Exploiting Redundancy to Facilitate Physical Interaction

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ABSTRACT

The control of kinematically redundant robots is often approached using nullspace projection, which requires precise models and can be computationally challenging. Humans have many more degrees of freedom than are required to accomplish their tasks, but given neuromechanical limitations, it seems unlikely that biology relies on precise models or complex computation. An alternative biologically inspired approach leverages the compositionality of mechanical impedance. In theory, nullspace projection eliminates any conflict between two tasks. In contrast, superposition of task-space impedance and a full-rank joint-space impedance may impose a task conflict. This work compared nullspace projection with impedance superposition during unconstrained motion and forceful physical interaction. In practice, despite their theoretical differences, we did not observe a substantial influence of the nullspace projector weighting matrix. We found that nullspace projection and impedance superposition both resulted in measurable task conflict. Remarkably, when the dimensionality of the nullspace was increased, impedance superposition was comparable to nullspace projection.

INTRODUCTION

Robots
7-26 DOF

Biology
>100 DOF

- Nearly all optimization methods struggle as dimensionality increases, known as the "**curse of dimensionality**" [Bellman 1966].
- If dimensionality was fundamentally a limitation of control then why is it so prevalent in biology?
- It seems unlikely that biology relies on precise models or complex computation.

METHODS

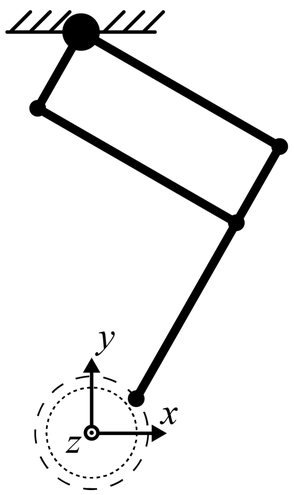
Task 1: Move end-effector in a circle — Task 2: Joint impedance resolves redundancy

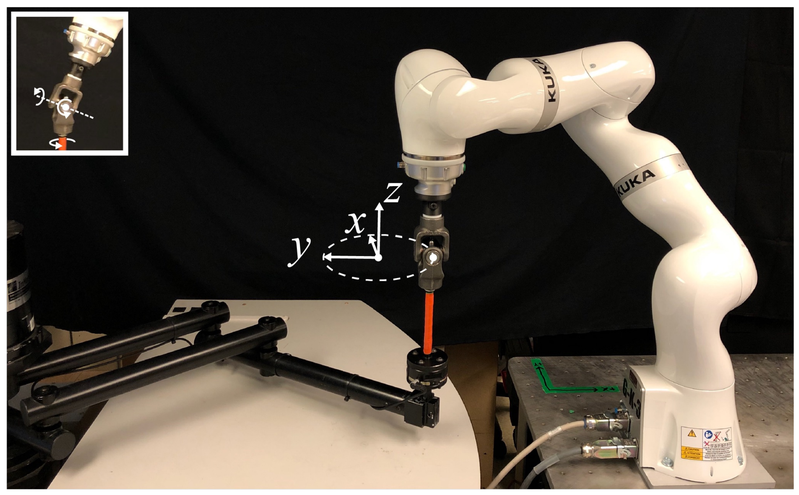
$$\boldsymbol{\tau} = \boldsymbol{J}^T[\boldsymbol{K}_x(\boldsymbol{x}_0 - \boldsymbol{x}) + \boldsymbol{B}_x(\dot{\boldsymbol{x}}_0 - \dot{\boldsymbol{x}})] + \boldsymbol{N}[\boldsymbol{K}_q(\boldsymbol{q}_0 - \boldsymbol{q}) + \boldsymbol{B}_q(\dot{\boldsymbol{q}}_0 - \dot{\boldsymbol{q}})]$$

Nullspace Projector: Prevents Task 2 from interfering with Task 1.

Conditions:
- Weighting Matrix $(\boldsymbol{0}, \boldsymbol{I}, \boldsymbol{M}(\boldsymbol{q}), \boldsymbol{B}_q, \boldsymbol{K}_q)$
- Nullspace Dimension (1D and 4D)
- Constraint (unconstrainted and constrained)
- Controller (standard, fast speed, low joint stiffness)

Nullspace Dim	=	[joint space dim]	-	[task dim]
1D	=	[7 rotational]	-	[3 translation + 3 rotation]
4D	=	[7 rotational]	-	[3 translation]





RESULTS

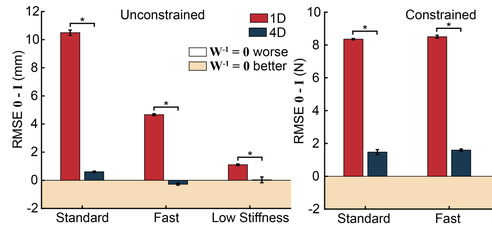
Goal: regulate the translational behavior in the plane of the InMotion robot.

1D nullspace condition:
- Superposition ($\boldsymbol{0}$): large task conflict
- Nullspace projection ($\boldsymbol{I}$): almost eliminated the task conflict

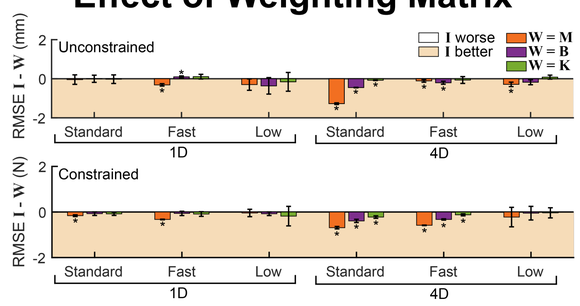
4D nullspace condition:
- Superposition and nullspace projection resulted in comparable task conflict.

This observation was robust across the investigated conditions.

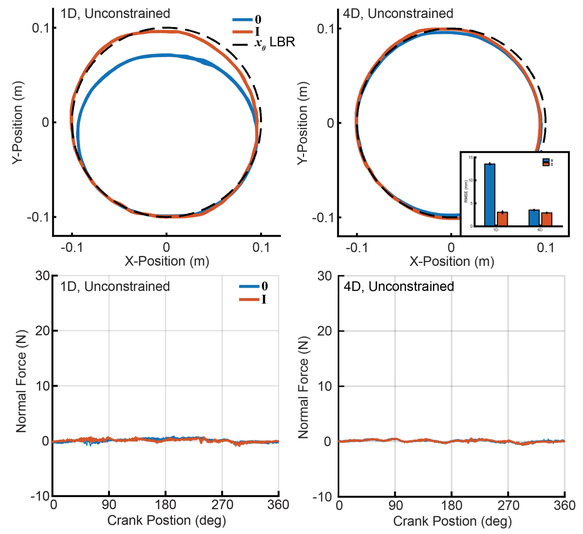
Effect of Condition



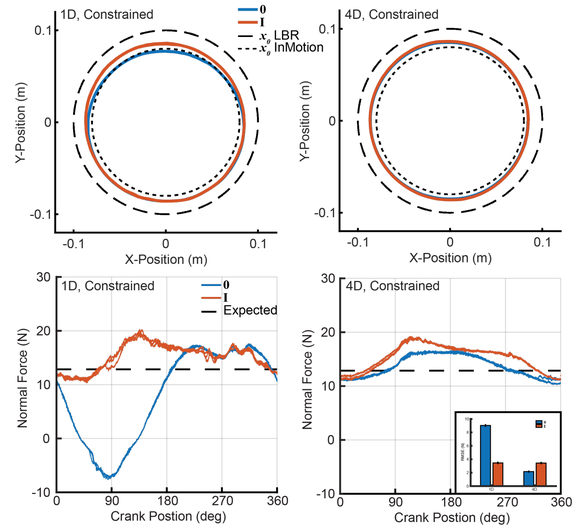
Effect of Weighting Matrix



Unconstrained



Constrained



DISCUSSION AND CONCLUSIONS

When the nullspace dimension increased, superposition was comparable to nullspace projection.

Dimensionality may be a "blessing" not a "curse".

Impedance superposition may be better for biological type cases:
- Small joint space stiffness
- Large nullspace between end-effector space and joint space

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