A Gradient-Descent-Based Null Space Planner for Dexterity Optimization during Upper-Limb Robot-Mediated Rehabilitation

Ajay Anand, Charlie Lambert, Jono Jenkens, Carson J. Wynn, and Laura A. Hallock

Rocky Mountain American Society of Biomechanics
The University of Utah
HRELab Human–Robot Empowerment

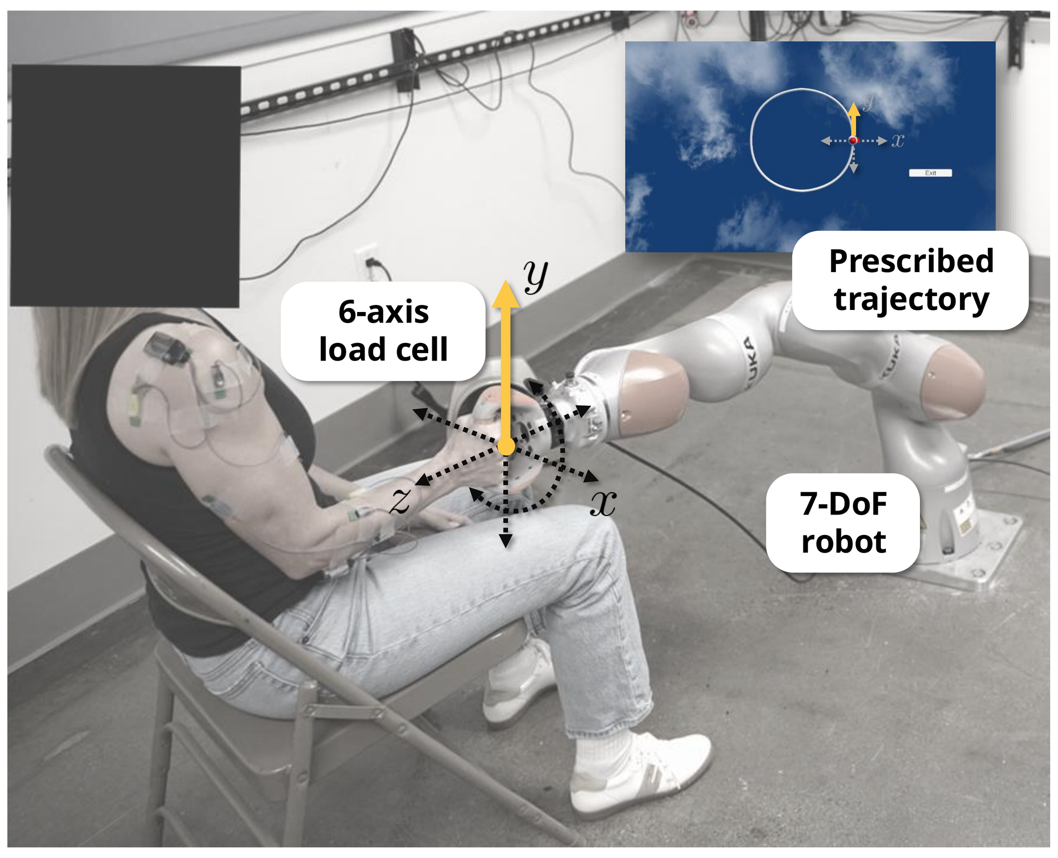
Null-space manipulability optimization enables **stable, high-dexterity 6-DoF robotic rehabilitation trajectories** without compromising end-effector tracking accuracy.

Motivation

- **Robot-mediated rehabilitation systems** could enable scalable post-stroke therapy through repeatable, task-relevant training that reduces clinician workload.
- However, 3D training in the large workspaces required for natural motions often moves the robot into **kinematic singularities** that degrade manipulability and controllability.

→ **GOAL**: Implement a **null-space dexterity optimization controller** for our **OpenRobotRehab** platform [1], enabling smooth, unconstrained **6-DoF** movements that avoid singularity.

Rehabilitation Platform

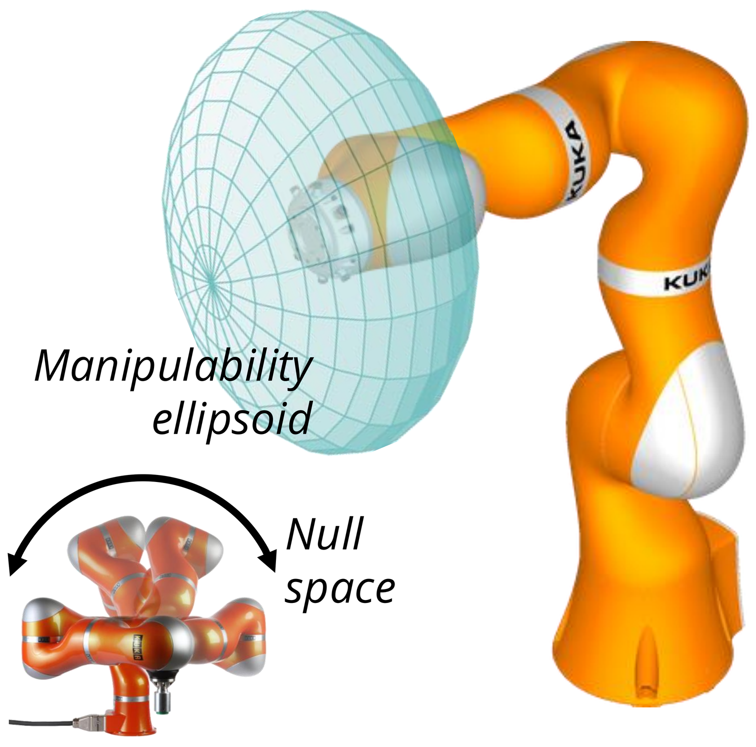


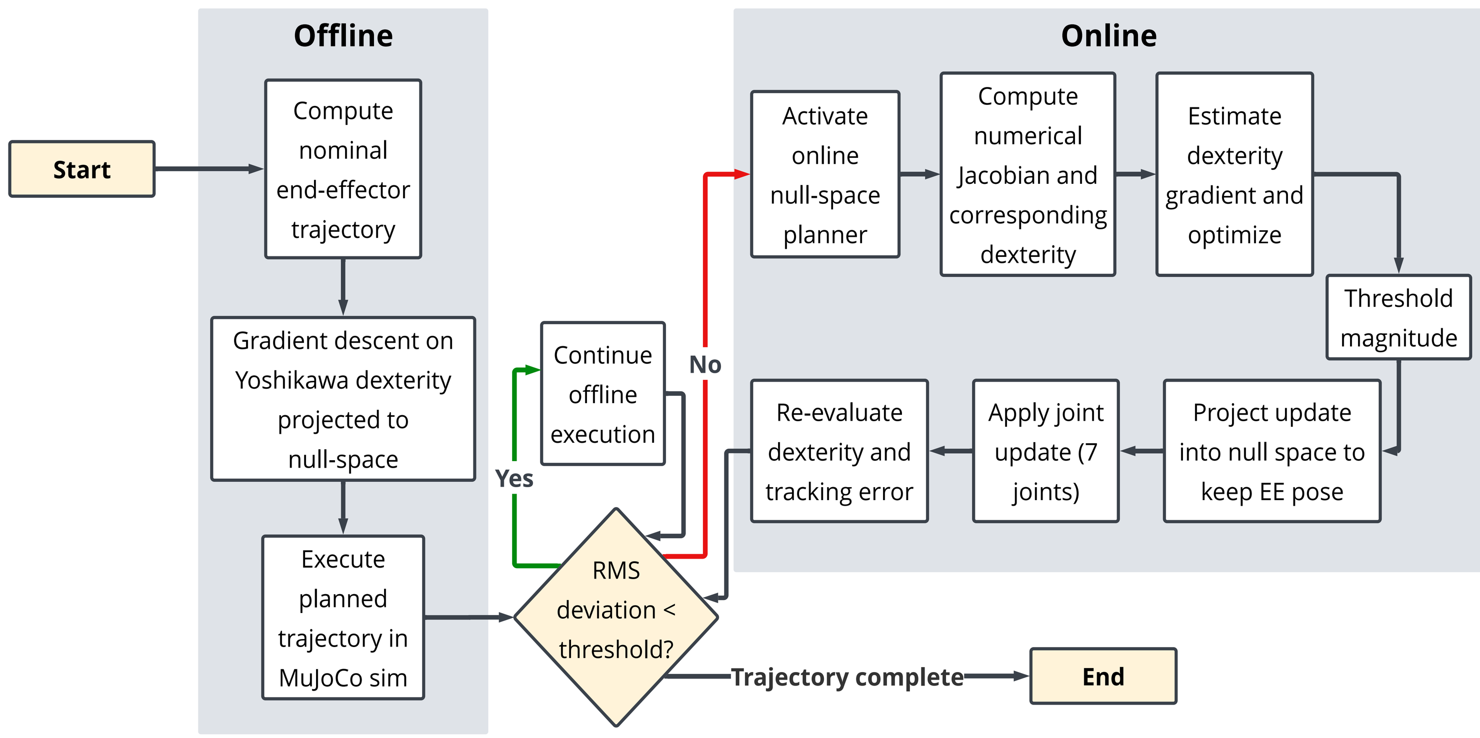
The **OpenRobotRehab** [1] upper limb rehabilitation platform. Users follow displayed trajectories by transmitting forces and torques through a Bota Systems SensONE 6-axis load cell to move a KUKA LBR iiwa 14 R820 7-DoF cobot.

End Effector Trajectory Planning Algorithm

Given a known (prescribed) end effector trajectory, we aim to **adjust joint positions in the "null space"** (i.e., without changing end effector position), taking advantage of the redundant degree of freedom to avoid singularities and maintain dexterity.

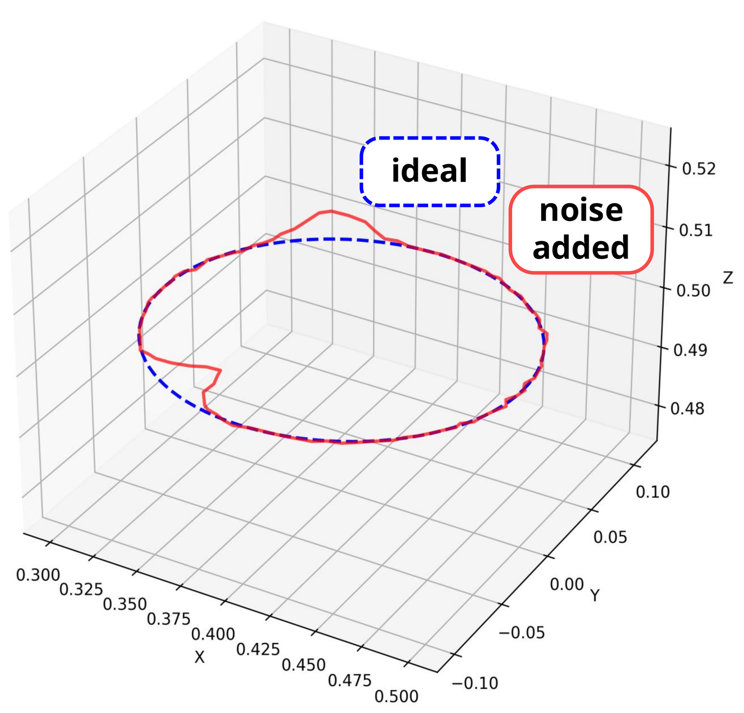
Specifically, we optimize the **Yoshikawa Index** [2] $w = \sqrt{\det(JJ^T)}$, which describes the volume of the manipulability ellipsoid.





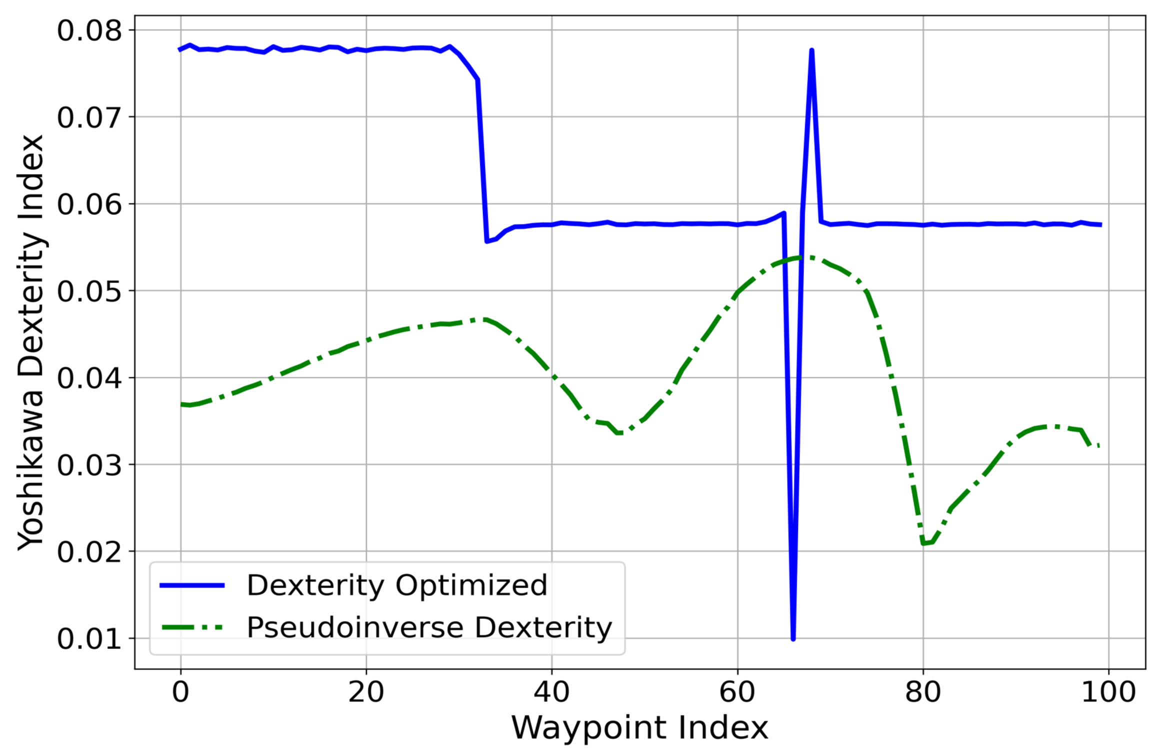
Evaluation and Results

The **dexterity optimization algorithm** was evaluated by injecting **stochastic perturbations** into ideal rehabilitation trajectories to simulate human motion variability.



Simulated human tracking of a 3D circular trajectory. The ideal robot path *(blue dashed)* is perturbed with Gaussian noise and random deviations to produce the human-like trajectory *(red solid).*

- The **Yoshikawa Index is consistently elevated** using our optimization algorithm, indicating an increase in scalar dexterity corresponding to improved global kinematic conditioning.
- However, **hardware experiments** reveal that scalar dexterity maximization is **insufficient** near **kinematic singularities**, where gains do not translate to improved control along **task-relevant directions**.



Comparison of Yoshikawa dexterity along a 100-point trajectory for naive *(green)* and optimized *(blue)* controllers. The optimized controller maintains higher manipulability across nearly all waypoints, with a brief disturbance near waypoint 65 due to local Jacobian conditioning.

Conclusions

Our planning algorithm **improves** global scalar **dexterity** along **large-workspace rehabilitation trajectories**, but

- often **relies on the online planner**
- **does not** ensure improvements in **task-relevant dexterity**, due to the **lack of directional sensitivity** in scalar manipulability metrics despite structured, known motion directions in rehabilitation tasks.

Current Extensions

- Reformulation of the **dexterity optimization controller** as a **fully online** method to adapt to uncertainty and variability in human-in-the-loop rehabilitation tasks.
- Replacement of scalar objectives with **directional manipulability optimization**, integrating task-direction weighting into the null-space, **improving task-relevant velocity transmission** across large-workspace rehabilitation motions.

Acknowledgments / Sponsors/ References

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[1] Anand et al, ICORR 2025
[2] T. Yoshikawa, MIT Press, 1990