Pneumatic Shoulder Exosuit Project Overview

Summer 2025

RAL Paper

Green: Finished; Orange: Doing; Black: To be done

To-Do List - RAL Paper

Task	Lead Person	Supporter	Deadline
Make control block diagram figure	Antonio	-	9/12
Test noise (compare v1 and v2 with muffler, enclosure, anti-vibration)	Antonio	-	9/15
Plan to resolve actuator wearbility - supplies purchased	Suzanne	Muxiao, Sreenidhi, Josephine	9/19
Characterize step response of system	Antonio	Suzanne	9/19
Make pump/control box wearable	Antonio	Suzanne	9/22
Transfer function and bode plot for desired vs. actual pressure	Antonio	Suzanne	9/26
Static torque characterization (varying angles/pressure) of actuator	Suzanne	Antonio, Muxiao, Sreenidhi, Josephine	9/26
Control box v2 shipped to NYU (Antonio done all testing on his side)	Antonio	-	9/30
Dynamic torque/hysteresis modelling	Suzanne	Antonio	10/20
Actuator wearability issues resolved (easy don/doff, armpit gap, arm cuff)	Suzanne	Muxiao, Sreenidhi, Josephine	10/17
Finalize plan for human subject testing	Suzanne	Antonio	10/17
Complete human subject testing (5 subjects - IMU, EMG)	Suzanne	-	10/22
Paper first draft complete (up to 8 pages)	Antonio, Suzanne	-	10/24
Paper ready to submit	Antonio, Suzanne	-	10/31

Pillar Table

Problem 1: SOTA pneumatic exosuits use model pressure instead of torque. This is less useful since pressure then has to be converted to torque to compensate for arm weight or other load. Usually involves user calibration testing, but would like to eliminate this step.	**Problem 2:** Control box for pneumatic exosuits can be very loud due to the air pump, making them unpleasant to use. There is a need to explore ways to reduce the noise level.
Objective 1: Model torque directly as a function of angle, pressure and change in pressure. Can use this torque model to know how much support the exo is providing.	**Objective 2:** Evaluate different methods of noise reduction and compare. Also consider trade off of extra weight and size.
Method 1: Use a simple NN to model the torque given angle, pressure and change in pressure. The data is collected via a benchtop test (to get ground truth torque) at a series of fixed angles and tracking a sine wave of pressure at different speeds.	**Method 2:** Consider three noise reduction techniques and their combinations: silencer, padded enclosure, anti-vibration mounting. Test sound levels with each method and compare.
Results 1: Evaluate NN on test data to show strong predictive ability for torque. In human subject test, use to monitor torque provided by robot while user completes tasks. Show that EMG is lower using exo than with no exo, even in absence of calibration test.	**Results 2:** Show reduction in noise level when using these techniques and rank in terms of usefulness, considering effectiveness of reducing noise, weight, cost and size.

Torque Modelling

NN

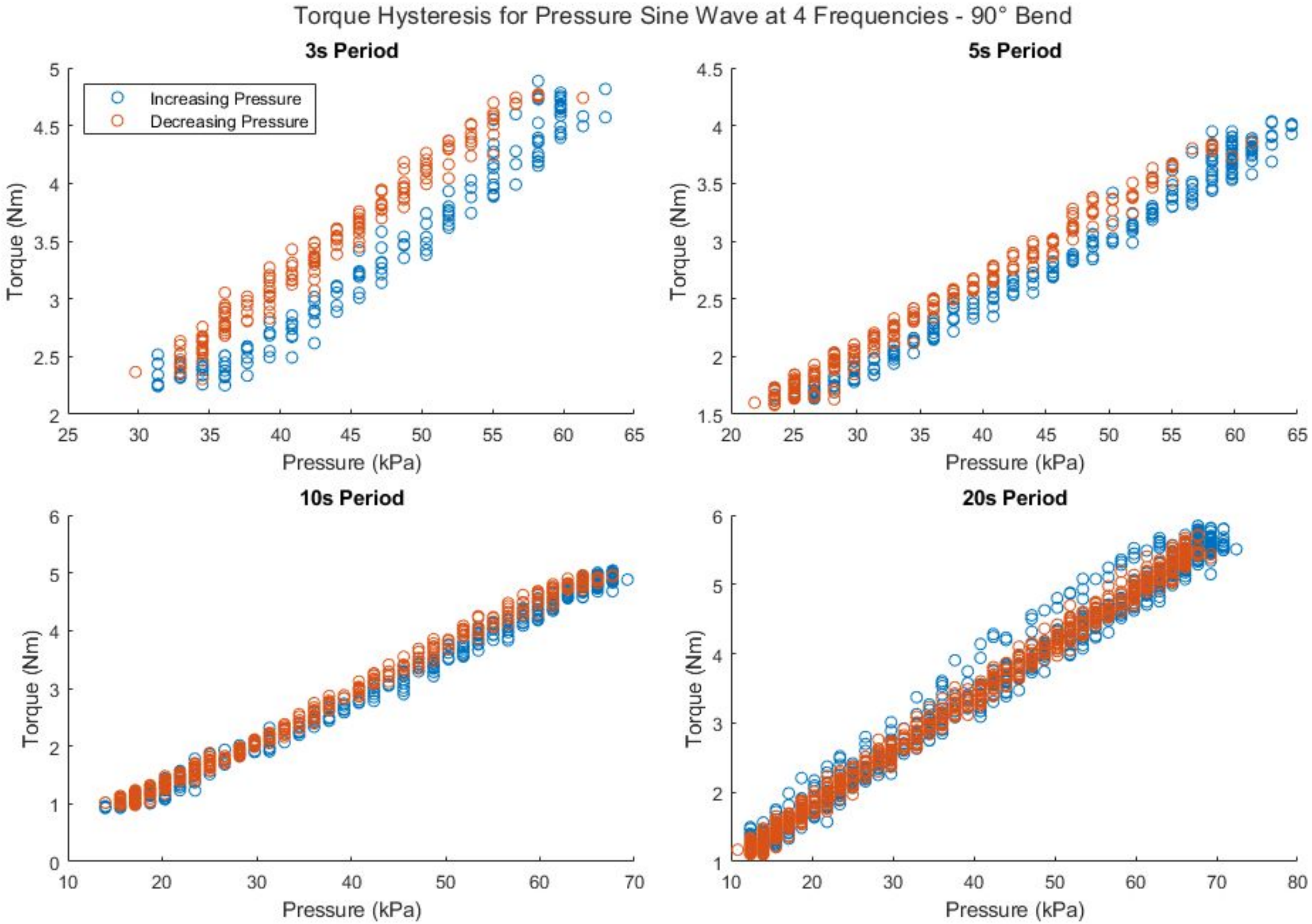
- Inputs: pressure, angle, change in pressure*
- Output: Estimated torque
- Layers:
  - 2 hidden fully connected layers with 10 nodes each and relu activation
  - Drop out layers to prevent overfitting
  - 1 output node with linear activation

Additional Notes:

- From experiments (see next slide), we see hysteresis effect is much more important when pressure is changing quickly - thus change in pressure is an important parameters
  - Results show including change in pressure reduces RMSE of model

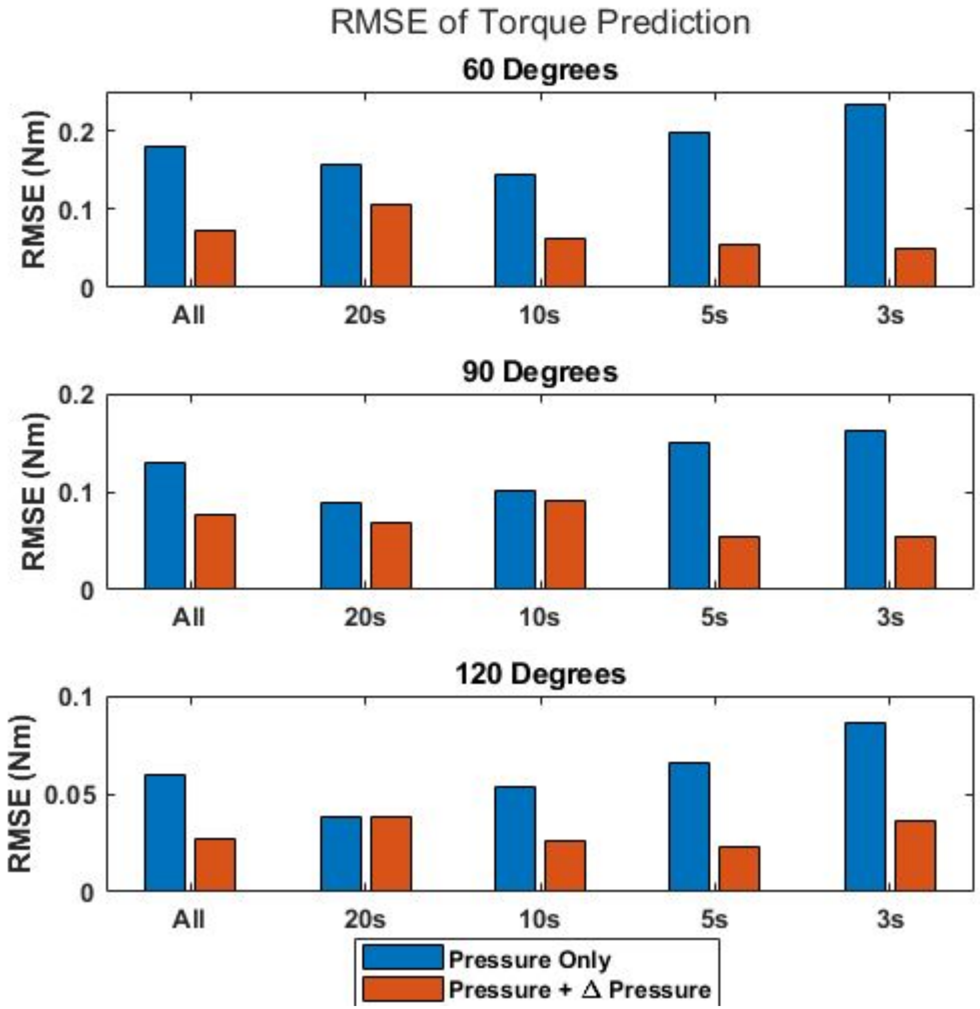
Torque Hysteresis

- Hysteresis modelling of torque vs. pressure at a set angle
- Found that hysteresis is more prevalent at high inflation/deflation speeds (acts like a damper)
- Working on modelling torque using pressure and change in pressure to incorporate hysteresis



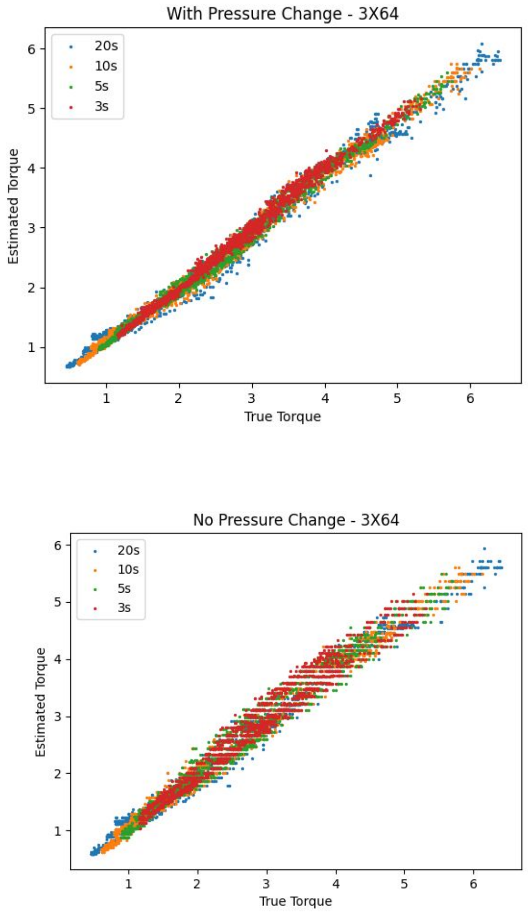
Torque Hysteresis Modeling

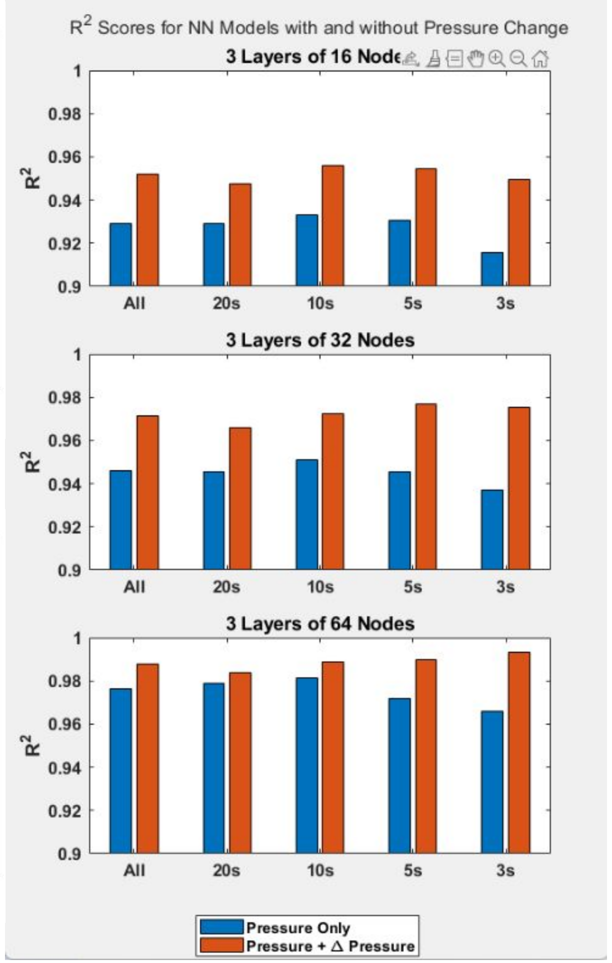
- Before doing NN, start with linear model
- Made two linear models to predict torque
  - One with only pressure as input
  - One with pressure and change in pressure as input (rate of change of pressure captures hysteresis effect)
- Model with change in pressure is better - particularly for fast cycles with more hysteresis



NN - Test and Train Both on Benchtop Results

- Need to finalize model size for NN
    - Larger models better performance, but slower/more memory
- See decline in performance for fast cycles for NN without change in pressure input



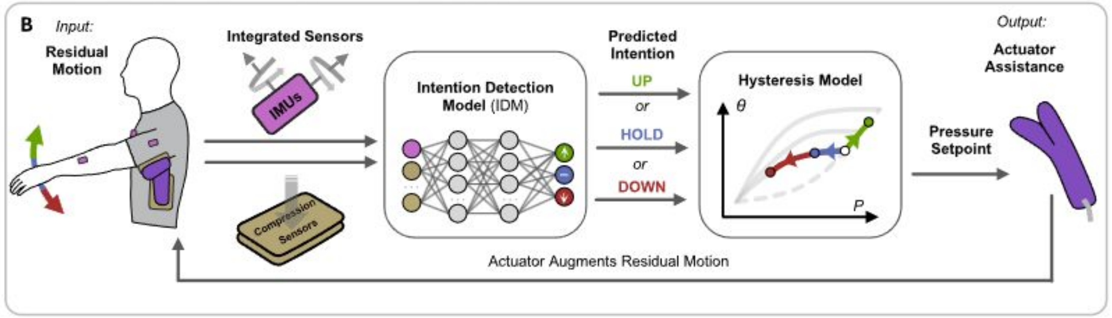


Torque Estimation - Human Test Challenges

- Benchtop model does not translate well to human test
  - Problem 1: Using estimated torque from weight and angle of arm as ground truth - not completely accurate, especially when arm moving up or down
  - Problem 2: Difficult for user to maintain limp arm consistently during test
  - Problem 3: Actuator attachment is different for benchtop and vest, so torque is different
- Potential Solutions:
  - Test on mannequin instead - guarantee no muscle activation and can get better estimate of weight. Plus can vary torque needed by adding weights
  - Scrap benchtop testing and instead rely on human subject testing and do leave-on-out method to validate
  - For future work: set up test frame that utilizes the mannequin instead of benchtop frame. This ensure attachment is similar in testing and use on humans. Would likely require too much set up to complete for 10/31 deadline.
- Plan
  - Start with mannequin idea and see if that works
  - If not, try human testing idea. This is likely to work but risky, because we cannot verify until we complete all human testing.

Harvard Nature Communications (Link)

- Note: The Harvard paper is primarily focused on the intention detection system. Since the RAL is not about intention detection, many of the limitations of that paper do not apply here. We can more directly use these for the follow up control paper.
- Limitations we can address in the RAL
  - **They use a model-based approach for the hysteresis** to convert between up/down/hold outputs from the NN and desired pressure. We can instead do a NN to eliminate assumptions made by a mathematical model.
  - **They have to train the model separately for each individual and predict pressure instead of torque.** Their model cannot adapt if the user picks up an object (thus changing the weight of the arm). Since our model outputs torque instead of pressure, the torque of picking up an object (of known weight) can be added directly added to the torque required by the system.
- Limitations to address to future controls paper.
  - Too many sensors. They used 3 IMUS and 3 compression sensors. We will use only 2 IMU sensors only to reduce setup time/cost/complexity.
  - Their NN is very simple but the ID problem can be complex. A more sophisticated network should be able to improve on these results. For our torque modelling, the surface is simpler, so a simpler model is appropriate.
  - Their model is categorical, it can only output UP, DOWN or HOLD, and the UP and DOWN outputs result in changes in angle of a step size of 5 degrees. This is not truly continuous as we plan for our model to be.



Human Subject Testing Plan

- Abduction test
- 5 subjects
- EMG - check Harvard/cable driven paper for muscles
  - Deltoideus Anterior
  - Deltoideus Medius
  - Trapezius Transversalis (middle)
- Static Holding Tasks
  - 1 minute
  - 90 degrees
  - Use body weight/height to decide how much torque to provide
    - Do 50% torque for the user
  - With exo and no exo conditions - randomize order
- Dynamic test
  - User is slack - no muscle activity above baseline
  - Robot pressure tracks sine wave
  - Use angle for estimate torque using body weight
  - Then compare to NN estimated torque

Human Subject Protocol

1. Go through consent + eligibility. Explain experiment. Get subject demographic information (height, weight, age, gender).
2. Place EMG sensors on (1) anterior deltoid, (2) medial deltoid, (3) upper trapezius, (4) biceps brachii (follow seniam guidelines). Check sensors are responding.
3. Do EMG MVC tests for each muscle.
4. Help participant to don exosuit. Ensure proper fit. Do test run to familiarize with feeling.
5. Dynamic Torque Test: Do each of the following tests in order randomized for each participant. Participant instructed to keep their arm limp while exosuit cycles through different angles and pressures. Each test should last for 3 minutes. Participant should not see arduino or arm angle information during this test to avoid anticipating angle. Participants can see their EMG data so they can self correct if they start to activate muscles. Record EMG, IMU (angle) and pressure (desired and actual).
   a. Follow sine wave from 0-100 kPa with period of 20 seconds. Arm straight.
   b. Follow sine wave from 0-100 kPa with period of 10 seconds. Arm straight.
   c. Follow sine wave from 0-100 kPa with period of 5 seconds. Arm straight.
   d. Follow mixed sine wave from 0-100 kPa with equally weighted signals of periods 20 and 7. Arm straight.
   e. Follow sine wave from 0-100 kPa with period of 20 seconds. Arm bent (hand on shoulder).
   f. Follow sine wave from 0-100 kPa with period of 10 seconds. Arm bent (hand on shoulder).
   g. Follow sine wave from 0-100 kPa with period of 5 seconds. Arm bent (hand on shoulder).
   h. Follow mixed sine wave from 0-100 kPa with equally weighted signals of periods 20 and 7. Arm bent (hand on shoulder).
6. Endurance EMG Test: Randomize the order of these two tests for each participant. Participant can see angle their arm is at (from alubi EMG) to ensure they are staying at desired angle. User holding 1kg.
   a. Without exo: Participant should hold arm at 90 degrees abduction for one minute. Record EMG and IMU.
   b. With exo: Calculate pressure needed to support half of users biological arm torque at 90 angle, using static benchtop pressure results and participants height/weight. Participant should hold arm at 90 degrees abduction for one minute while exo is pressurized to this pressure. Record EMG and IMU.
7. Remove sensors and exosuit from participant.

Project Objectives and Plan

Pillar Table

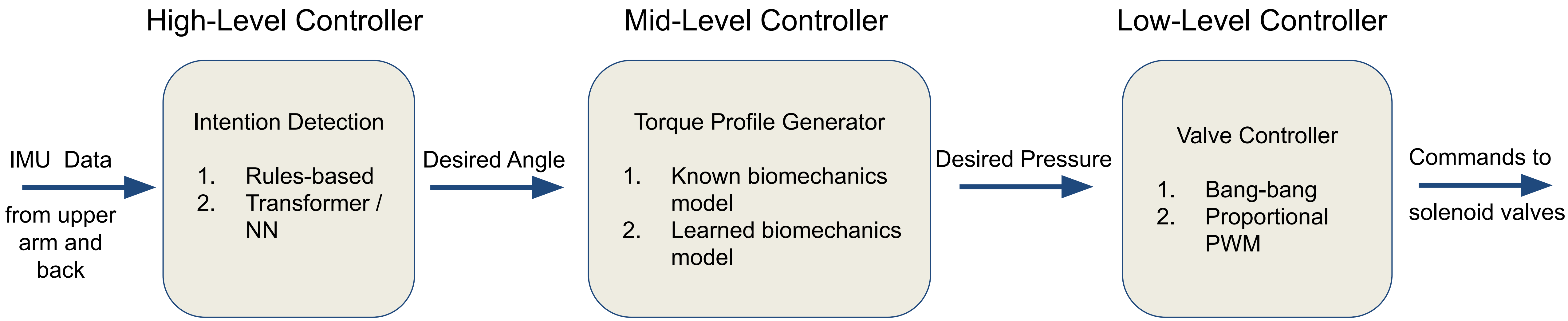
Problem 1: Intention detection in SOTA exoskeletons is not good enough. Other systems have no intention detection (most)or only have two states (inflated or deflated) so cannot handle all tasks, such as placing items on shelves of different heights.	**Problem 2:** SOTA exosuit controllers are not able to adapt to change in user's weight if they pick up/put down an object. Currently, SOTA controllers can be calibrated for a new user to set the desired pressure when inflated, but cannot adapt if the pressure needed to reach the inflation angle changes.
Objective 1: Improve on SOTA intention detection by allowing for continuous prediction angle (rather than inflated/deflated only).	**Objective 2:** Create a more adaptable controller that can 'learn' and update the mapping of pressure to angle throughout the task, allowing for the controller to automatically adapt when a weight is added or taken away.
Method 1: Use IMU sensors to detect user's motion. Create NN to translate IMU readings into predicted intended angle. Will need to collect data on human subjects moving their arms to various angles to build network. (note: start with rules-based version first).	**Method 2:** Create a controller that continuously updates the expected relationship between the pressure and angle based on feedback from the IMUs.
Results 1: Test on human subjects by instructing users to move arm to different angles and compute angle error for NN predicted angle.	**Results 2:** Test on human subjects as they complete tasks that involve picking up/putting down objects (pick-and-place) and see how expected mapping between pressure and angle changes. Compare angle error to static controller that does not adapt when objects picked up/put down.

To-do List - Controller

Green: Finished; Orange: Doing; Black: To be done

	Task	Person	Supporter	Complete By
1.	Integrate IMU sensors, convert IMU readings to angle, and create GUI showing IMU and pressure readings	Suzanne	-	6/30
2.	Create ‘rules-based’ version of high-level controller	Suzanne	-	7/15
3.	Create ‘known biomechanics’ version of mid-level controller	Suzanne	-	7/31
4.	Create ‘learned biomechanics’ version of mid-level controller	Suzanne	-	8/15
5.	Implement NMPC controller based on Righetti lab	Suzanne	-	9/1
6.	Create NN-based version of high-level controller (including subtasks of picking network architecture and data collection to build model)	Suzanne	-	9/21
7.	Data collection of subjects using exoskeleton, measuring IMU and EMG during ADL	Suzanne	-	10/15
8.	Data analysis and paper first draft	Suzanne	-	10/21
9.	Paper editing	Suzanne	-	10/31

Control Block Diagram



For high-level, start with simple rules-based controller (i.e. inflate more if arm rising, inflate less if arm lowering).

Once working, transition to novel NN-based controller (this is contribution for paper).

For known biomech model, weight of arm is known, so desired angle to desired pressure is simply linear relationship (but cannot adapt to new user, added weight, elbow bending)

For learned biomech model, relationship between angle and pressure is unknown (still assumed linear but proportion can change)

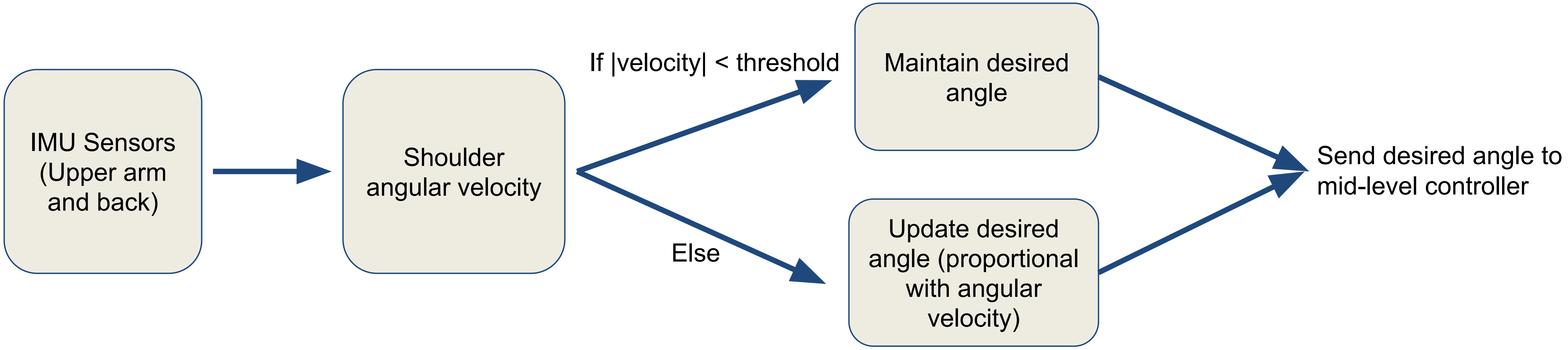
Both versions are continuous so could be seen as contributions of paper, but learned model also addresses changes in user/elbow position/weight held

Bang-bang controller is likely sufficient

Can make a bit more advanced with proportional PWM if needed

High Level Controller (Intention Detection)

Rules-Based:

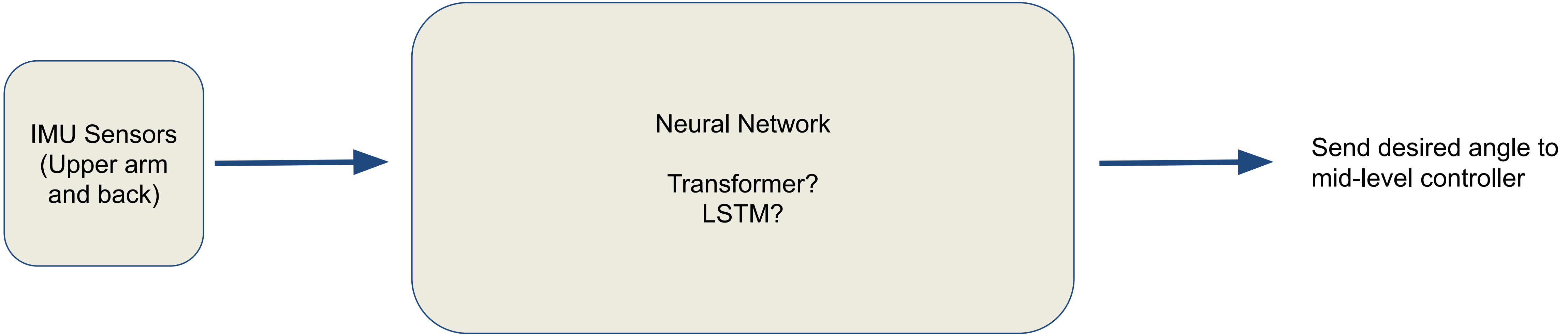


Notes:

- need to tune threshold and relationship between velocity and angle update
- rules-based version temporary first step, will transition to NN

High Level Controller (Intention Detection)

Neural Network:

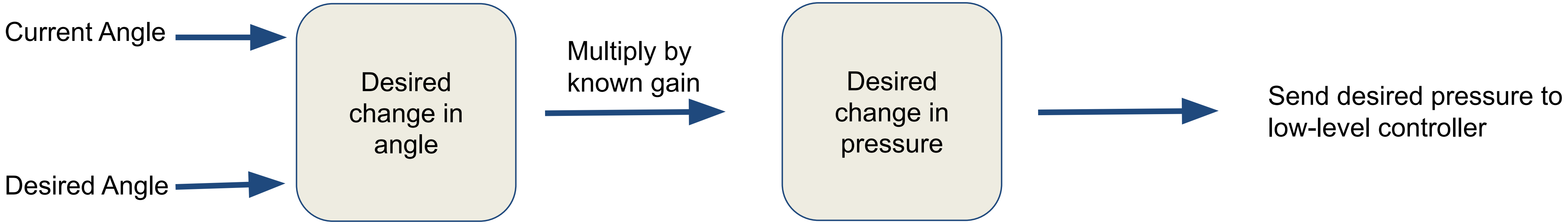


Notes:

- Need trials of various users lifting/lowering arm to different angles to train (ideally also while user is holding different weights)
- Talk to Haoran about suggestions for NN architecture

Mid-Level Controller

Known* biomechanics:

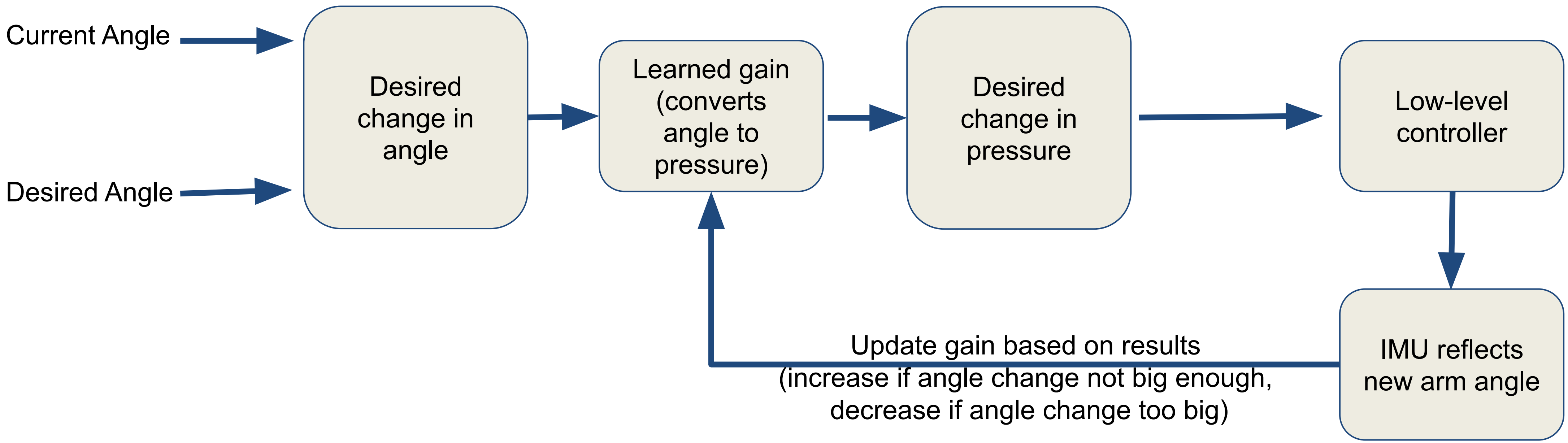


Notes:

- *known biomechanics here means the relationship between angle and pressure is known because arm weight is known (likely change this language)
- From lit review , proportional relationship between pressure and angle is reasonable assumption (note: lit review results limited to benchtop tests)
- Start with this and see if it works well. May need to make investigate more complex pressure/angle relationship or can move on to learned biomech controller

Mid-Level Controller

Learned biomechanics:

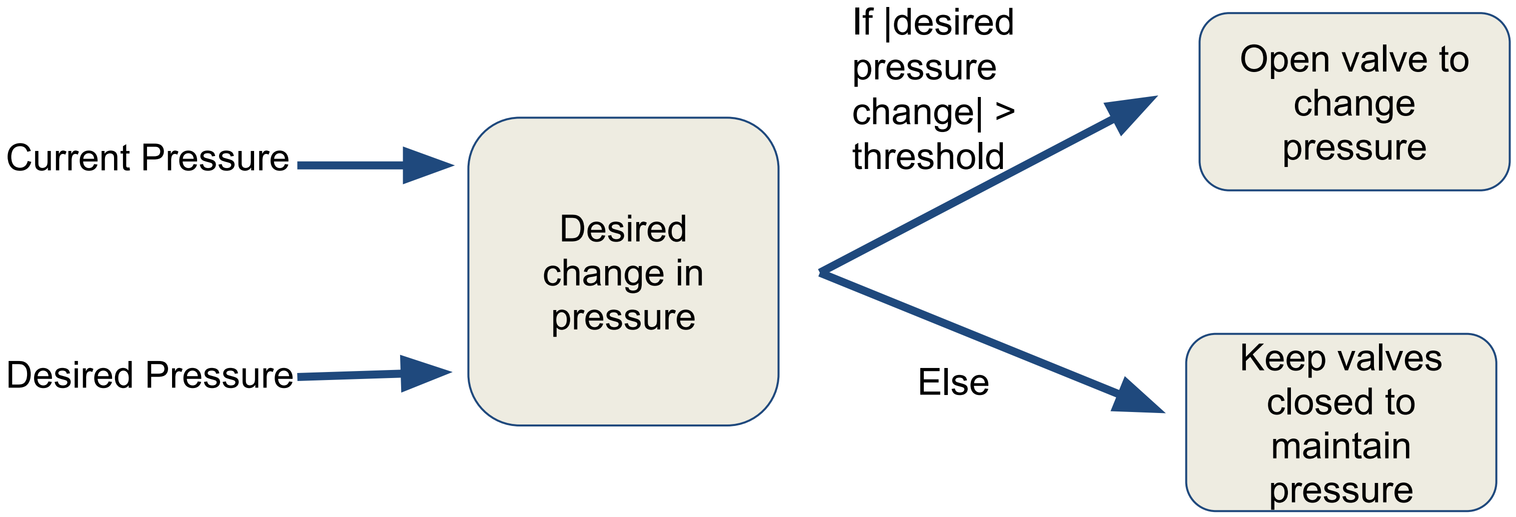


Notes:

- Instead of constant, pre-determined relationship between angle and pressure, let that relationship be a learned parameter, that updates while the robot is in use
- Gain here (describing relationship between angle change and pressure change) is learned and updated during robot use
- Thus, can adapt if load changes, such as user picks up object or bends elbow

Low Level Controller

Bang-Bang with hysteresis:



Notes:

- This is very simple but sufficient to get started
- Can upgrade to proportional PWM or other low-level controller if needed
- From preliminary testing, for large changes in pressure, this is basically equivalent to the PWM currently encoded for this robot
- Not a contribution of the paper

Human Subject Testing Plan

- 5 subjects - gender balance, healthy young adults
- Sensors
  - EMG sensors on upper arm and back
    - See seniam to decide on sensor placement
    - Need to try on wearables to finalize placement/avoid interference
  - IMU sensor to get arm angle
- Get MVC while resisting user lifting their arm (and something for the back?)
- Test - arm abduction hold
  - Test arm abduction at 90 degrees for ? seconds?
    - Research how long people can hold their arm out to decide length
  - They could also hold a small weight? Or just keep it simple
  - Do no help condition, 50% of estimated assistance, 100% of estimated assistance
    - Try this first on self to feel if useful to do two exo conditions here
- Metrics to Consider:
  - Muscle activity (RMS of EMG) as % of MVC
    - Expect lower muscle activity when exo is helping
  - Steadiness of angle - maybe easier to maintain position with exo help

Project 1 Details - GUI Progress

Video of GUI showing actuator and accumulator pressure with oscillating desired pressure

Note: this was a bench top test, so IMU readings do not correspond to changes in actuator pressure

Adapting to ALS Patients

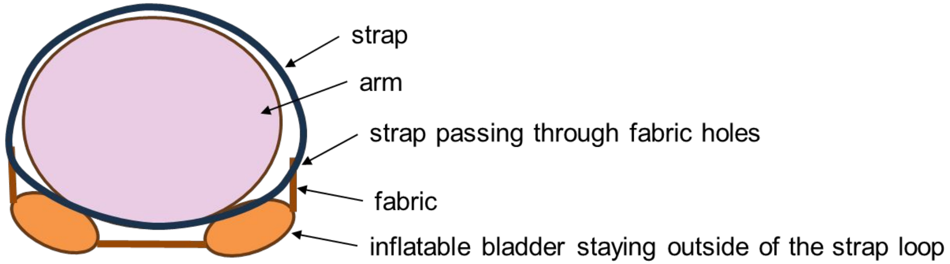
- Long-term goal of this exoskeleton is to create something useful for patients with ALS
- Controller (high-level motion intention detection with IMU and mid-level arm weight detection) can be adapted for use in ALS patients
- ALS patients often have tremors, which will affect IMU. Need to add filter or retrain NN for ALS patients to account for this.
- ALS patients often experience muscle weakness, so adaptive mid-level controller is specifically useful for these patients, who may not be able to compensate for increased weight of held objects or incorrectly tuned controller.

Problems

Wearability Concerns

- Identified: 25-09-04 by Suzanne
- Problem: The exoskeleton is not comfortable to wear or easy to don and doff. The current design pinches the skin of the users upper arm. Additionally, using the velcro straps requires dexterity that the user may not have.
- Proposed Solutions:
  - Try sewing into jacket (with non-stretchable fabric) to make it easier and simpler to don and doff
    - Note: this was previously attempted but jacket was too stretchy, so did not work correctly
  - Attach to the upper arm using a different strap, that does not pull as the actuator inflates (see diagram)

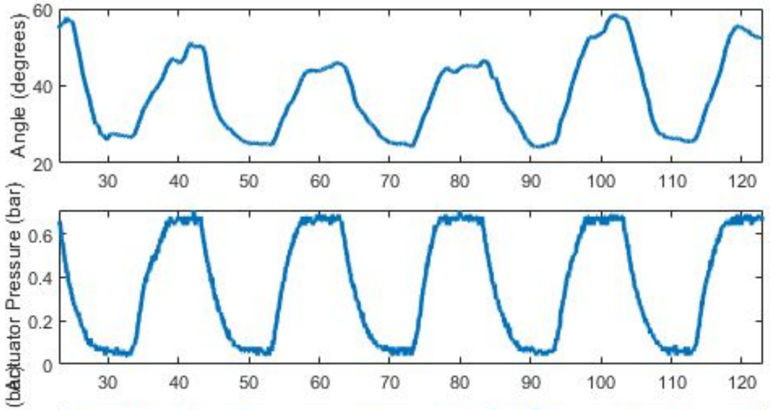
Illustration of the attachment around the arm - section view



Insufficient Range of Motion

- Identified: 25-09-04 by Suzanne
- Problem: The exoskeleton angle range of motion is only about 25-60 degrees (for pressures ranging from 0.02 to 0.7 bar, on 130lbs female subject). This is not enough range of motion for ADL. ([see video here)](#)
- Proposed Solutions:
  - Potentially there is too much gap between the armpit and the exoskeleton. Tightening or adding a strap around the upper chest could help with this problem.

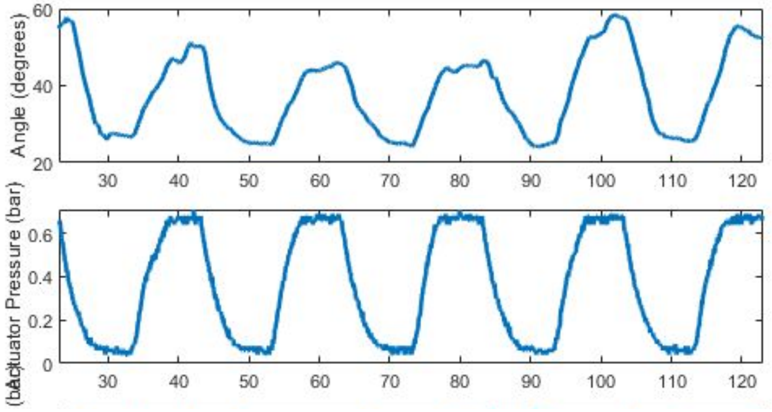
Limited Angle Range:



Proposed Solution:

Non-Zero Angle at Low Pressure

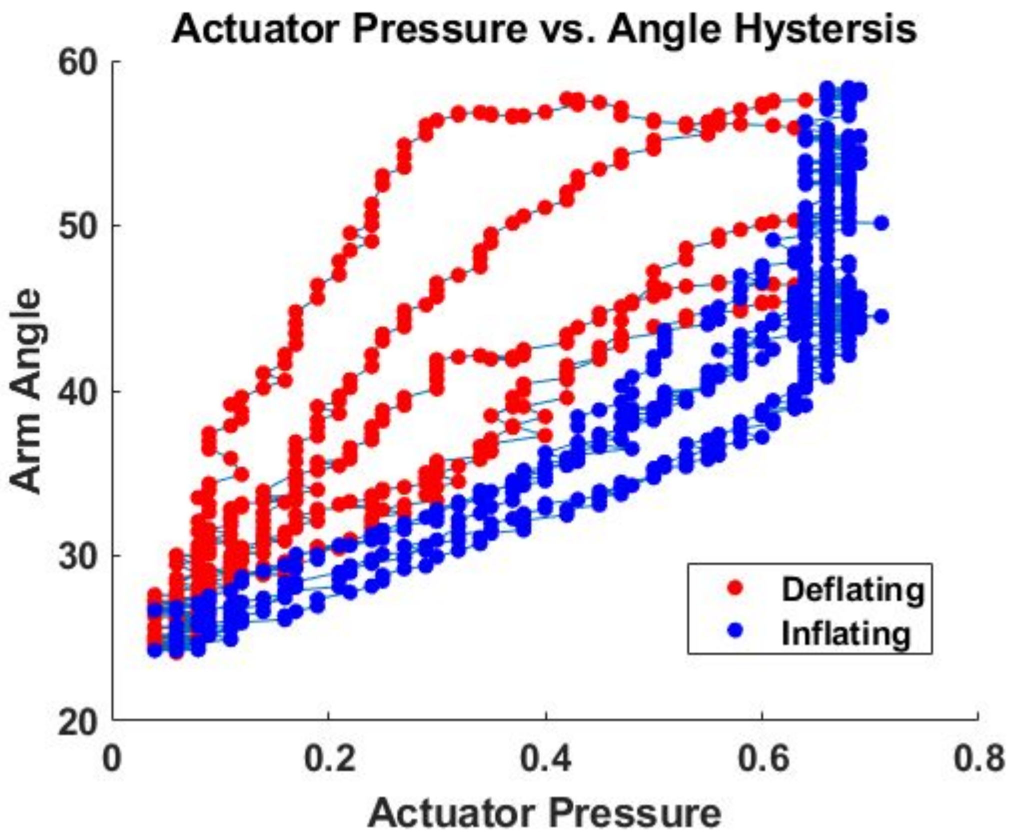
- Identified: 25-09-04 by Suzanne
- Problem: Even at very low pressures (0.02 bar), the arm angle does not return to zero, but instead remain high at about 25 degrees. This would not be comfortable for use and would restrict the user. (see video here). Note this does not happen when exo is totally deflated (i.e. before turning on) but on subsequent pressure cycles.
- Proposed Solutions:
  - Try setting pressure to slightly below zero. This could be due to a sensor error (sensing lower pressure than is truly in the actuator) that leaves more pressure than is requested.



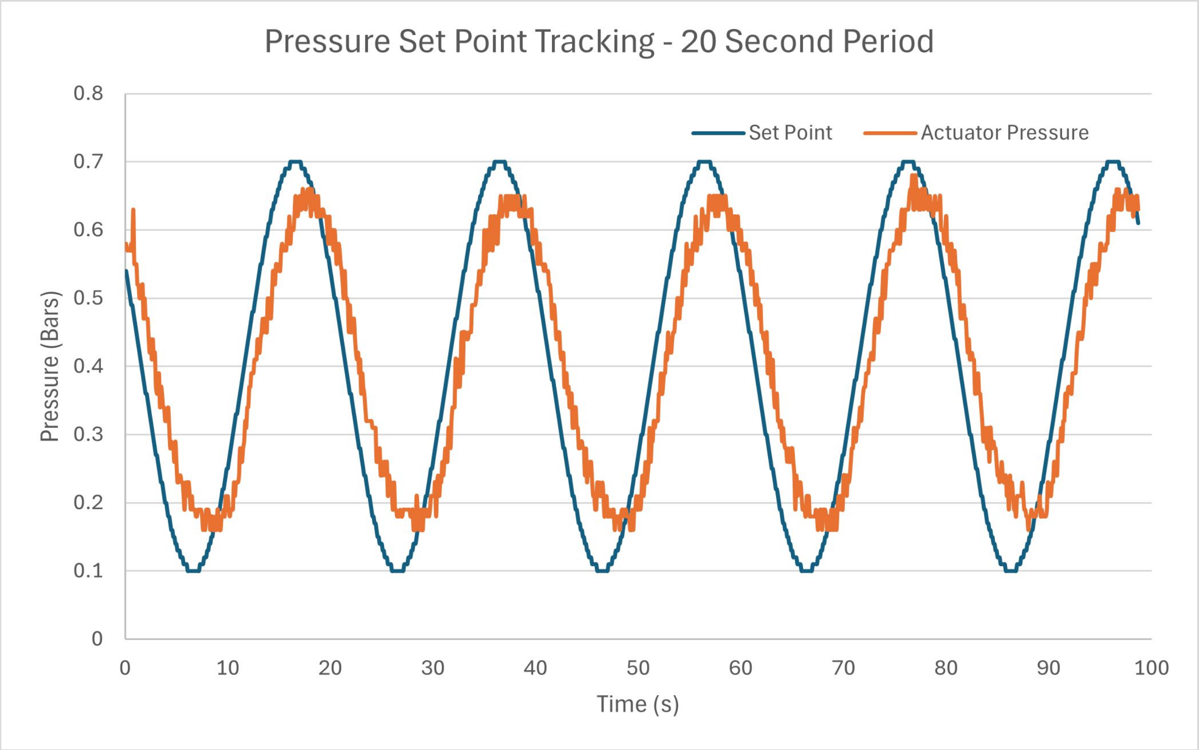
Testing

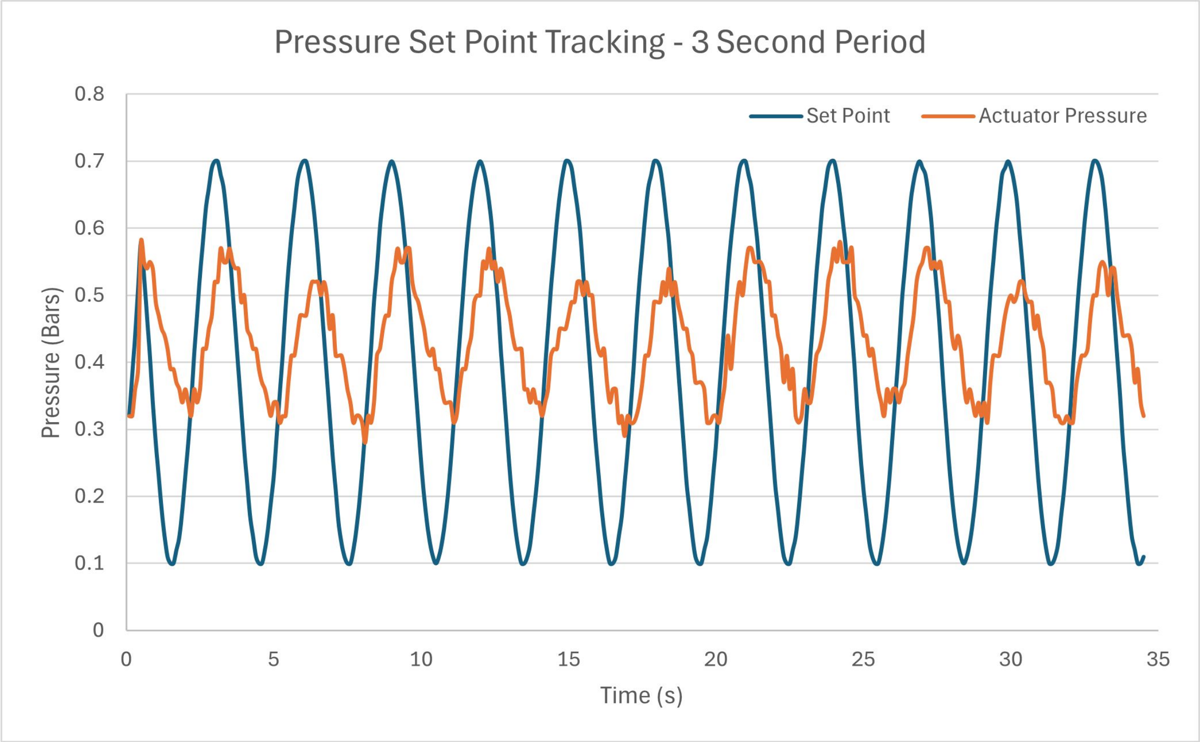
Hysteresis Test

- Date: 25-09-04
- Tested on one subject (female, 5'7", 130lbs) at pressures ranging from 0.02 to 0.7 bar, over 20s cycle. Subject help arm straight throughout test, but otherwise did not activate muscles.
- Hysteresis is evident (as expected) and there seems to be more angle variability when deflating compared to inflating.
- Angles only vary from ~25 to 60 degrees, not sufficient for range or motion.



Exosuit Pressure Tracking





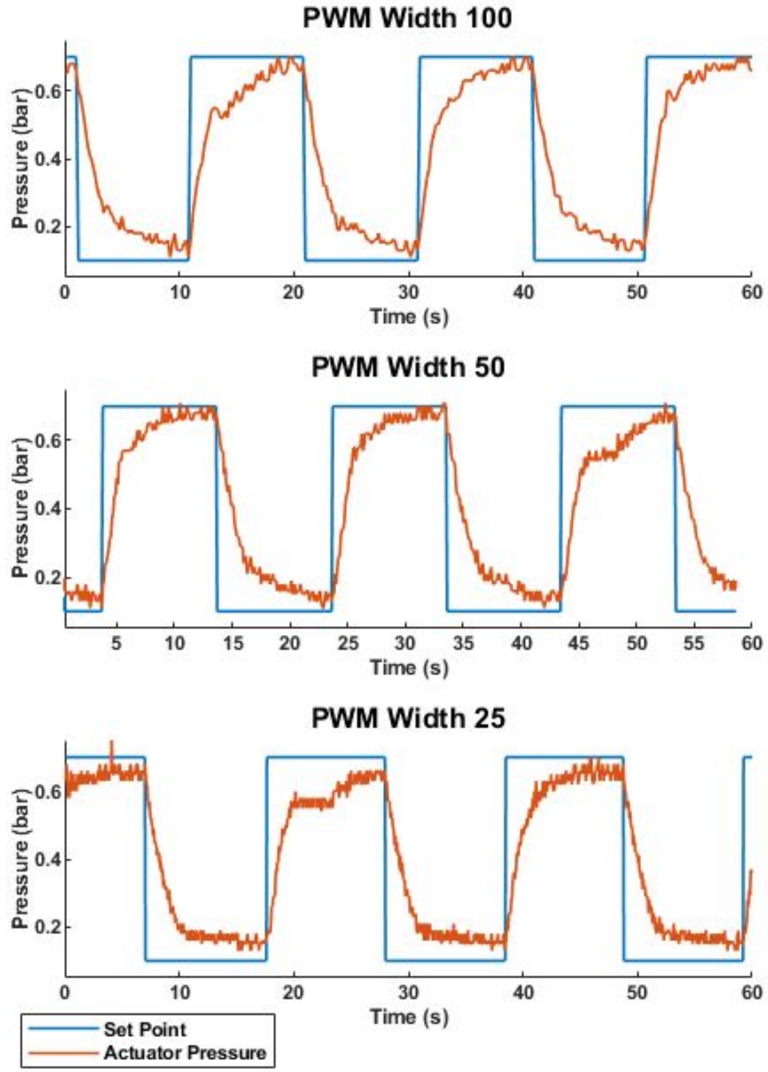
- On current settings, 3 seconds/cycle is too fast to track this pressure sine wave
- Variables to consider:
  - What range of pressures do we actually need to support the arm
  - How does changing valve PWM affect pressure tracking
- Note: Harvard paper sets target of 10 seconds/cycle

Speed Tests

- Also tested different PWM pulse widths for controller to reach set point that oscillates between 0.1 and 0.7 bar every 10 seconds
- Very similar errors for all PWM widths
- Can't quite reach set point due to tolerance factor built into code (might be interesting to adjust)
- Smoother values for wider pulse width
- Valves switching on/off a lot more for short width, could affect power consumption?

Error between set point and actual actuator pressure

Pulse Width (ms)	MSE (bars)
100	0.0323
50	0.0335
25	0.0313

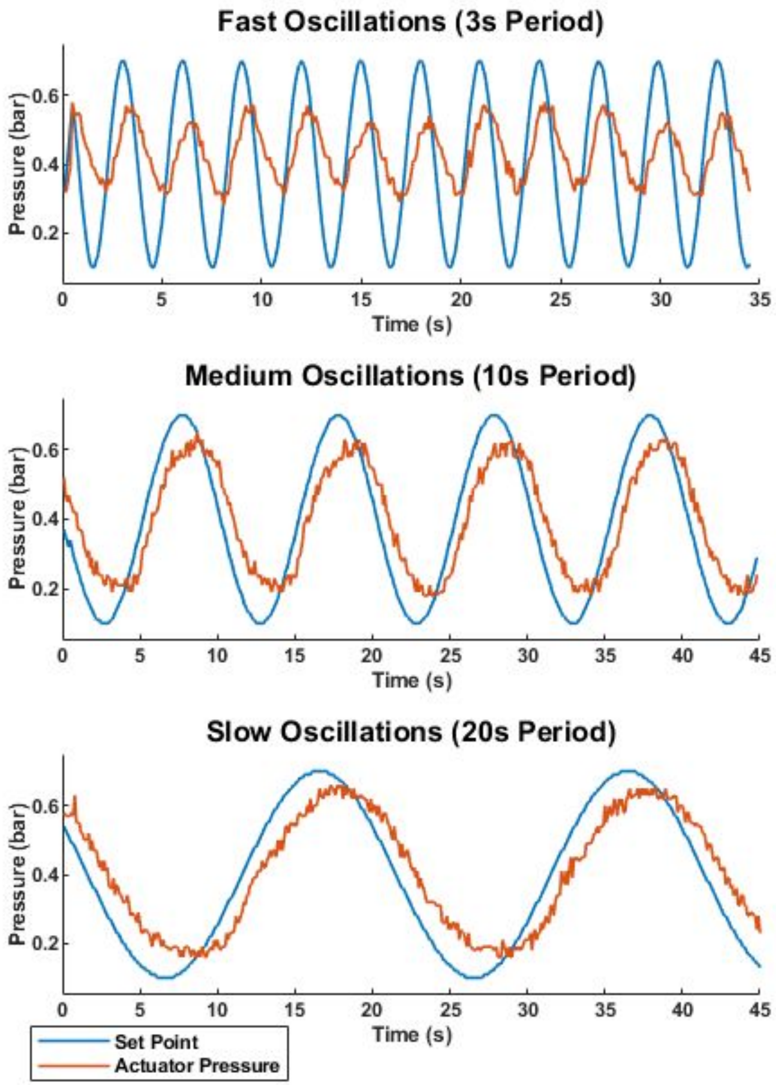


Speed Tests

- Big difference in performance when going from 3 second cycles to 10 second cycles
- Slight improvement again when slowing down further to 20 second cycles
- All with PWM width of 50ms
- Note: Harvard paper sets target of 10 seconds/cycle

Error between set point and actual actuator pressure

Speed	MSE (bars)
Fast	0.0320
Medium	0.0115
Slow	0.0086



PWM Gain

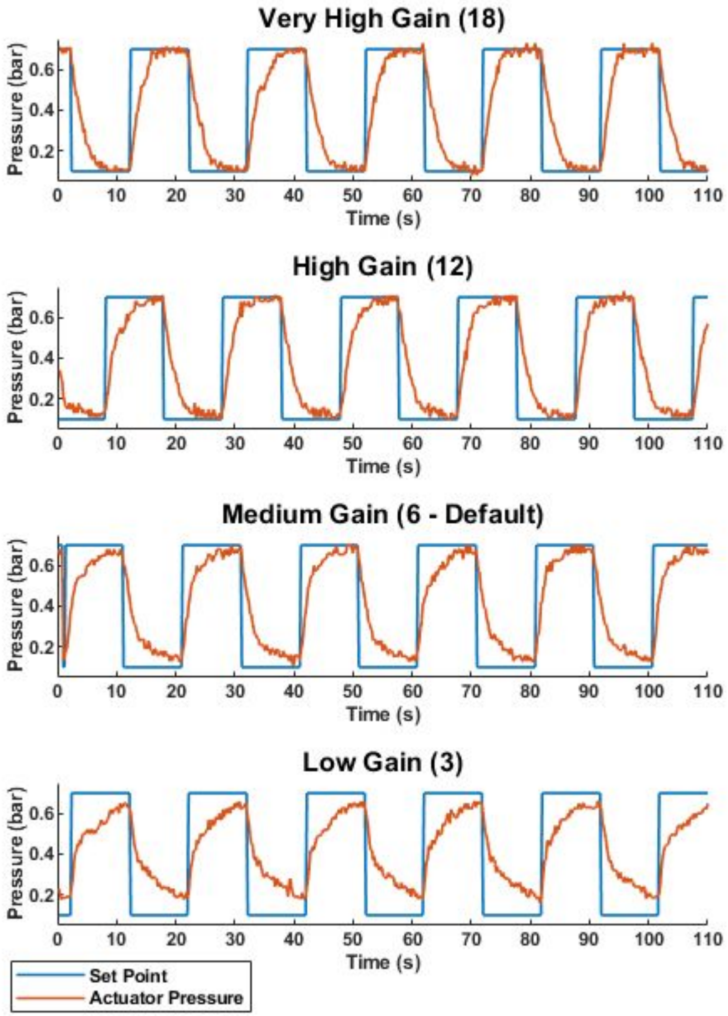
- Tested 4 levels of PWM gain
- Note at higher levels of gain, when error is large, the gain saturates (as valve stays open for maximum time), so there is a limit on how quickly we can adjust to big errors
- All gains <=6 have similar performance for large errors in set vs. actual pressure due to saturation
- There is also a lower saturation where the valves stay closed - we see this for the gain of 3 and 6 where the pressure levels out without quite reaching the target values
- Testing done with PWM pulse width of 100 and 10 second cycles

output is error*gain

```
void pneumatic_PWM(int valve_PIN, float output) {
  if (output < 0.2) { output = 0; }
  if (output > 1) { output = 1; }
```

PWM Gain

- Gain of 3 is too low (slower and does not reach target value)
- Gain of 6 (default value in code), 12 and 18 have similar profiles when the error is large due to saturation
- Gain of 12 and 18 are the only ones that consistently reach the target value within 10 seconds, though there is some chattering (switching between inflate/deflate), especially at 18 that might be less efficient. Gain of 6 often levels out around 0.67 instead of 0.7
- From a user perspective, difference between 0.67 bar and 0.70 bar is not noticeable, but still good to be precise if possible



Exo Try on

- Tried on exo to see how it feels to use it
- Was a bit difficult to put on by myself
- Seemed to arc away from my body at armpit without a strap there to secure it
  - Note: Can add additional chest strap to help with this, see Harvard paper
- 0.7 bar pressure seems quite high
  - My arm was supported with ~0.3 bar
- At higher pressures, either the velcro on my arm didn't hold, or it squeezed uncomfortably, like a blood pressure cuff
  - Note: stretchy velcro is recommended to avoid this

IMU Connection Notes

- ID of IMU (for connection page) is 00:04:3e:XX:XX:XX, where XXXXXX is the number on the sensor
  - Link (must be on raspberry pi network to connect)
  - Order matters in connection page. Typically 1 is trunk, 2 is left thigh, 3 is right thigh
  - See WL_IMU.cpp and WL_IMU.h in github (test_IMU folder) to see which pins correspond to which connection numbers

Meeting Notes

Meeting with Prof. Su - Notes

Date: May 29, 2025

Lit Review Format/Overall Notes:

2-3 slides on SOTA - include quadrants or line to show where different papers lie

Break into motion detection and torque profile generation

Ideally want to design end to end controller

Try to identify problems with cable exo as well

Ideally identify controller/solution for pneumo that is applicable to cable exo as well

In slides, include Control Blocks (Talk to Antonio): Planning -> Low Level Control

Get NMPC code + state estimation from IMU from Ludo

Re: Angle control idea: Don’t call it position control, continuous control is better

Areas to include in lit review/project idea generation:

- Motion/Intention Detection
  - Look into transformer - Haoran SWIM
  - See manifold in Rutgers
  - Frontiers (Switzerland)
  - ludo state estimation
- Torque profile generation
  - nMPC
  - gravity comp
  - RL
- Low level control for pneumatics - force control
  - **Continuous** control RAM paper Cornell Zhao
  - How to make faster/less noisy
- End to End Control (via learning in sim)
  - Ludo already has simulator
  - Nature paper
  - Drone nature paper from U Zurich Davide Sacamora

Links to Other PPTs

- Literature Review
- Paper Writing
- Project Updates Folder

- Exo Tutorial Slides