Comparison of Two Series Elastic Actuator Designs Incorporated into a Shoulder Exoskeleton

Rafael Casas, Tianyao Chen, Peter S. Lum
Biomedical Engineering Department, The Catholic University of America, Washington, D.C.

Background & Clinical Relevance

- 800,000 new strokes in the United States each year
- Fifty percent of individuals with stroke > 64 year old
  - Persistent hemiparesis at six months post-stroke
  - 26% are dependent in activities of daily living (ADL)
  - survivors often experience long term disability that includes impaired movements and unnatural synergies between muscle groups[1]
- Upper extremity is a focus of rehab w/ Reaching and grasping movements often impaired
  - **Robot-assisted therapy** can have significant effects on motor control and muscle strength[3] by assisting patients with the completion of their movements[2]
  - Provides assistance via forces applied to the limb may facilitate effective practice

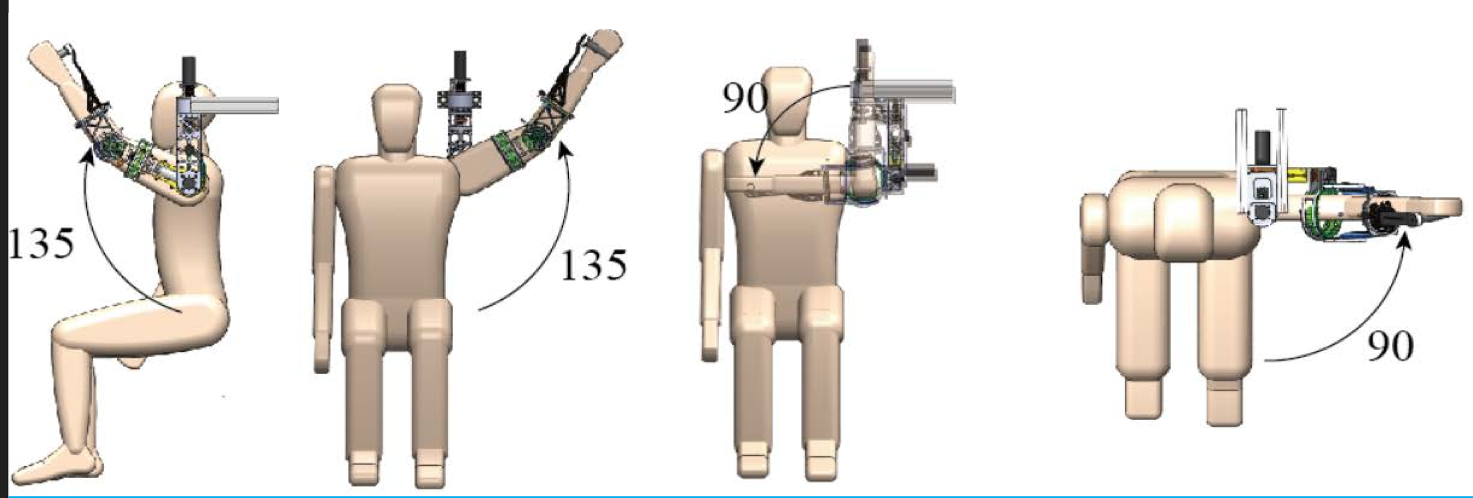
Design

Requirements:

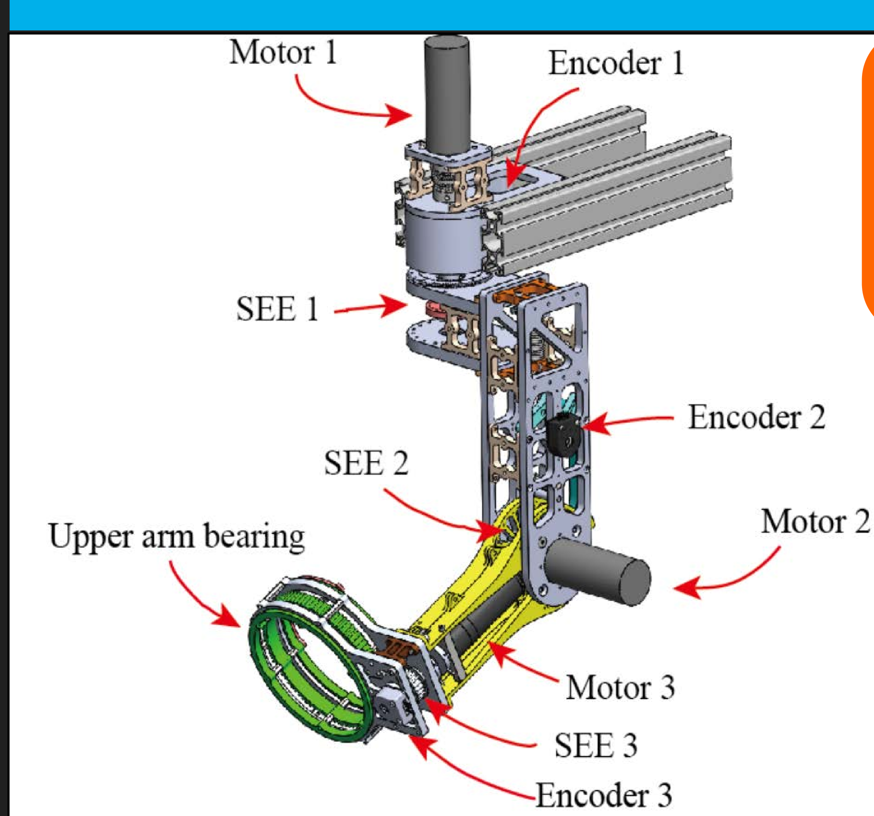
- Robotic exoskeleton design must provide accurate torque control
- Provide a range of impedances depending on the rehabilitation mode used such as “free mode” and “wall mode”

Current Design:

- 135 degree ROM for shoulder flex/extension, 90 degree upper arm rotation, and 90 degree for abduction
- *Novelty: Each motor is combined with a series elastic element in order to reduce reflected inertia and impedance while also being able to simulate high stiffness similar to a wall*



CAD model of the exoskeleton.



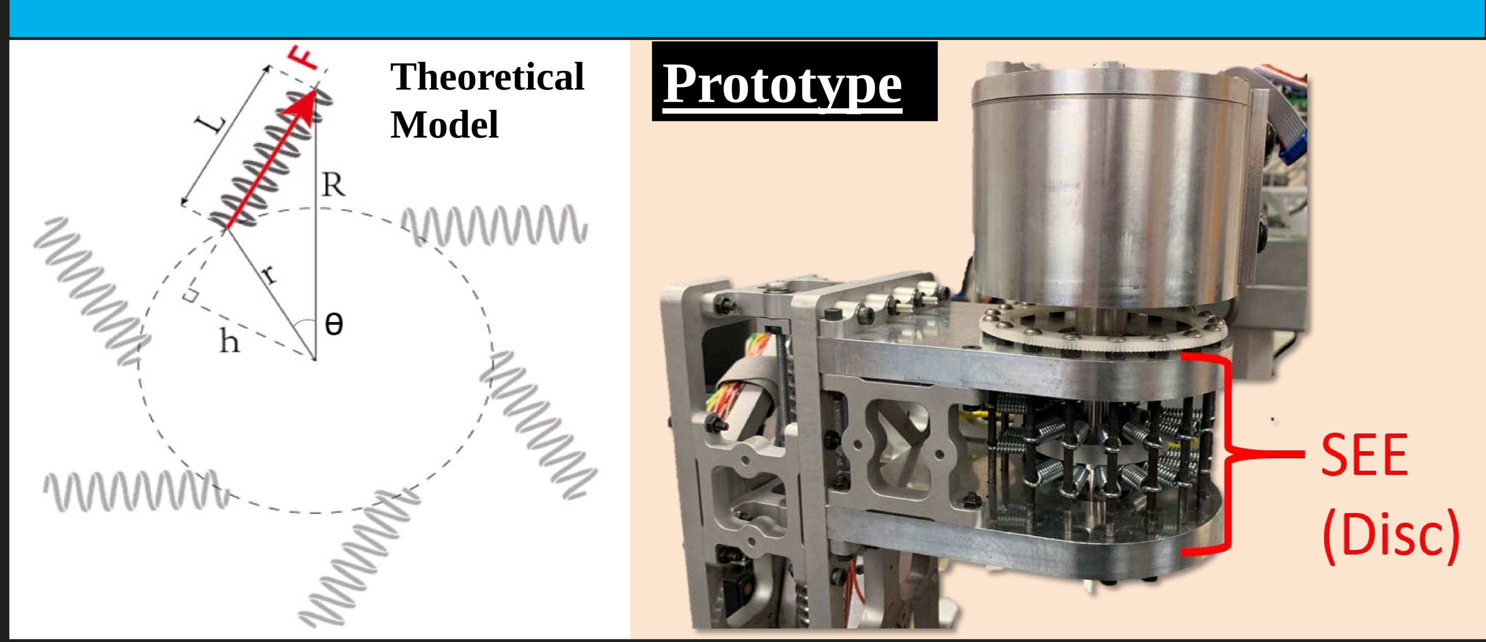
What is an SEE?

- A torsional spring between actuator and the arm
- Torque control via high feedback gain positional control

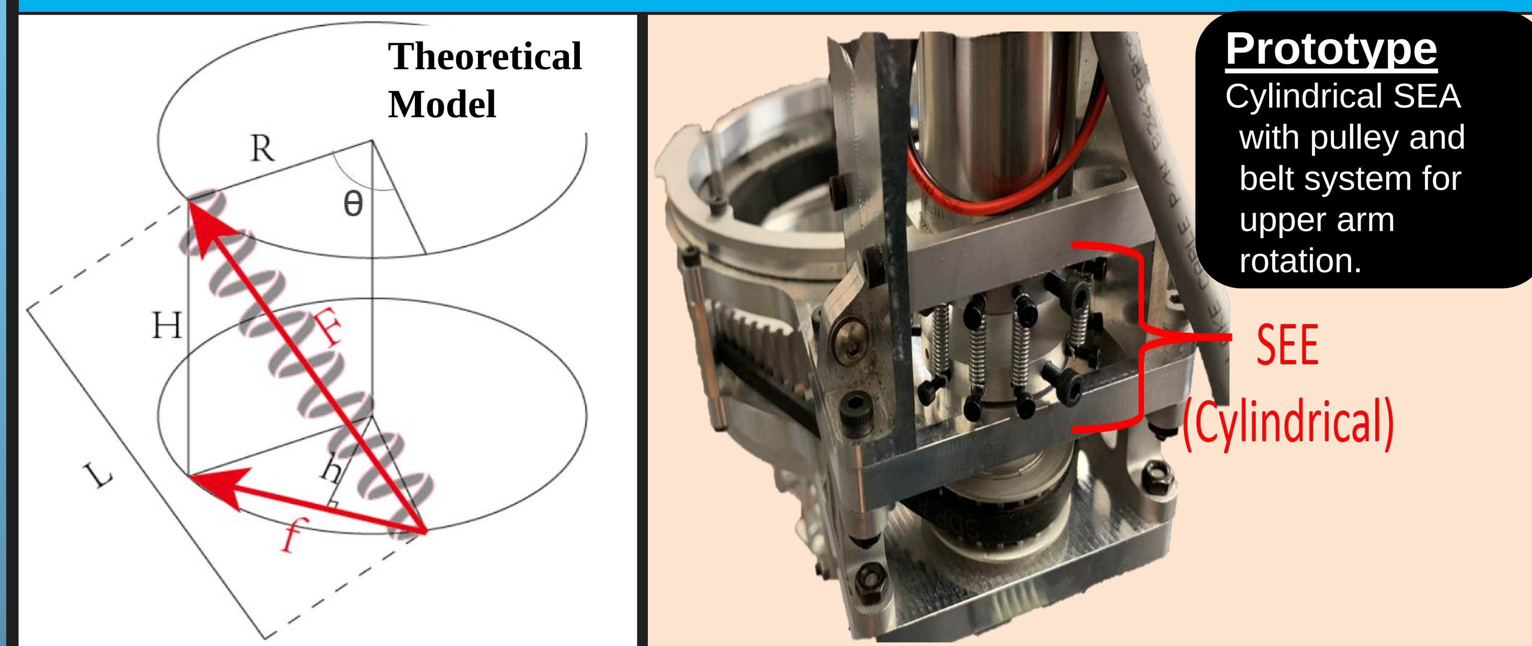
M1 +SEE 1-shoulder horizontal abduction/adduction
M2 + SEE 2-upper arm flexion/extension
M3+SEE 3 -internal/external rotation

*SEE 1 & SEE 2 are similar designs

Disc-Shape SEA Design for Shoulder Abd/Add



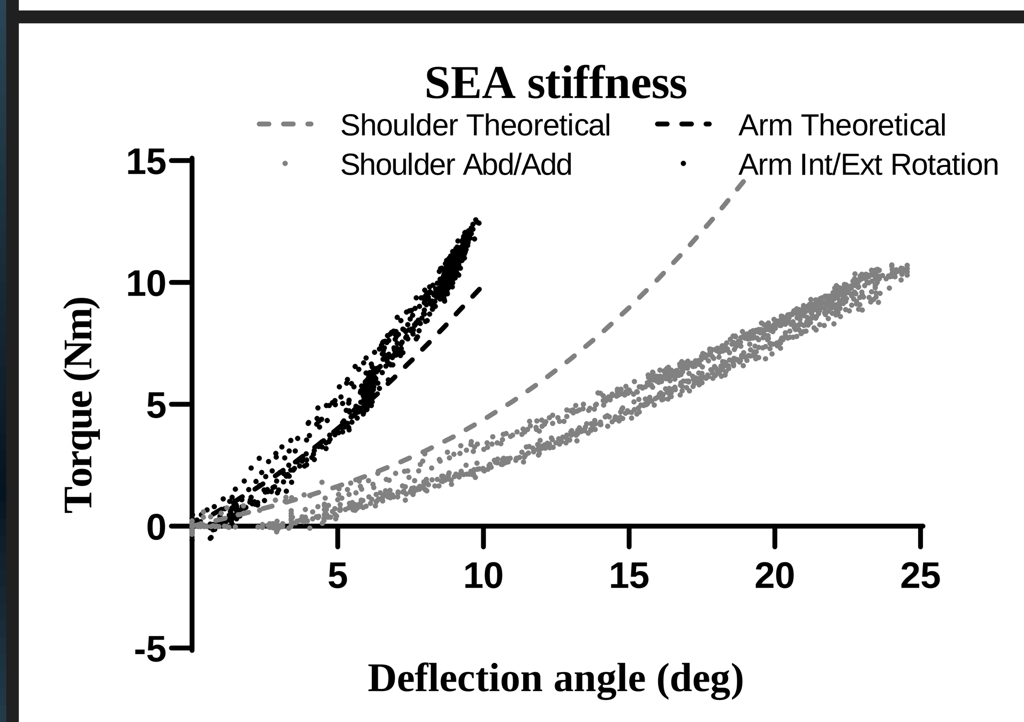
Cylindrical SEA Design for Arm Rotation



Methods

Stiffness Profiles

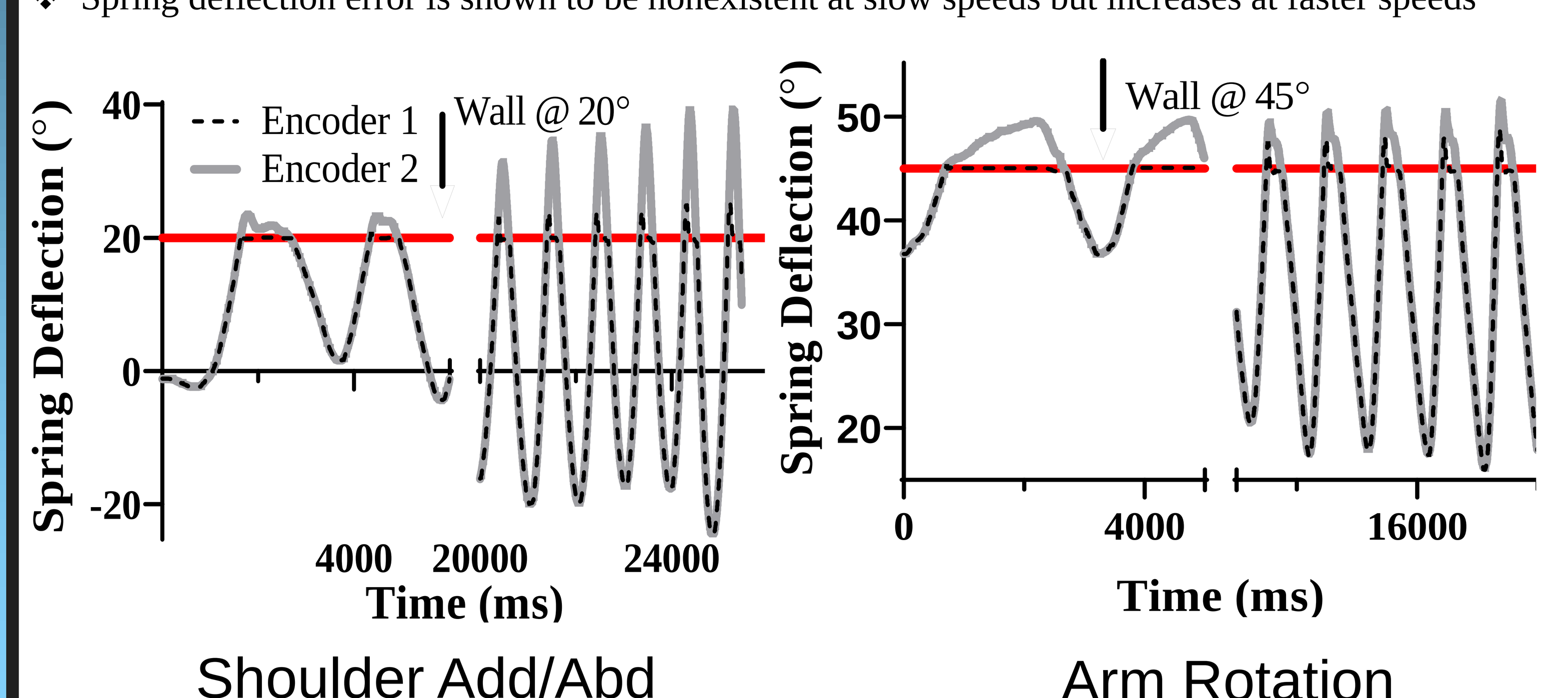
- SEE stiffness profiles were identified by slowly pushing and pulling the joint through an attached force sensor as the motor held the “proximal” position of the SEE constant
- Disc shaped SEE included 28 tension springs, each with a stiffness of 19 N/mm and peak force of 85 N
- Cylinder shaped SEE has 10 tension springs, each with a stiffness of 2.26 N/mm and peak force of 15.7 N
- Over the full range of operation, the stiffness increased from 0.13 to 0.63 Nm/deg for abd/adduction and 0.44 to 2.10 Nm/deg for int/ext rotation



The experimental stiffness was may have been lower than the theoretical calculations in the disc-shaped SEA because the springs can bend in addition to extend, especially at high loads. Bending was not included in the theoretical model

Wall Mode

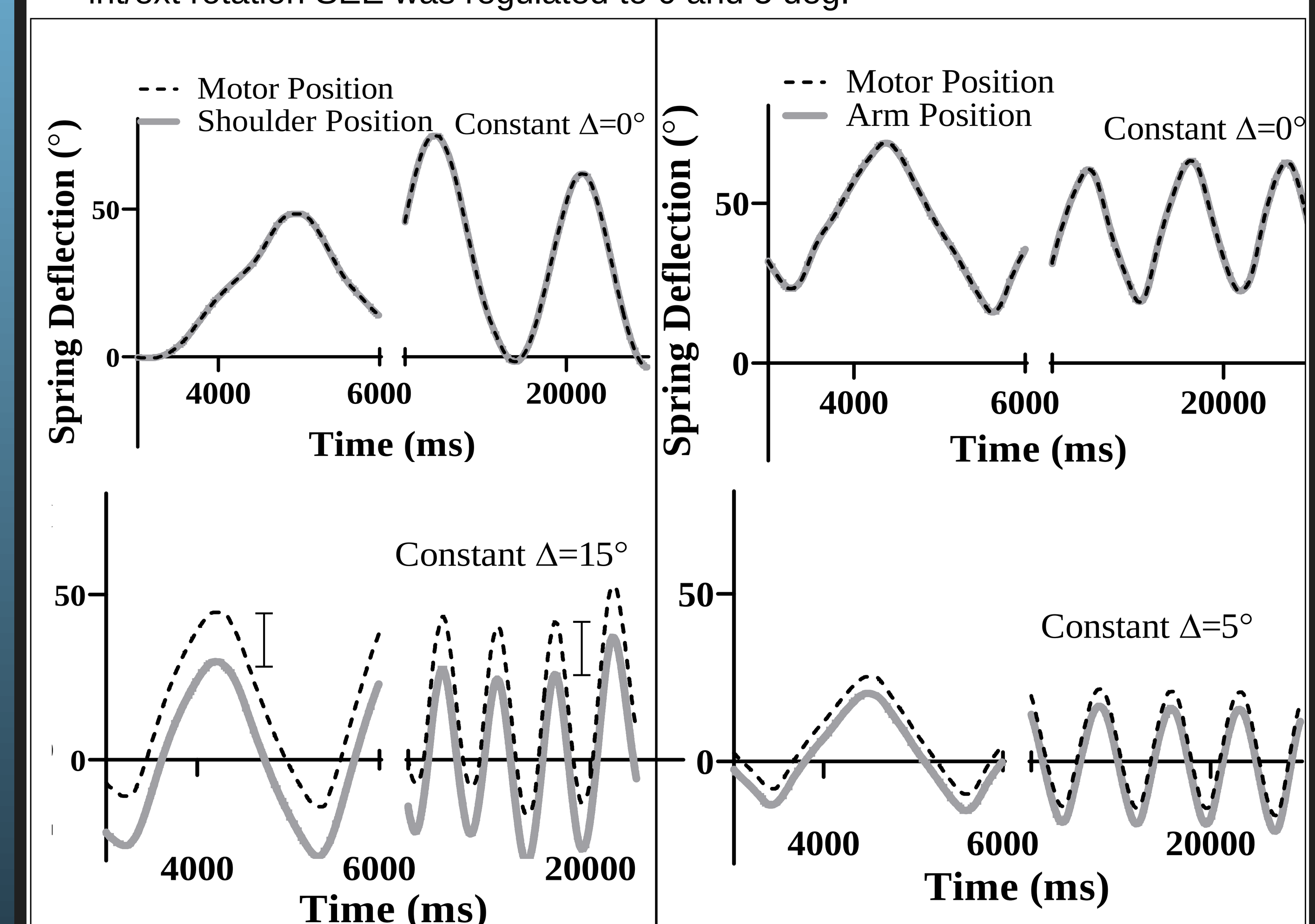
- Simulation of walls or physical stiffnesses are an important component for haptic interfaces.
- User operates in free mode for a certain range of motion. When a specific angle is exceeded, the end-effector behaves like a stiff wall.
- The figure below shows that for both DOF, the proximal SEE position is held at the wall interface angle when the user position exceeds this angle.
- A wall is simulated at a specified spring deflection for both SEA designs. Both designs were tested at slow and fast arm movement speeds
- Spring deflection error is shown to be nonexistent at slow speeds but increases at faster speeds



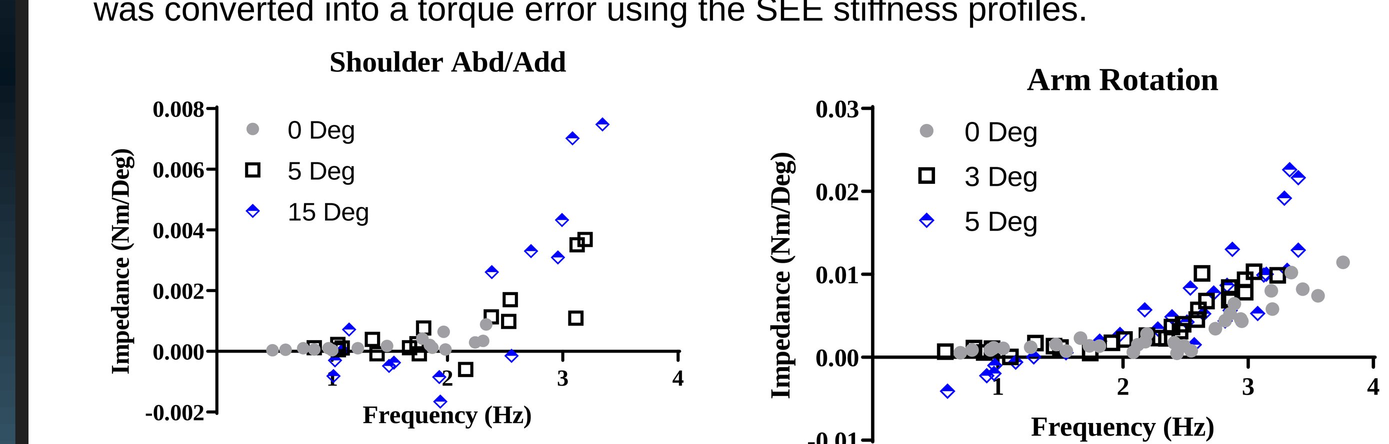
Results

Constant Mode

- To test free mode, the SEE was regulated to a value of zero deflection as the user moved the joint in sinusoidal pattern movements at different frequencies.
- We also tested the ability to apply a constant torque to the user, as the user moved in sinusoidal patterns.
- The abd/adduction SEE was regulated to 0 and 15 deg of deflection, while the int/ext rotation SEE was regulated to 0 and 5 deg.



- In these constant torque experiments, the impedance method was also used to quantify the residual torque error by subtracting the constant desired torque from the output torque.
- Each peak generated one point on the estimated transfer function between distal (input) and proximal SEE position (output).
- For each peak, the amplitude and period of the sinusoidal movement was determined by comparison to the previous min.
- The amplitude ratio and frequency was calculated for each peak. This amplitude ratio was converted into a torque error using the SEE stiffness profiles.



Conclusion

- Shoulder exoskeleton was designed and built with two novel SEA designs
- Benchtop performance was suitable for stroke rehabilitation therapy
- Exponential shaped SEE stiffness allowed adequate performance in both low and high impedance environments such as free mode and wall mode
- Future work should focus on further weight reduction and testing in stroke patients

References

1. E. J. Benjamin et al., "Heart Disease and Stroke Statistics—2019 Update: A Report From the American Heart Association," Circulation, p. CIR. 0000000000000659, 2018.
2. V. S. Huang and J. W. Krakauer, "Robotic neurorehabilitation: a computational motor learning perspective," Journal of neuroengineering and rehabilitation, vol. 6, no. 1, p. 5, 2009.
3. J. M. Veerbeek, A. C. Langbroek-Amersfoort, E. E. Van Wegen, C. G. Meskers, and G. Kwakkel, "Effects of robot-assisted therapy for the upper limb after stroke: a systematic review and meta-analysis," Neurorehabilitation and neural repair, vol. 31, no. 2, pp. 107-121, 2017.

Contact: casas@cua.edu