Characterizing Joint Compliance and Dynamics in SEA Arm Exoskeleton for Post-Stroke Rehabilitation

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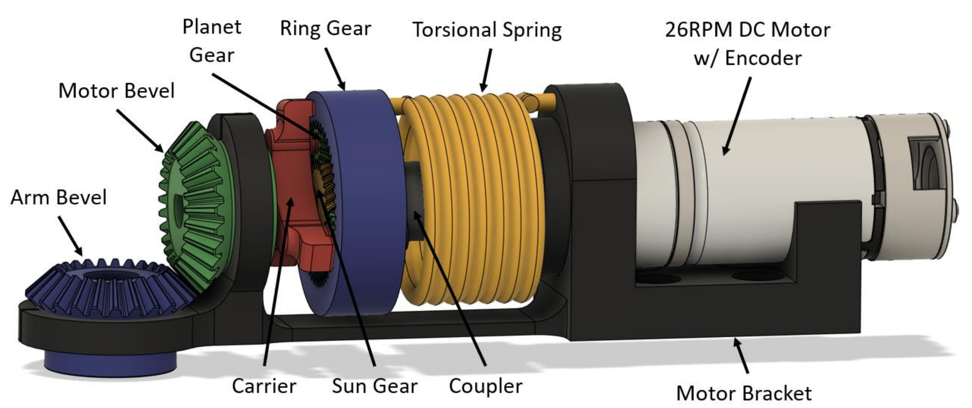
Introduction

Approximately 15 million people experience a stroke annually, with 62%-88% of survivors suffering from post-stroke upper limb impairment [1,2]. Rehabilitation involves intensive repetition of elbow movements, often limited by patient fatigue or spasticity [3]. Exoskeletons can assist in such exercises but are often uncomfortable and may cause injury due to their rigid interactions with the patient's arm [4]. To address this, a 3D printed exoskeleton with a Series Elastic Actuator (SEA) compliant elbow joint was designed. It uses an elastic elbow joint comprised of a helical planetary gear and a torsional spring, providing a more comfortable and cost-effective assistive device for post-stroke rehabilitation [4].



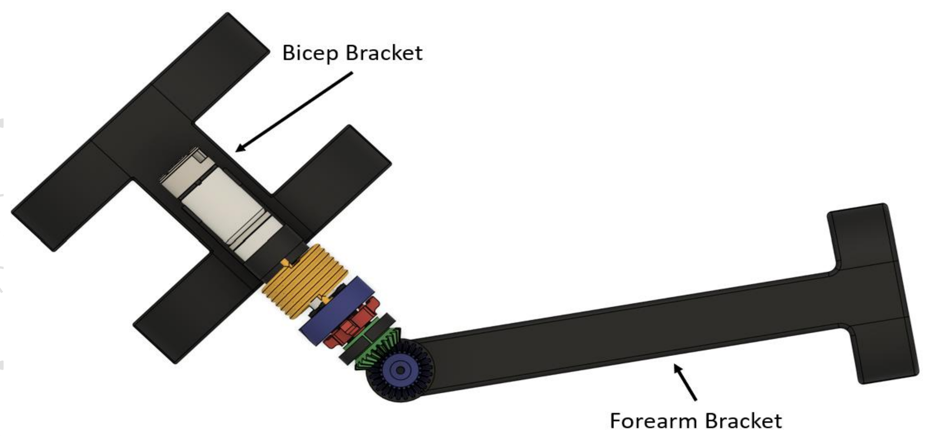


Fig 1 (Jenks, B. & Stefanovic, F.):
Top
Component view of torsional spring and planetary gear SEA joint.
Bottom
Full model of the SEA device interaction with exoskeleton brackets.

Experimental Methods

To determine the compliancy of the SEA elbow joint, two tests were run to characterize the device.

Test 1: Static compliance test

- Method: Apply force until spring starts to deform, then record joint angle using IMUs.

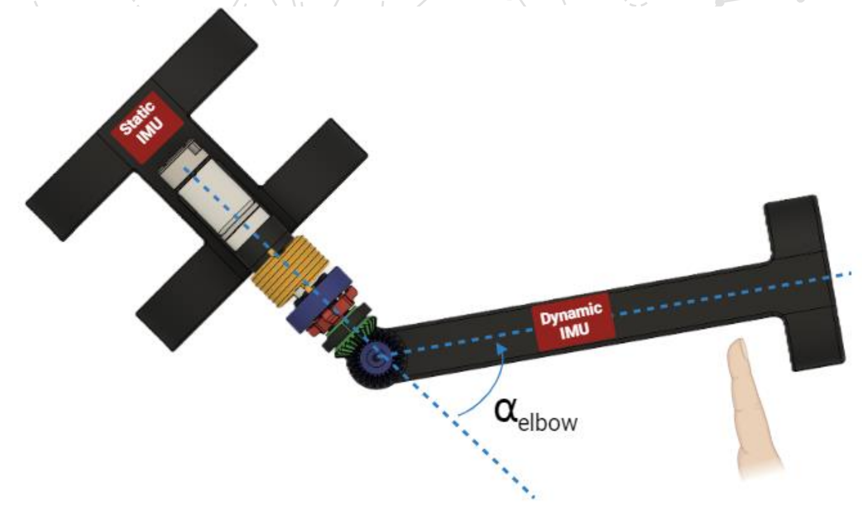


Fig 2 (Created with BioRender):
Schematic for static testing procedure.

Test 2: Dynamic compliance test

- Method: Vary speed at which forearm rotates to desired angle. Collect joint angle data to observe overshoot and oscillations caused by SEA joint.
- Hypothesis: Increased forearm rotation speed = larger overshoot and subsequent oscillations before stabilizing.

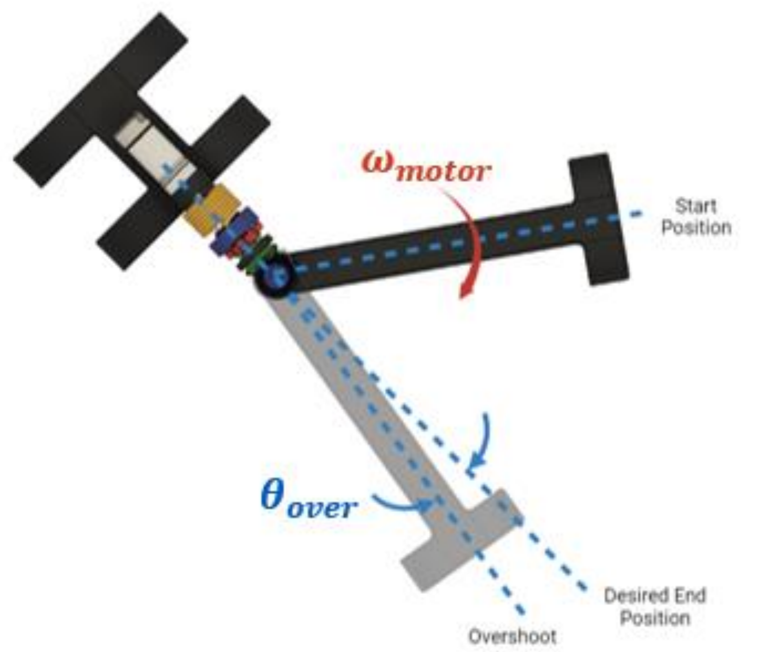


Fig 3 (Created with BioRender):
Schematic for dynamic testing procedure.

Results

Test 1: Static compliance test

- Across 4 trials each, the average system compliance (C_{sys}) and the average gear compliance (C_{gear}) were measured.

$$C_{sys} = 22.22°$$
$$C_{gear} = 14.80°$$

- Spring compliance (C_{spring}) can be calculated through:

$$C_{spring} = C_{sys} - C_{gear} = 7.42°$$

Test 2: Dynamic compliance test

- Raw angular velocity data for the forearm was integrated in MATLAB to acquire angular position data.

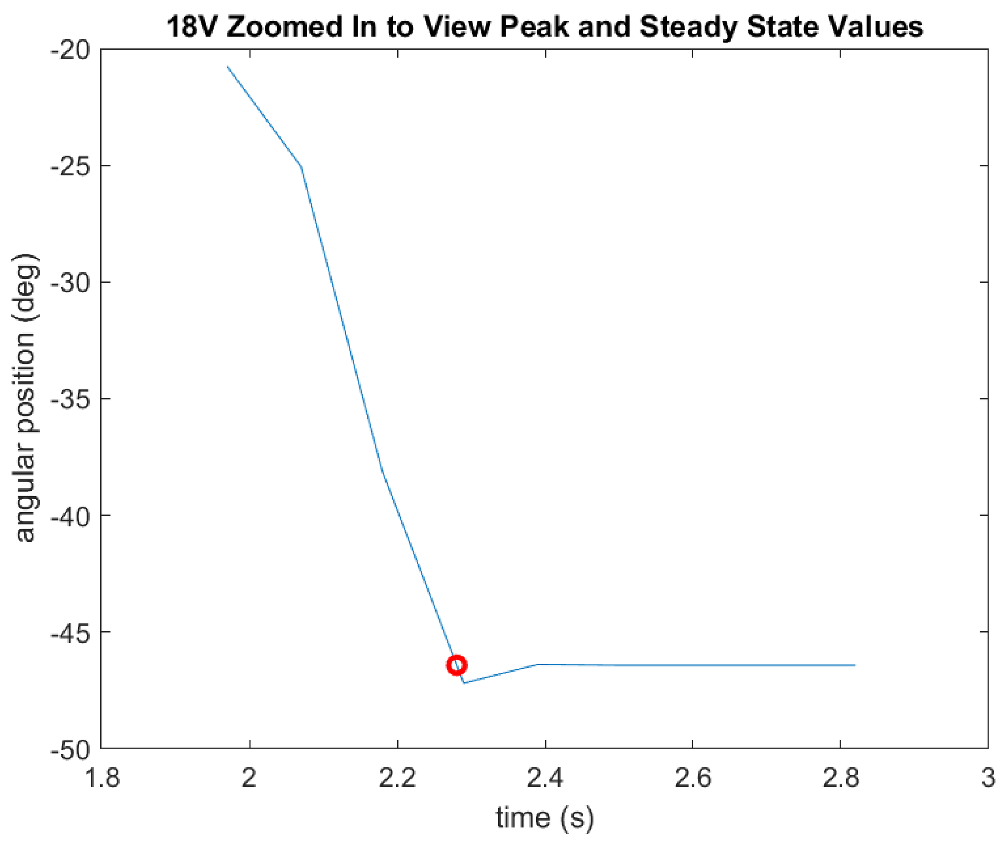


Fig 4 (H. Levan):
Example of MATLAB graph created for 5 trials ranging from 12-18V. Zoomed in to better view the moment of overshoot and subsequent transition to steady state.

- Within MATLAB, percent overshoot (%os) and settling time (T_s) were calculated. With these parameters, the following equations were used to calculate the damping ratio (ζ) and natural frequency (ω_n) of the system. Table 1 contains all important parameters to characterize the dynamics of the joint when its motor is supplied with different voltage levels.

$$\zeta = \frac{\ln(\frac{100}{\%os})}{\sqrt{\pi^2 + (\ln\left(\frac{100}{\%os}\right))^2}} \qquad \omega_n = \frac{4}{T_s \zeta}$$

Table 1: Necessary parameters to characterize joint dynamics. .

Voltage Supplied (V)	Max Forearm Speed (rad/s)	Overshoot (deg)	Oscillation Amplitude (deg)	%Overshoot	Settling Time (s)	Damping Ratio	Natural Frequency (rad/s)
12	-1.952	0.0000	0.0000	0.0000	0.0000	1.0000	0.00
14	-2.372	-0.1054	-0.1054	0.2156	0.1369	0.8903	24.14
16	-2.798	-0.4532	-0.4721	0.8718	0.1800	0.8901	22.97
18	-3.186	-0.3833	-0.4778	0.8146	0.2683	0.8788	18.47
20	-2.956	-0.0441	-0.0498	0.0845	0.1740	0.8930	27.62

Conclusion

This study characterizes the compliance and dynamics of a planetary gear/torsional spring SEA exoskeleton design to improve elbow joint rehabilitation. Under static loads, the joint achieved a total system compliance of 22.22°, with the torsional spring contributing 7.42° of compliance for user safety and comfortability.

In a dynamic test in which the joint's motor was supplied with different voltage levels, the system was found to maintain a relatively constant damping ratio, even at higher speeds. In general, a higher forearm rotation speed resulted in larger overshoot angles, as well as longer settling times before the system reached steady state.

Future work may include incorporating machine learning to recognize user intent and EMG sensors. These steps would further develop the device to improve rehabilitation success, with the hope of it eventually being utilized as an every day assistive device.

References

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