System Identification and Control of Anatomically Accurate Biomechanical Human Limb Models

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Background

Previous studies suggest that the neural responses in the motor cortex may be encoding:

1. High level parameters such as **elbow position**.
2. Low level parameters such as **muscle activity**.
3. Patterns of **goal driven models**, such as PIDs trained to output signals to excite muscles [1], [2].

However, the limitations of these models include:

1. Do not consider **anatomically correct** models [3].
2. Do not consider the **complex underpinnings of musculoskeletal dynamics** such as non-linear muscle actuators.
3. Require **experimentally recorded data**, such as muscle activity, for training.
4. Cannot predict motor cortex neural responses during unobserved conditions, since they do not generalize well to changes in environment and perturbation analyses.
5. Do not elucidate the role of the motor cortex as a controller for the musculoskeletal dynamics [4].

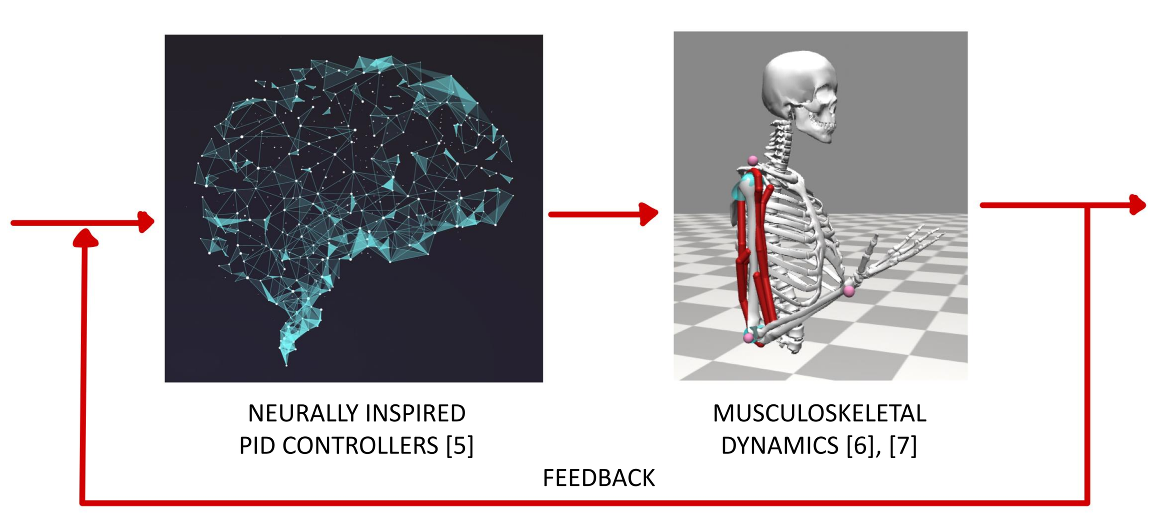


Fig. 2: Proposed Internal Model of Sensorimotor Control Loop

Summary

We developed a simulation framework to model the cerebrocerebellar neural dynamics of the motor cortex as a set of time-invariant PID controllers. We trained the controllers on a 10^{th} **order linear dynamical system** which acted as a linear approximation of the nonlinear musculoskeletal dynamics of the OpenSim model. We observed that:

1. The system performed well on the training data but **performed poorly on held-out data**. It may not have identified the dynamics properly.
2. The **step response was blazing fast** with a rise time of 0.009 seconds, a settling time of 0.047 seconds, and an overshoot of 18.7327%. This allowed the gain settings to be decreased significantly in manual tuning to allow the plant to track the reference with good quality.
3. Tracking only the elbow joint appears to cause **oscillatory behavior for the shoulder joint**.

Trajectory Tracking Performance

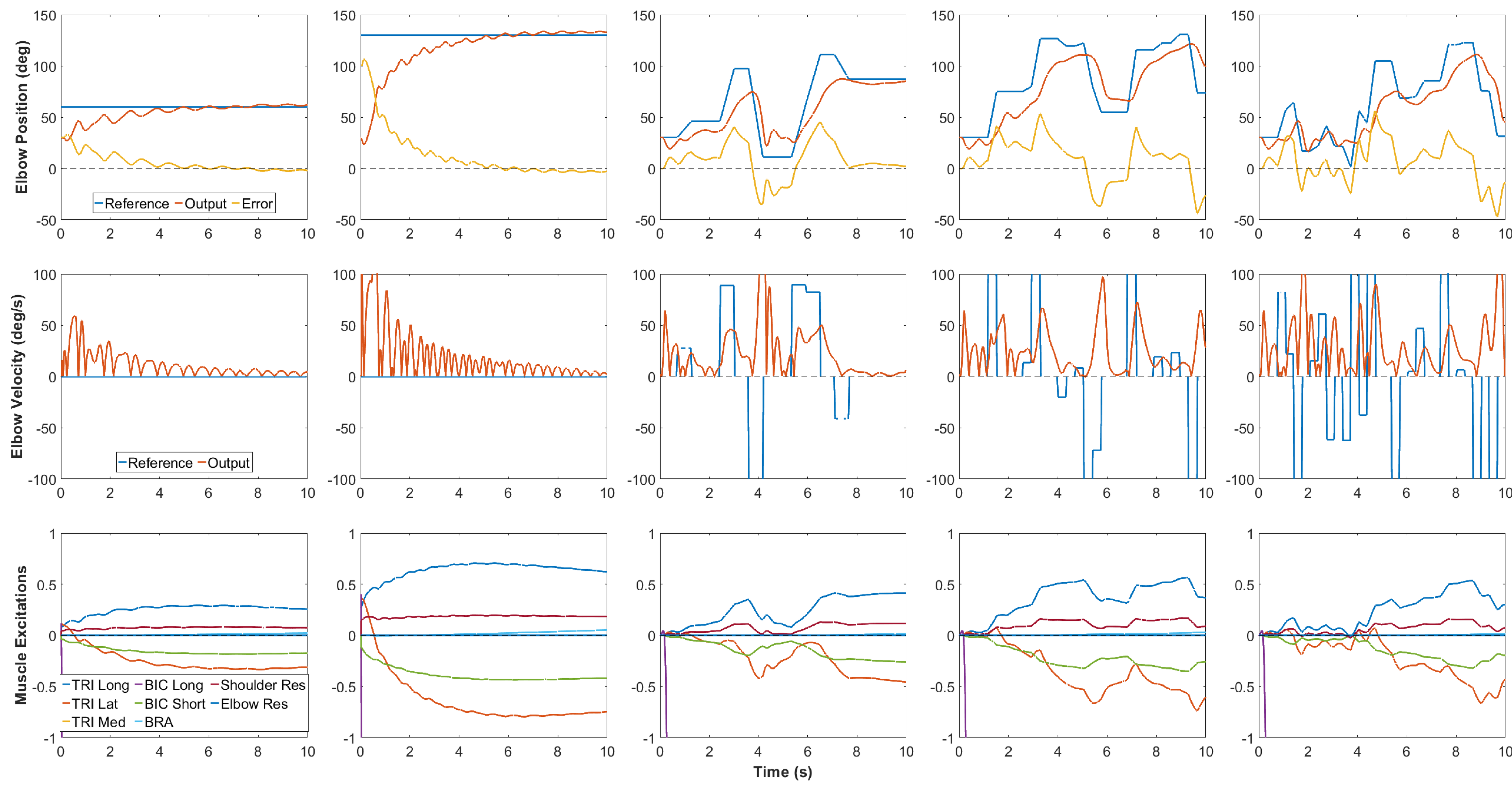


Fig. 1: Reference Tracking Performance of the System. Elbow Position and Velocity and the resulting Muscle Excitations are Displayed.

Methods and Technical Details

System Identification

- 5000 motions for training with 500 for validation.
- Eight inputs (muscle activations) and two outputs (elbow joint angular position and speed).
- Estimated linear dynamical systems of order 2 to 15.

Control Loop

- Designed a PID controller to each muscle input to drive the system towards a reference input.
- Tested the tracking performance of complex signals and step signals using a discretized control loop and an application to control the system.

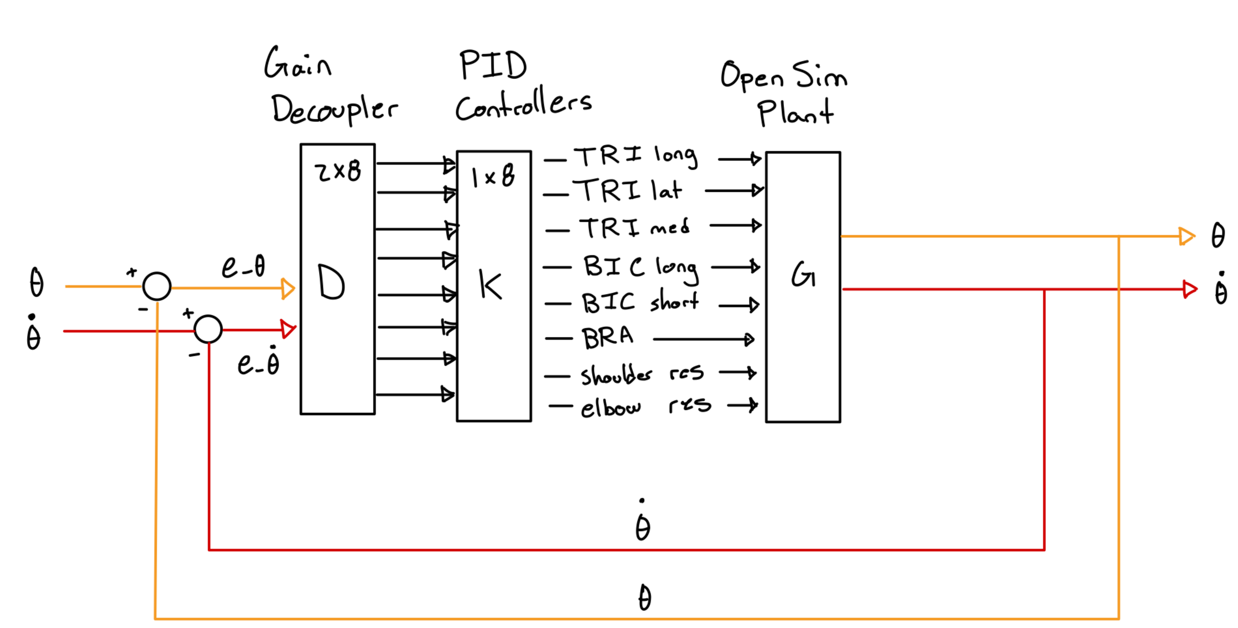


Fig. 3: Implemented Control Loop Structure

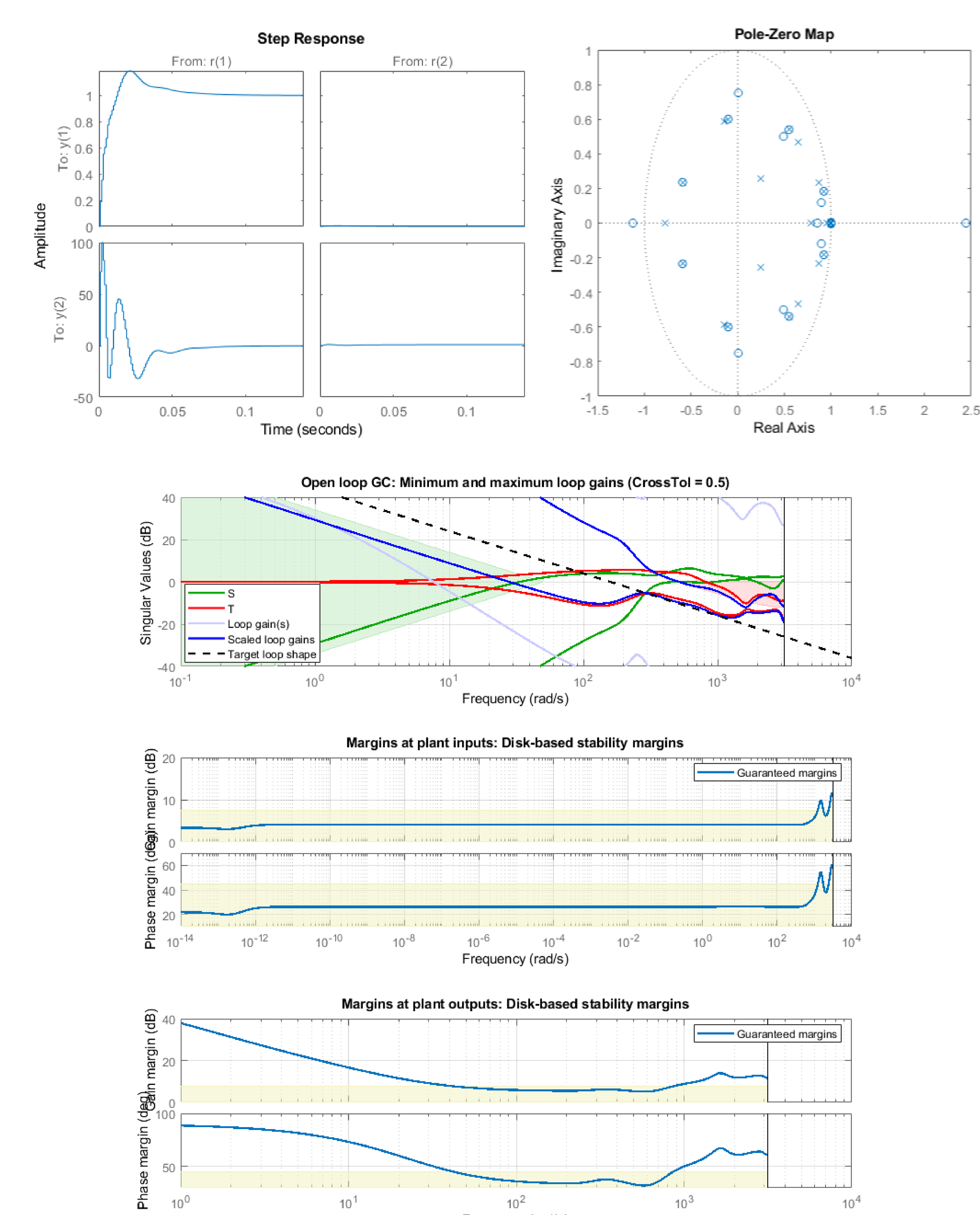
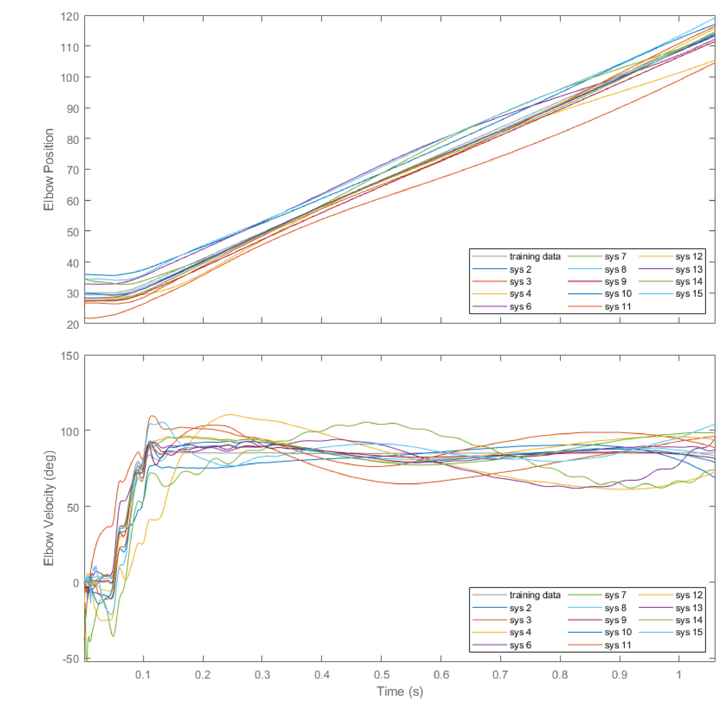


Fig. 4-6: (4) Step Response, (5) Pole-Zero Map, and (6) Frequency-Domain Response of the 10^{th} Order System.

System Identification



System Order	Training NRMSE	Validation NRMSE
2	87.11%	-43.25%
3	69.57%	-218.0%
4	85.18%	-18.74%
6	87.23%	-178.9%
7	90.15%	-232.1%
8	97.99%	-66.00%
9	90.17%	1.531%
10	96.67%	-56.08%
11	92.13%	-64.49%
12	95.63%	-28.28%
13	96.42%	-106.6%
14	94.26%	-32.85%
15	84.38%	-296.7%

Table I: Position NRMSE

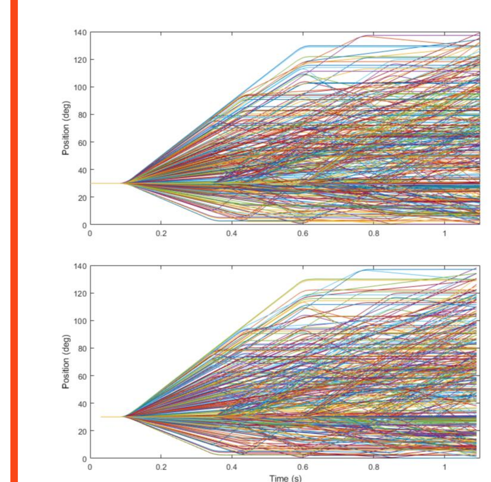


Fig. 7: Training Motions: (top) Ideal and (bottom) OpenSim's Approximation

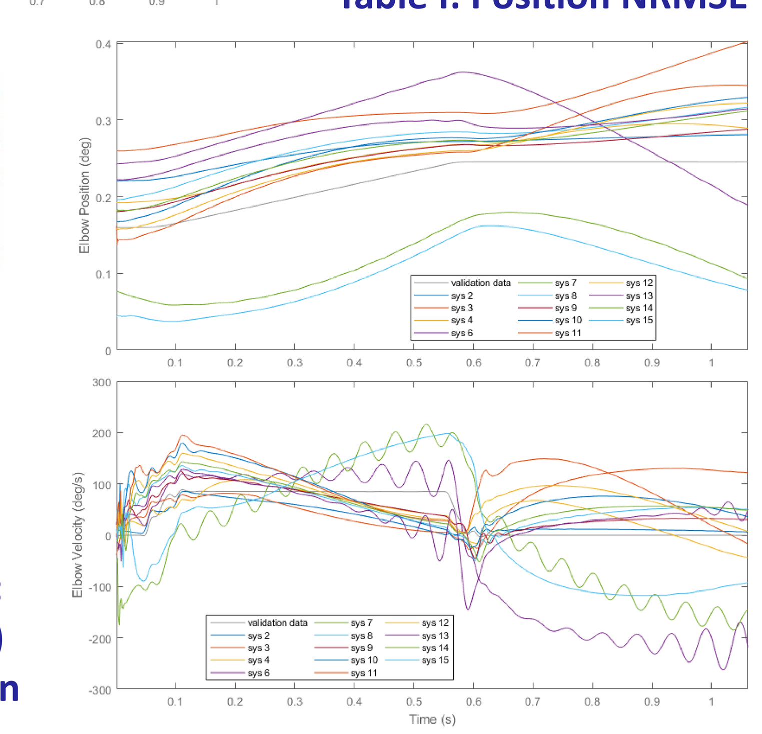


Fig. 8-9: Comparison of Each System Order with the (8) Training Data and (9) Validation Data. A System of Order 10 was Chosen.

Future Directions

1. Improve reference tracking ability of the controllers through retraining on better data sets, addition of derivative component in the designed controllers, and or modeling biophysical bounds in the cerebrocerebellar dynamics.
2. Pursue the design of assistive neuroprosthetic devices which implement controllers to add compensatory forces to restore motor neural dynamics compromised by damage or disease [8].
3. Expanding the neural dynamics to include a spiking model of the efferent alpha motor neurons as they excite motor unit recruitment [8].
4. Expanding the musculoskeletal dynamics to include the ability to track the shoulder joint and to track the wrist and fingers.

References

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