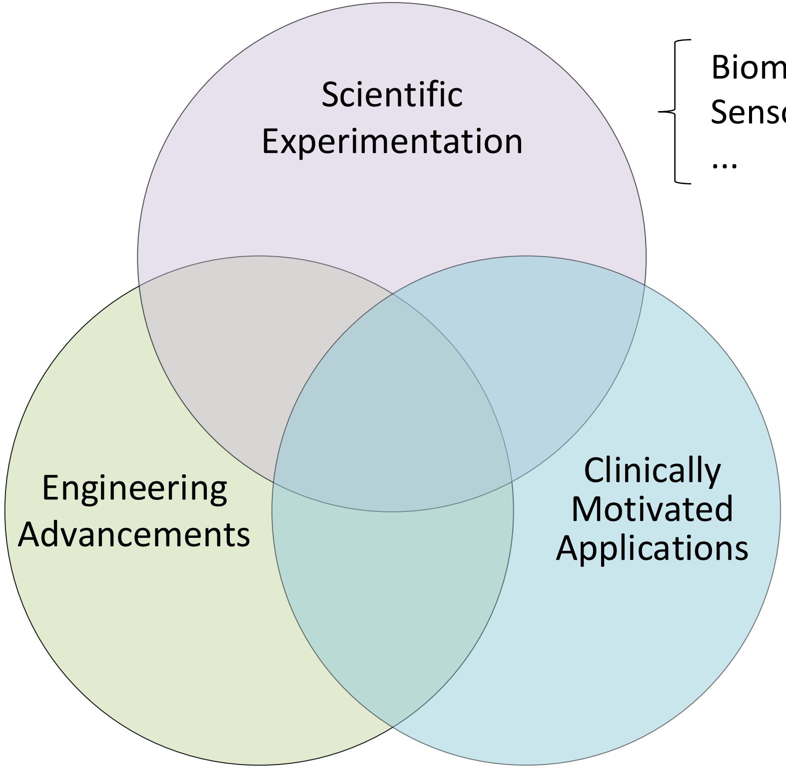
  - Clinical evaluations
- New research horizon
  - Converging themes
  - Prior work
  - Potential directions

Converging Research Themes

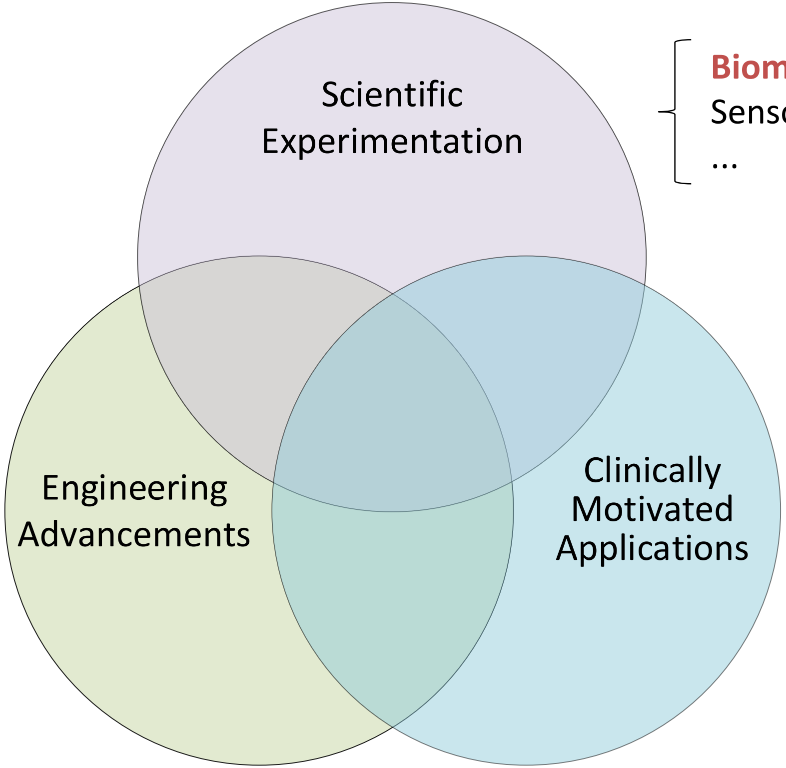
Biomechanics
Sensory & neuromuscular systems
...



New devices
Control schemes
User interfaces
...

Therapeutic treatments
Assistive technologies
Telemedicine
...

Converging Research Themes



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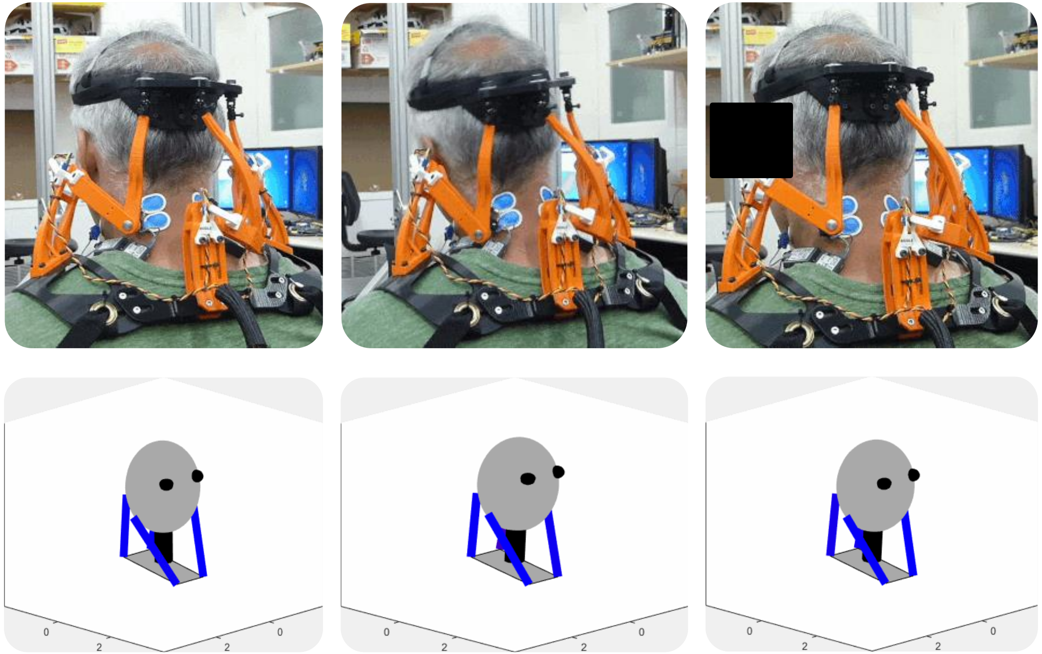
Prior Work – Movement

Rope model to explain muscle-movement pattern of head-neck

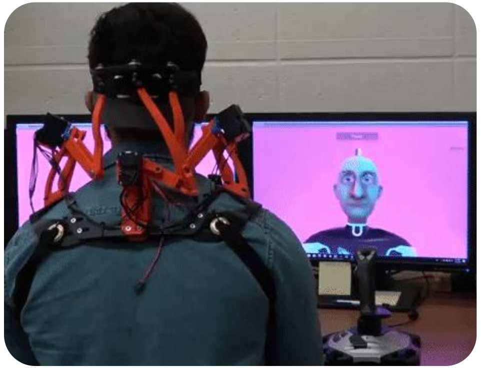


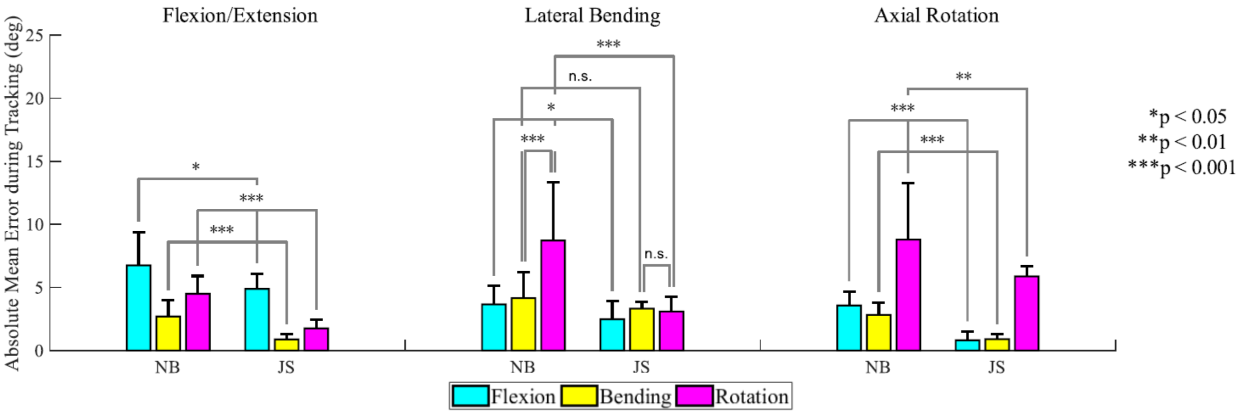
- Head-neck movement in healthy can be explained by a four-rope model.
- These ropes work in pairs to actuate a specific head rotation.

Zhang et al., *Annals of Clinical and Translational Neurology* (2019)

Prior Work – Movement

How well does head-neck command orientations?





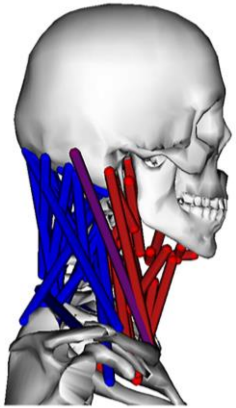
- The head-neck can command orientation;
- But the head-neck commits more tracking errors and time delays than the hand-wrist.

Zhang et al., *IEEE Transaction on Neural System and Rehabilitation Engineering* (2019)

Potential Research

Computational biomechanics

- Predictive simulation models
- Infer design of wearable robots



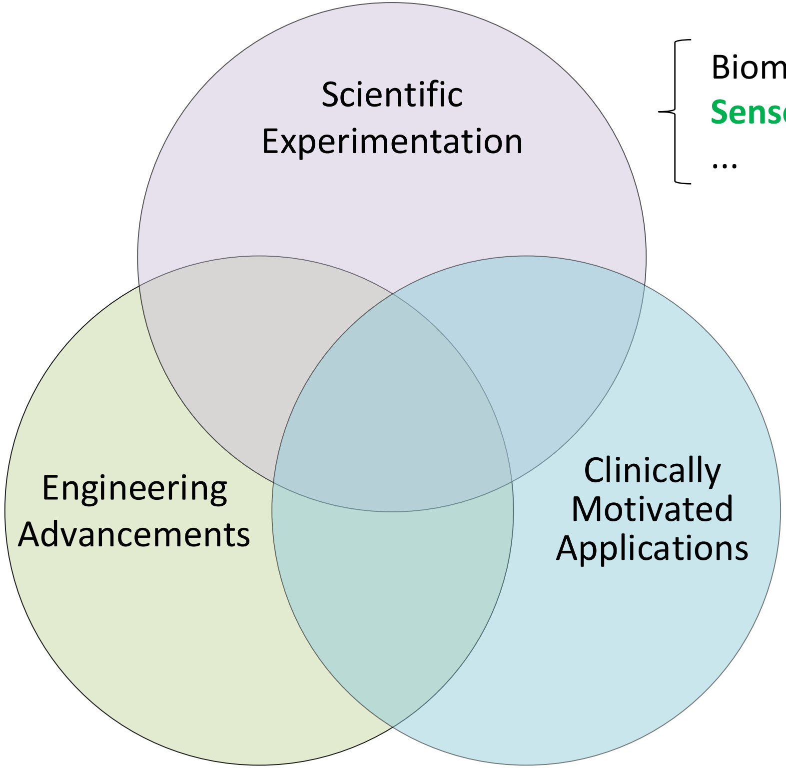
Mortensen, Vasavada, and Merryweather, *Plos One* (2018)

New devices

https://www.youtube.com/watch?v=_VCLX5MD_LA

https://en.wikipedia.org/wiki/Quadcopter

Converging Research Themes



Biomechanics
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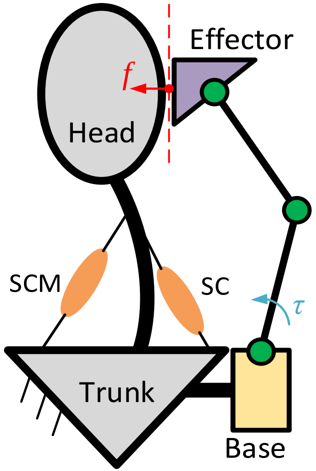
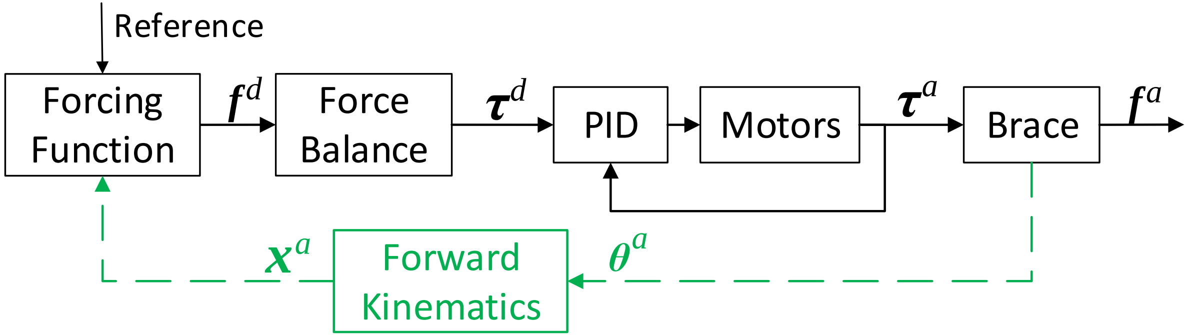
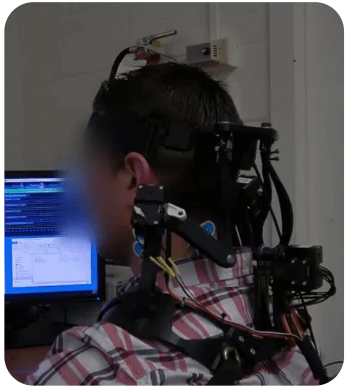
Prior Work – Force Control

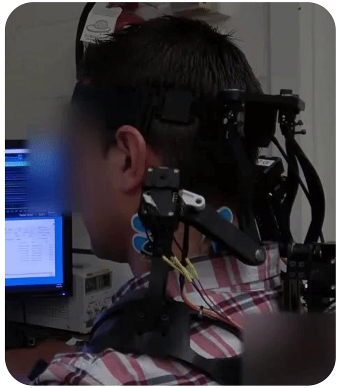




f^d can be a function of

- Time
- Head orientation

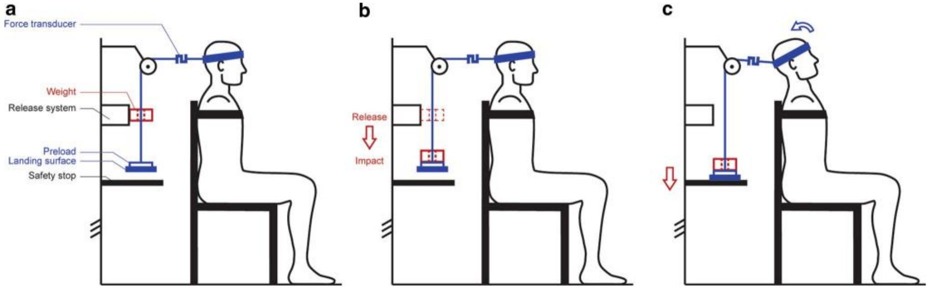




Zhang et al., *IROS* (2020)

Potential Research

- Study neuromuscular response to perturbation



Le Flao, Brughelli, Hume, and King, *Sports Medicine* (2018)

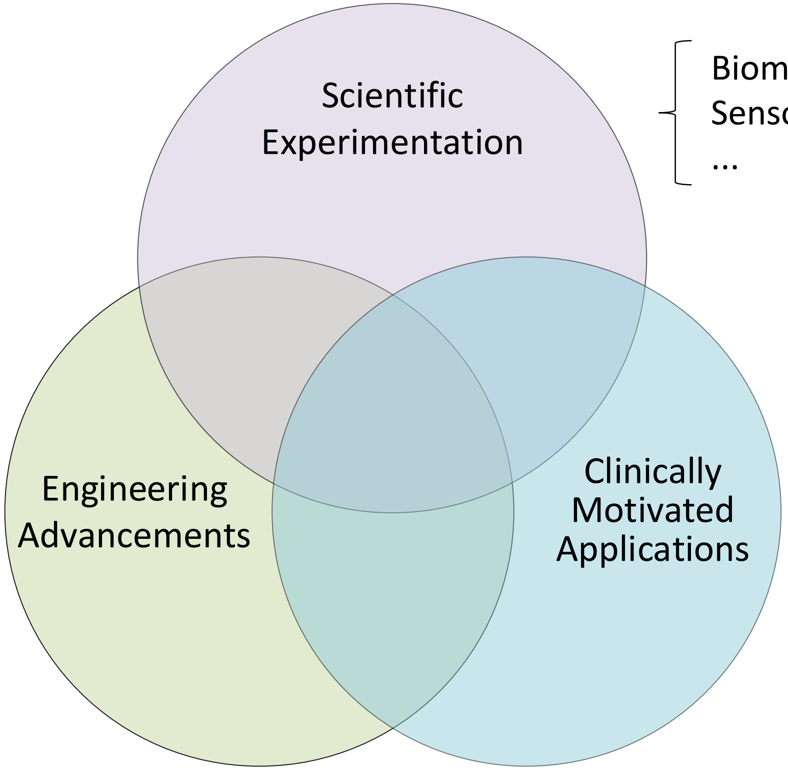
- Render forces (g-force, impact, etc.)

https://www.cxcsimulations.com/

https://en.wikipedia.org/wiki/Flight_simulator

- Training/evaluating motor functions

Converging Research Themes



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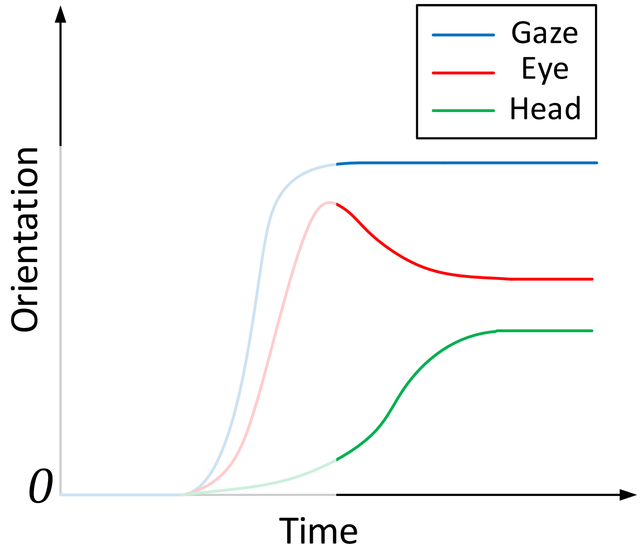
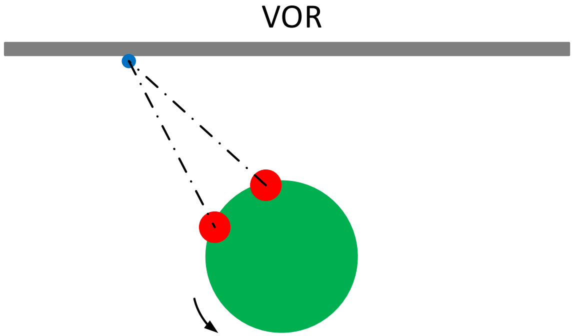
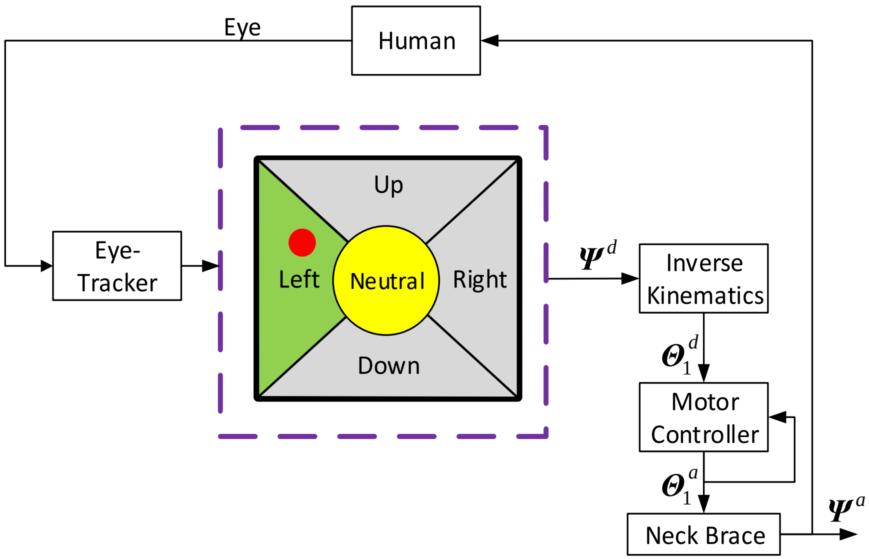
Bio-inspiration

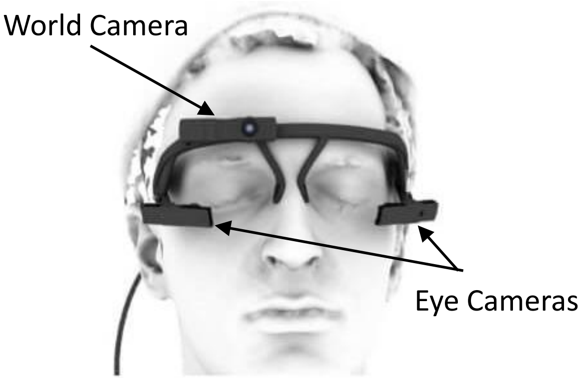




Head-eye response to a target in the field of view

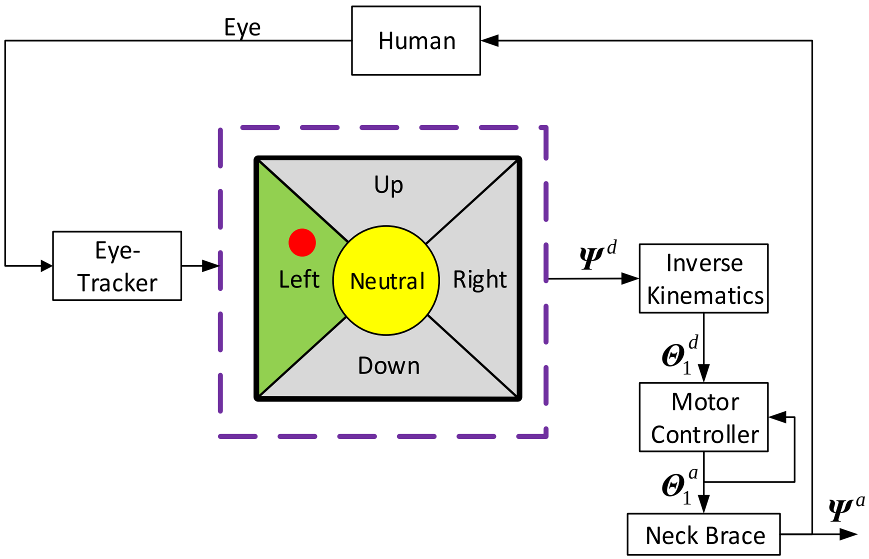
Prior Work – Bioinspired Eye Control





Chang, Zhang, and Agrawal, *BioRob* (2020)

Prior Work – Bioinspired Eye Control



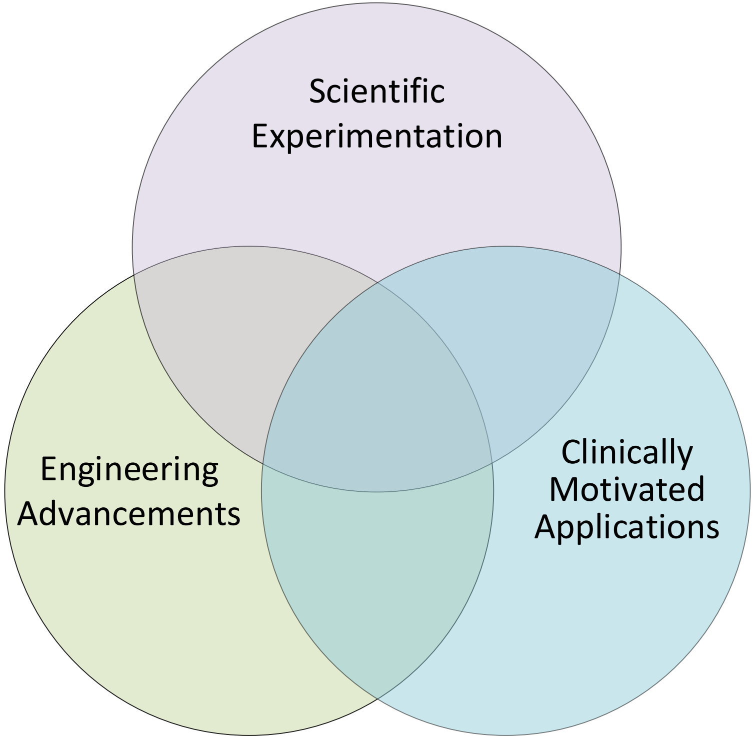
- This controller is proved to be correct;
- But, this rule-based controller is not intuitive and intelligent enough.
  - Data-driven approach
  - Adaptive control
  - End-to-end learning

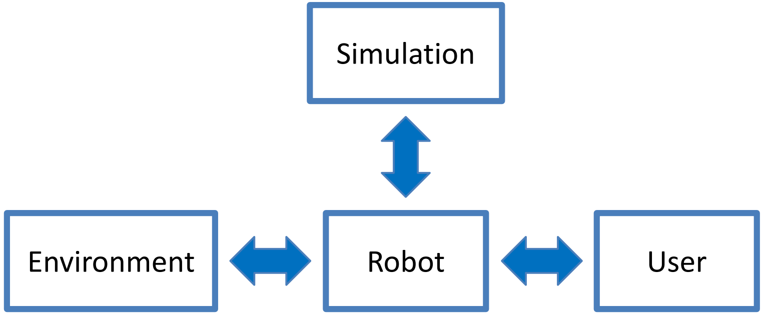
Takeaways

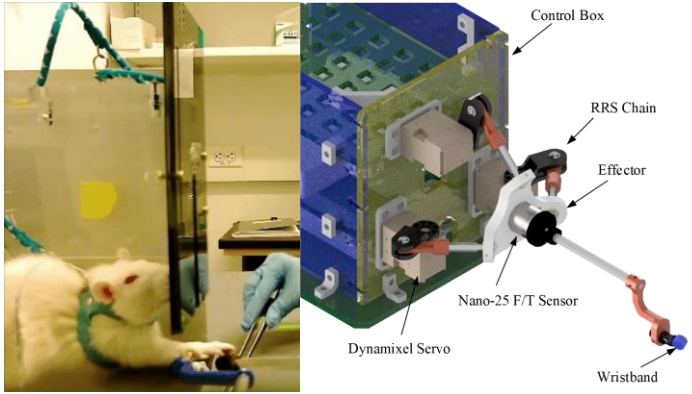
- A wearable robotic neck brace has been developed for head drop, but has promising potential to also contribute to other clinically or scientifically motivated research.

- Head-neck rehabilitation using robotics is a new but exciting field. The research topic is multi-disciplinary and diverse, calling for experts in many fields to contribute.

Takeaways







Zhang et al., *Journal of Mechanism and Robotics* (2021)

Acknowledgements

Advisor

Students

Funding

NSF

ALS ASSOCIATION

Collaborators

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THANK YOU!