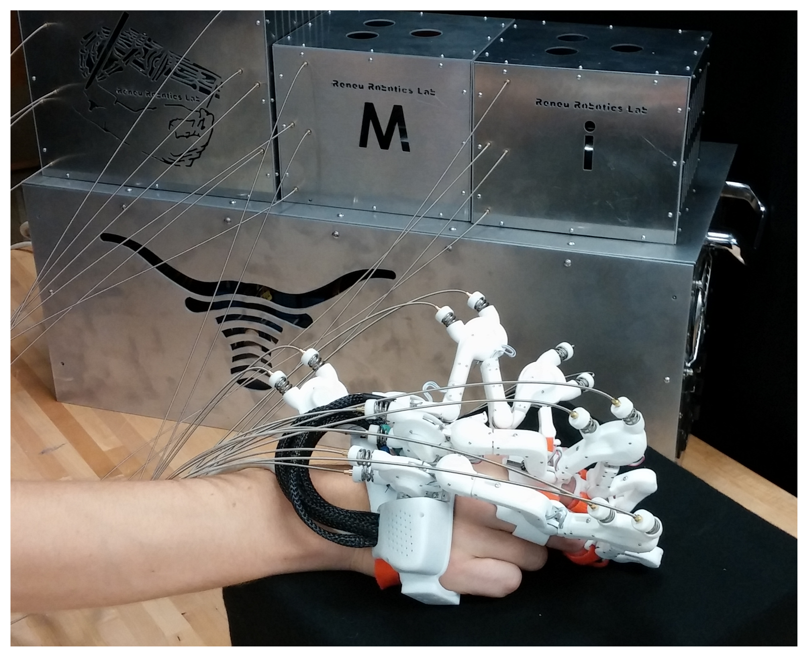
Design and Development of a Cybernetic Rehabilitative Hand-Wrist Exoskeleton

Youngmok Yun†, Priyanshu Agarwal†, Jonas Fox†, Dylan Losey‡, Kaci E. Madden†, Ali Utku Pehlivan‡ Evan Pezent‡, Chad G. Rose‡, and Fabrizio Sergi‡
Rehabilitation & Neuromuscular (ReNeu) Robotics Lab, Mechanical Engineering Department†, University of Texas at Austin
Mechatronics & Haptic Interfaces (MAHI) Lab, Mechanical Engineering Department‡, Rice University
UT PI: Prof. Ashish D. Deshpande† Contact: ashish@austin.utexas.edu | omalleym@rice.edu Rice PI: Prof. Marcia O'Malley‡

Objective: To design and develop a torque-controlled hand-wrist exoskeleton prototype for rehabilitation.

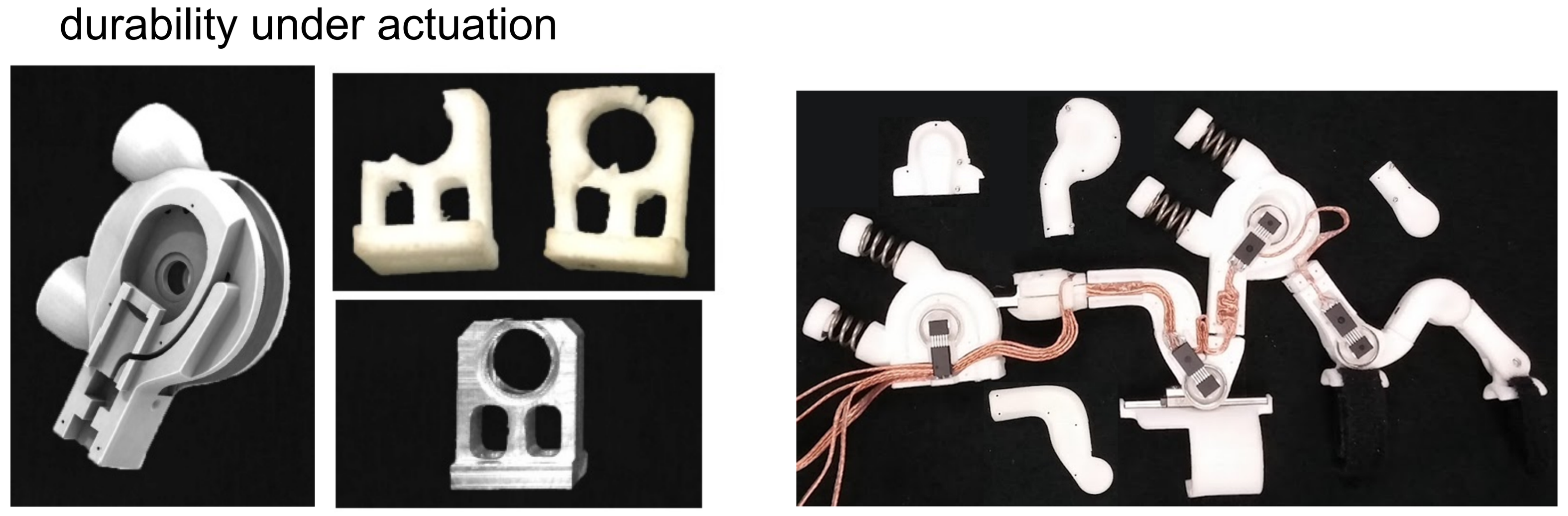
UT Hand Exoskeleton Ver 1.0



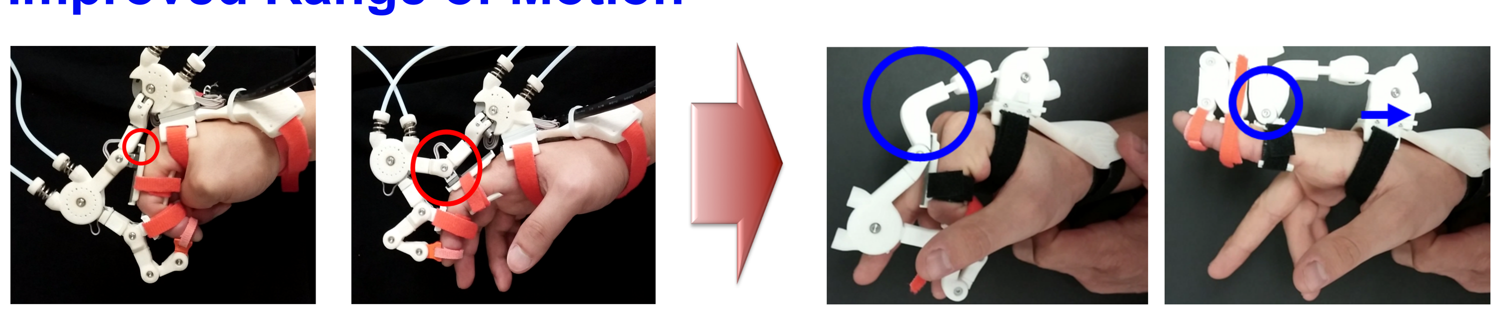
- The exoskeleton is designed for **hand rehabilitation**.
- The exoskeleton consists of **thumb, index, and middle finger** modules.
- Series-elastic actuators (SEA) **control the torque of finger joints.**
- Redundant sensors **estimate the torque and joint angles** of hand.

Robust System

- **Hybrid material** design for strength and robustness
- SLS - **Nylon** parts used for lightweight infrastructure
- Metal machining - **Steel and aluminum** parts used to increase durability under actuation
- **Embedded electronic elements, PCB, connector and cover** improved the robustness of system and reduced the noise in sensor reading and actuation.



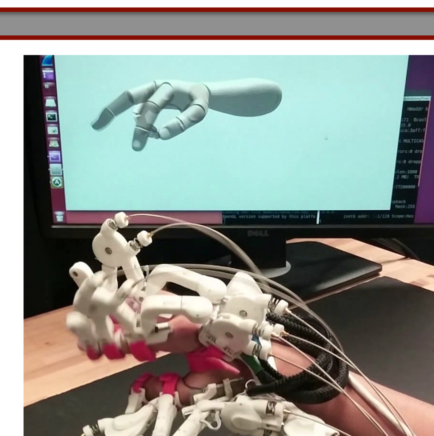
Improved Range of Motion



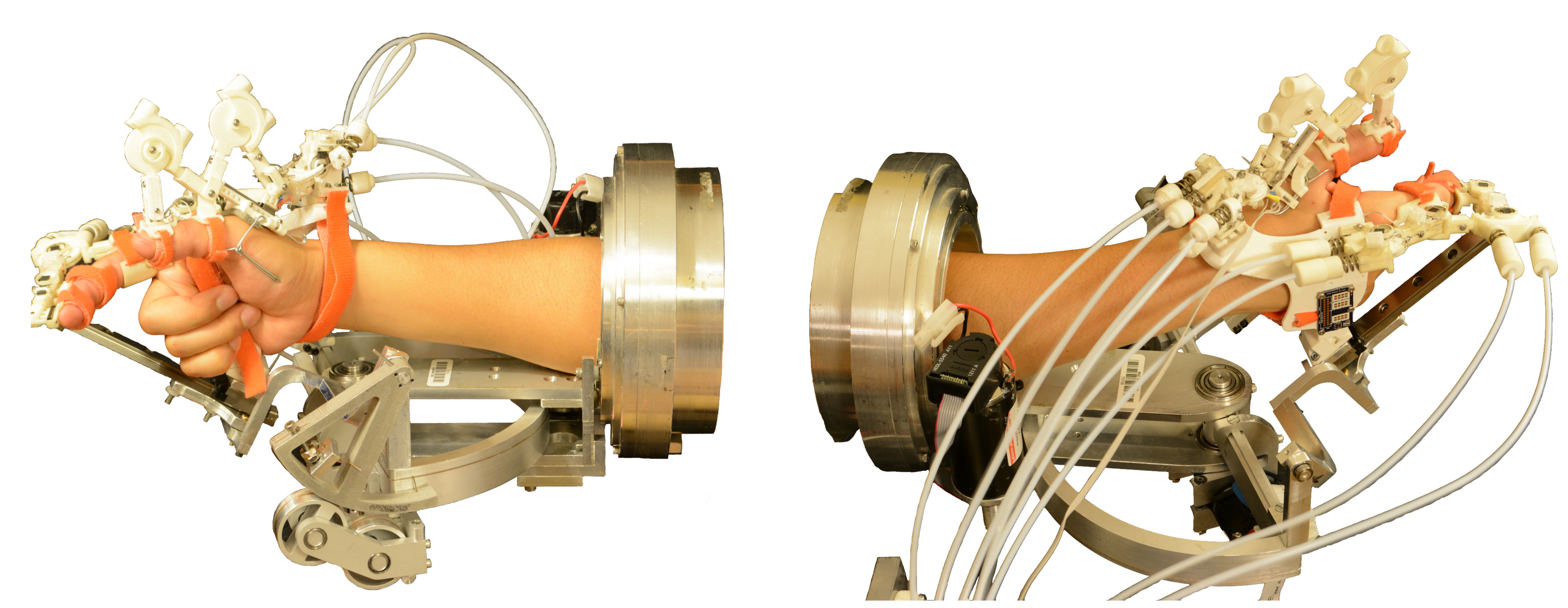
- The optimized linkage design results in increased range of motion and kinematic robustness to hand size variation.

Real-time Hand Pose Estimation

- Accurate joint angle and torque estimation is critical for rehabilitation robots.
- Real-time hand pose estimation is performed with redundant sensor configuration.
- A virtual hand model is developed to visualize the hand pose.



Hand-Wrist Exoskeleton Prototype



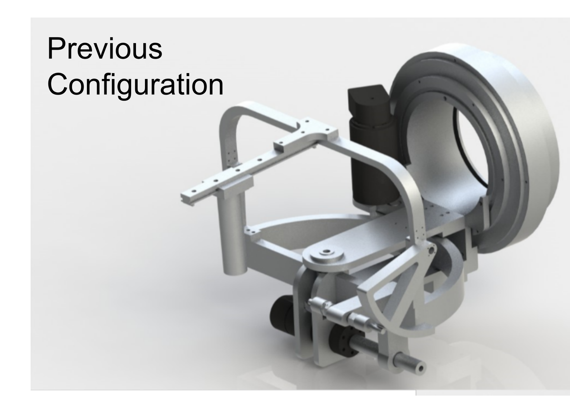
Hardware Design and Integration

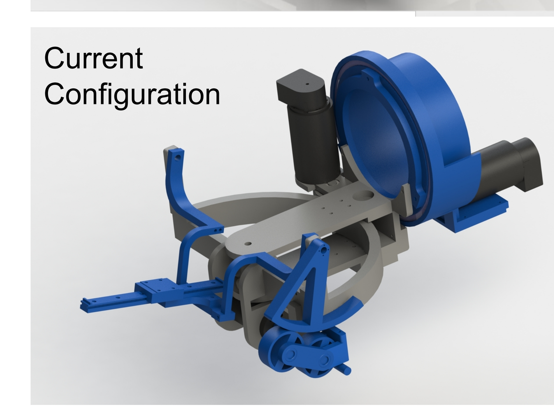
Modifications to Wrist Exoskeleton:

- Radial/ulnar DOF supports and capstan cable transmission modified to allow cable routing and interfacing with hand exoskeleton
- Forearm DOF changed from direct drive motor to closed capstan arc for evaluation purposes

Ongoing Design Work:

- Open forearm capstan to improve ingress and egress from exoskeleton
- Reduce flexion/extension capstan arc diameter for decreased device inertia



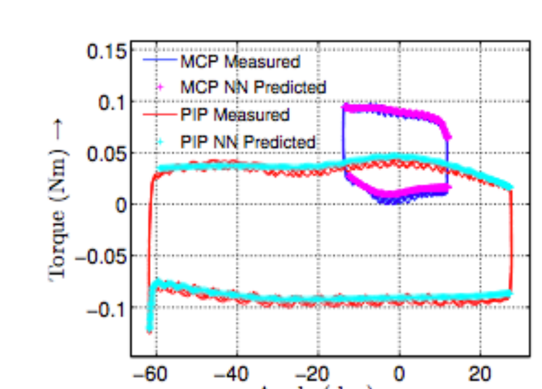


Ergonomic interface

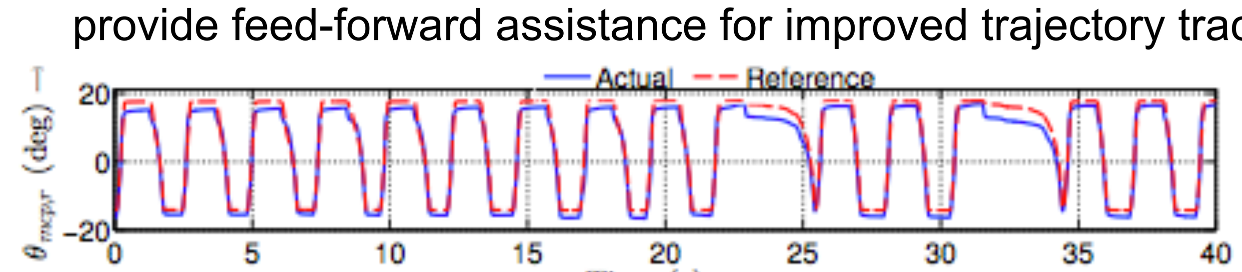
- Interface needs to adhere to 3D contours of each finger to maximize comfort and ensure transfer of forces.
- Ergonomic dorsal hand saddle hugs the hand topography.
- Design of a glove with integrated nylon finger saddles is being developed.

Assist-As-Needed Controllers

- Learned force-field control
- Assists trajectory following by using neural network model to map joint torques and angles

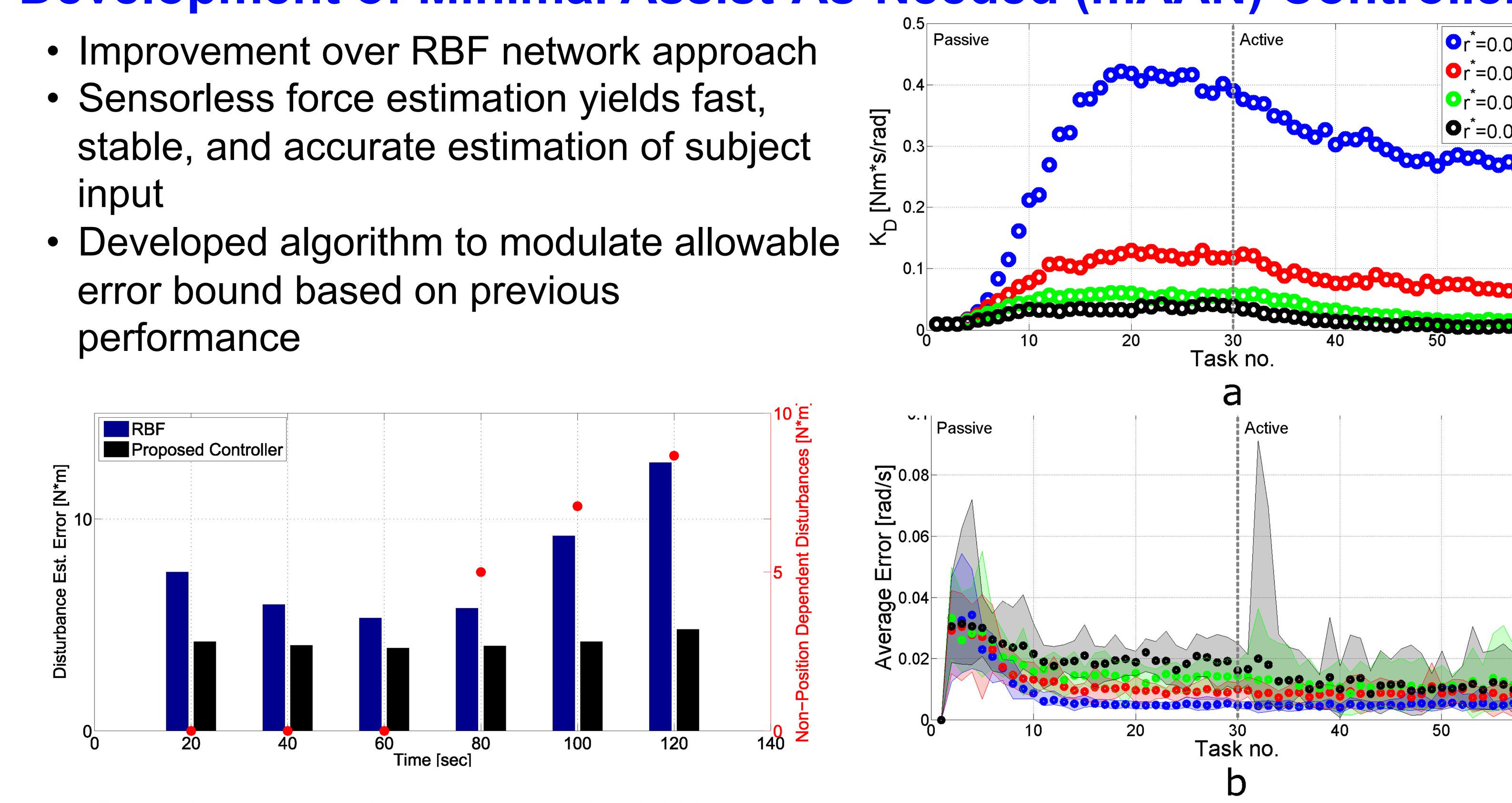


- Adaptive assist-as-needed control
- Estimates coupled finger-exoskeleton torque requirements using RBF to provide feed-forward assistance for improved trajectory tracking



Development of Minimal Assist-As-Needed (mAAN) Controller

- Improvement over RBF network approach
- Sensorless force estimation yields fast, stable, and accurate estimation of subject input
- Developed algorithm to modulate allowable error bound based on previous performance



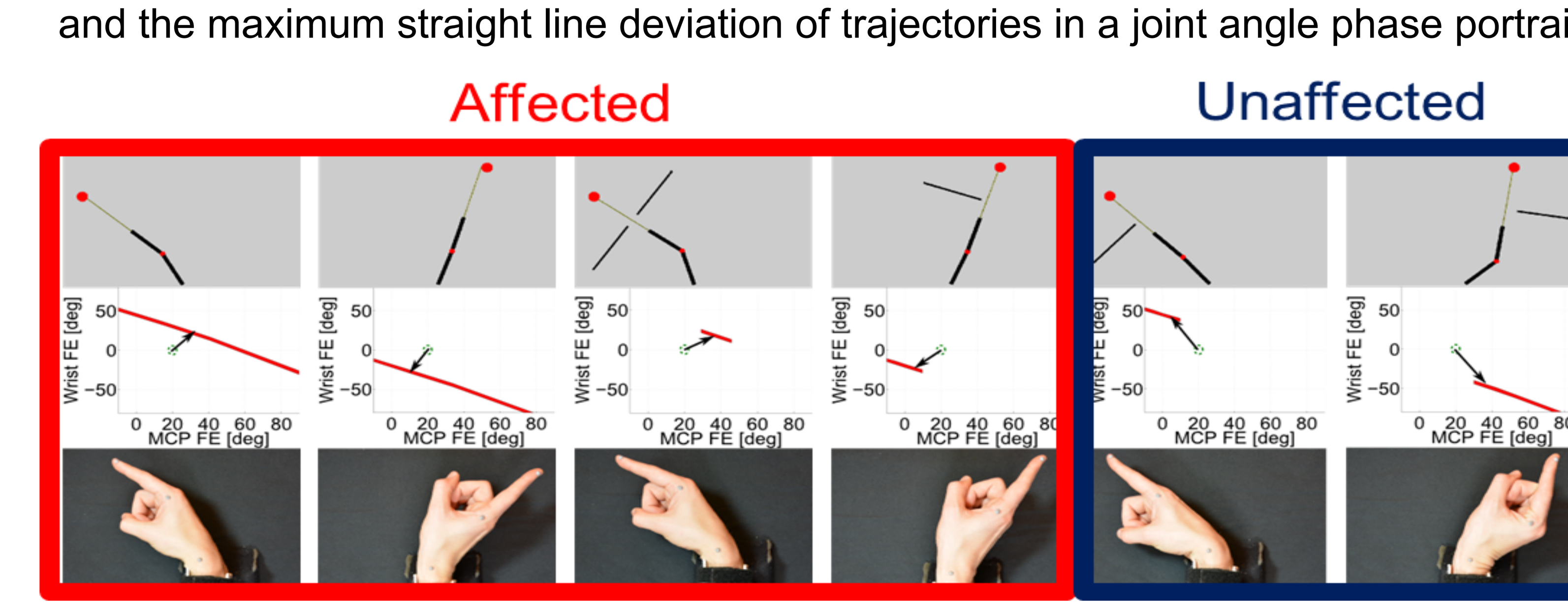
Gaussian approach vs. proposed mAAN controller during subject input estimation. The bar graph represents the norm of torque estimation error for both techniques over 20 second intervals. The red dots signify the magnitude of non-position dependent disturbances present over the same intervals.

Effect of error bound modification algorithm on feedback gain and average error. **(a)** Feedback gains for passive subjects (1-30) are higher than for involved subjects (31-60). As the allowable error decreases, the magnitude of robotic assistance increases. **(b)** The plotted points represent the mean error across all subjects and the shaded regions depict the corresponding variance. As the bound radius increases, subjects display more independence from the given trajectory.

mAAN controller encourages active participation and ensures goal completion!

Kinematic Joint Coupling in Wrist and Finger Pointing

- Investigated the device as a measurement tool through kinematic analysis
- Metrics used were peak time delay between wrist and finger join velocity maxima, and the maximum straight line deviation of trajectories in a joint angle phase portrait



Each column shows a task, with the visualization shown on top. The middle figure is the solution manifold of joint angles that successfully reach the target. Finger and wrist flexion/extension range of motion form the axes. The bottom figure shows the pose required to complete the task. Highlighted in red and blue, are the affected and unaffected tasks, respectively.

Joint couplings are sensitive to inertial and friction disturbances, and kinematic constraints!

Acknowledgement

The authors gratefully acknowledge the support of the National Science Foundation through grants NSF-CPS-1135949/1135916

Selected References

1. P. Agarwal, J. Fox, Y. Yun, M. K. O'Malley, and A. D. Deshpande. An Index Finger Exoskeleton with Series Elastic Actuation for Rehabilitation: Design, Control and Performance Characterization. Int'l J Rob Res, 2015. (in press)
2. A. U. Pehlivan, F. Sergi and M. K. O'Malley, "A Subject Adaptive Controller for Wrist Robotic Rehabilitation", IEEE/ASME T Mech (in press, DOI: 10.1109/TMECH.2014.2340697)
3. A.U. Pehlivan, F. Sergi, A. Erwin, N. Yozbatiran, G. Francisco, and M.K. O'Malley, "Design and validation of the RiceWrist-S exoskeleton for robotic rehabilitation after incomplete spinal cord injury," *Robotica*, Available on CJO 2014 doi:10.1017/S0263574714001490