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Assessing Repeatability of CLEVERArm Exoskeleton Using Healthy Subjects: A Pilot Study

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Introduction

- **Upper Extremity (UE) Exoskeleton Advantages**
  - Aligns with the anatomical axis of patients' UE
  - Provides quantifiable metrics that can track patient improvement for trajectories that are:
    - Single-degree-of-freedom (sDOF)
    - Multi-degree-of-freedom (mDOF)
    - Activities-of-daily Living Tasks (ADL)
- **Limitations of Exoskeleton Trajectories**
  - Constant kinematic compatibility between exoskeleton and UE during the motion is difficult.
  - Current validated trajectory models are limited to only point-to-point reaching and sDOF movements.

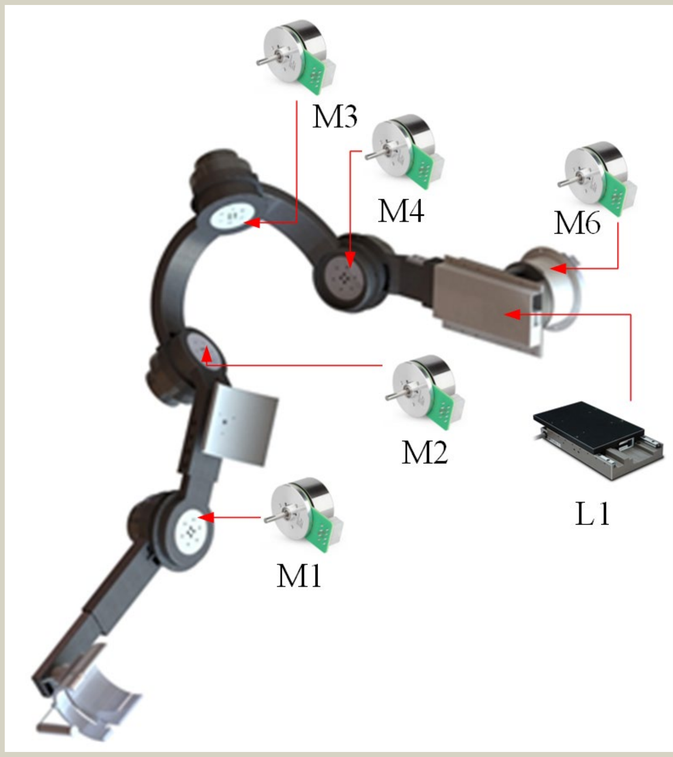
Study Objective.

- *To statistically validate the CLEVERArm (compact, lightweight, ergonomic, VR/AR-enhanced rehabilitation arm) exoskeleton's repeatability and reliability when completing both sDOF and mDOF movements using 18 subjects*
  - *Repeatability - completing trajectory multiple times*
  - *Reliability - consistency in replicating the inputted trajectory*

Movements Used to Validate CLEVERArm Exoskeleton

Name	DOF	Task Description	Configuration
Task 1	Single	Elbow Flexion-Extension	0-140°
Task 2	Single	Shoulder Abduction-Adduction	0-90°
Task 3	Single	Shoulder Flexion-Extension	0-90°
Task 4	Multiple	Reaching to Head	As needed
Task 5	Multiple	Eating Activity	As needed
Task 6	Multiple	Combing Activity	As needed

Methodology



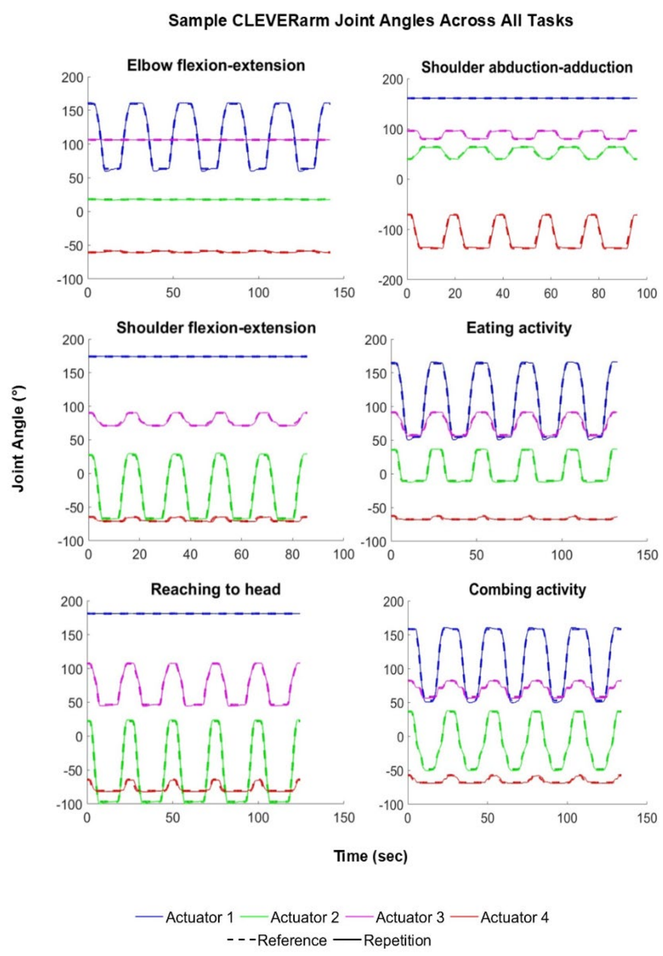
Schematic of the CLEVERArm with active DOF labeled: M = rotary motor/encoder, L = prismatic motor/encoder



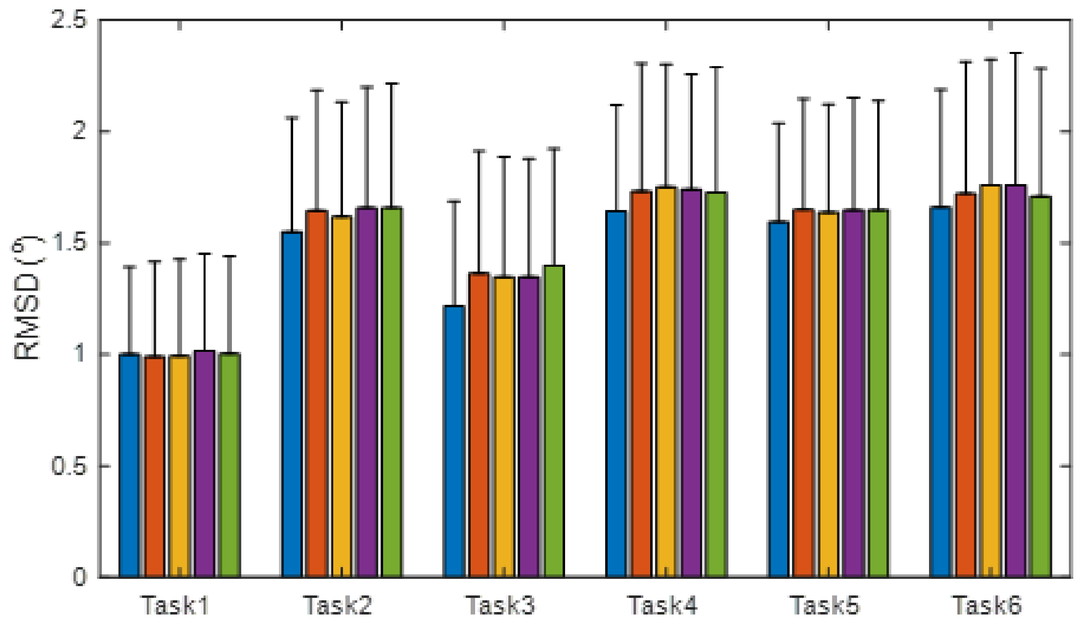
Subject wearing the CLEVERArm preparing for movement

- **Controllers**
  - Baseline Gravitational Compensation
  - Uniform PID Controller applied simultaneously to actuators M1-M4. Passive Therapy Mode
    - Kp = 1.5, Ki = 0.03, Kd = 0.002
- **Validation Metrics**
  - RMSD between reference and repetition signals (5 consecutive movements)
  - Analysis of Variance (ANOVA)
  - Intraclass Correlation Coefficients (ICCs)

Results and Discussion



Metric	Actuator	Elbow Flexion-Extension		Shoulder Abduction-Adduction		Shoulder Flexion-Extension		Reaching to Head		Eating Activity		Combing Activity	
		Mean	STD	Mean	STD	Mean	STD	Mean	STD	Mean	STD	Mean	STD
RMSD	Actuator 1	2.03	1.14	0.54	0.54	0.18	0.39	0.69	0.53	2.51	0.86	2.27	0.84
	Actuator 2	0.89	0.40	2.64	0.74	0.87	0.78	2.77	0.90	1.78	0.62	2.07	0.82
	Actuator 3	0.51	0.30	1.81	0.85	0.93	0.81	1.96	0.65	1.29	0.42	1.38	0.51
	Actuator 4	0.61	0.48	1.54	0.72	3.41	1.11	1.49	0.98	0.98	0.51	1.20	0.58
Correlations	Actuator 1	1.00	0.00	0.37	0.48	0.09	0.32	0.61	0.46	1.00	0.00	1.00	0.00
	Actuator 2	0.76	0.42	1.00	0.00	0.53	0.50	1.00	0.00	0.99	0.00	1.00	0.00
	Actuator 3	0.39	0.54	0.98	0.02	0.27	0.66	0.99	0.02	0.66	0.01	0.97	0.11
	Actuator 4	0.38	0.44	0.78	0.40	0.99	0.00	0.78	0.36	0.54	0.46	0.73	0.48



Task	ICC	95% CI	
		Lower	Upper
1	0.99	0.97	0.99
2	0.97	0.94	0.99
3	0.93	0.87	0.97
4	0.96	0.93	0.98
5	0.97	0.95	0.99
6	0.97	0.94	0.99

- **ICC for all Movements**
  - Range from 0.93 to 0.99
  - Excellent test-retest ability

- **PID Performance**
  - Clear consistency across all five repetitions without major variation
    - Low RMSD – 3.42°
    - High Correlation – 0.99
  - RMSD values low for each movement
    - sDOF < 1°. mDOF < 2°
  - Average RMSD consistently remains below 2° for all iterations
- **Task and Repetition Effects**
  - ANOVA showed significant effects for both task ($p < 0.01$) and repetition ($p < 0.01$)
  - Differences between tasks accounted for a substantial proportion of the variability in the data ($\eta 2 = 0.340$)
  - Repetition had a smaller effect size ($\eta 2 = 0.007$)

Conclusion

- **The CLEVERArm rehabilitation capabilities include:**
  - Producing consistent outcomes for both sDOF and mDOF
  - Capture changes in UE movement over time
  - Reproduce desired movements accurately

References

1. A. Zeiaee, R. S. Zarrin, A. Eib, R. Langari, and R. Tafreshi, "CLEVER-arm: A Lightweight and Compact Exoskeleton for Upper-Limb Rehabilitation," IEEE Robotics and Automation Letters, vol. 7, no. 2, pp. 1880–1887, 2022.
2. A. Zeiaee, R. Soltani-Zarrin, R. Langari, and R. Tafreshi, "Kinematic Design Optimization of an Eight Degree-of-Freedom Upper-Limb Exoskeleton," Robotica, vol. 37, no. 12, pp. 2073–2086, 2019.