Powered Prostheses: Minimizing Multi-Activity Motor Torque Through Parallel Elasticity and Convex Optimization

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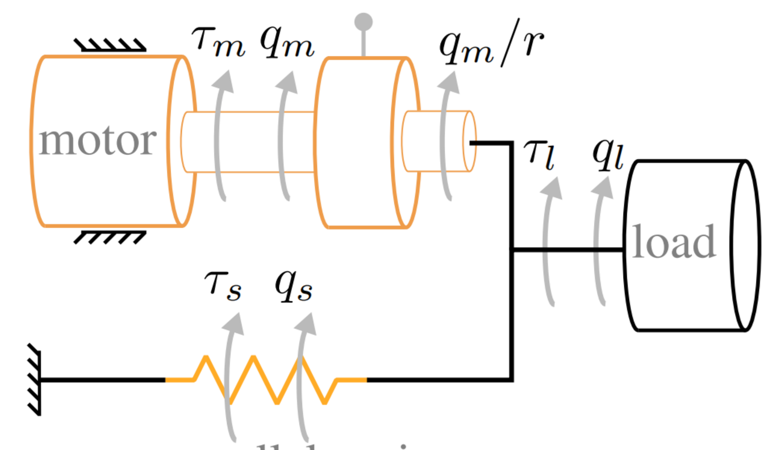
Challenge: Multi-activity Torque-reducing PEA Design

Popular design methods focus on minimizing energy/torque of a single activity, which causes the spring to increase torque during other activities.

Linear elastic element

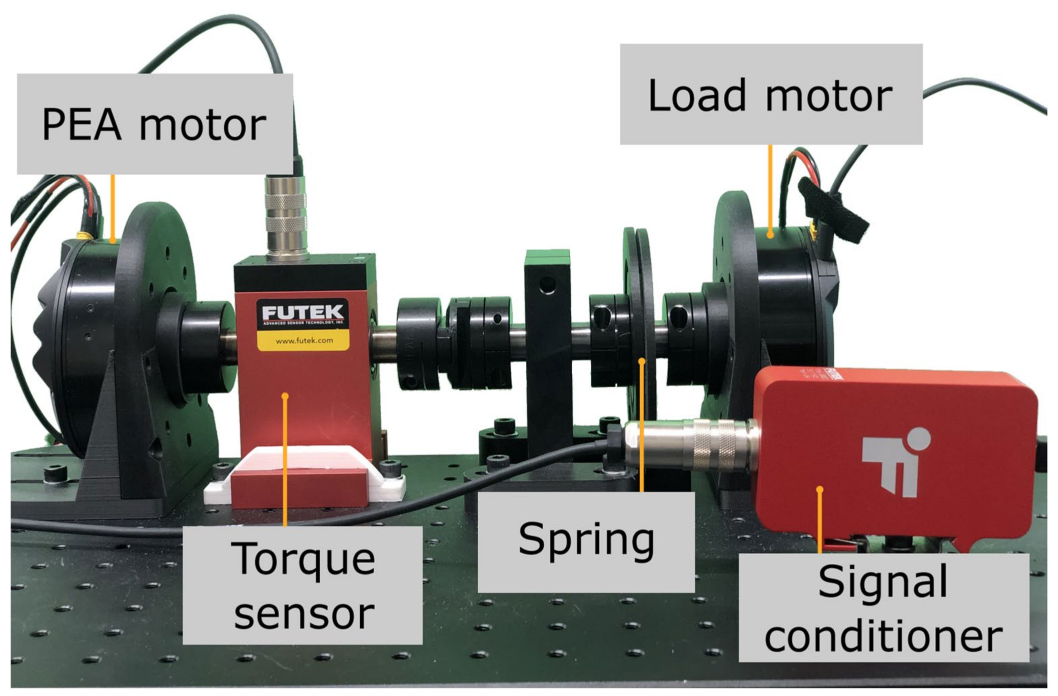
$\tau_s = k q_s$

Motor torque is an **affine function** of optimization variables (i.e. spring stiffness and preload torque)

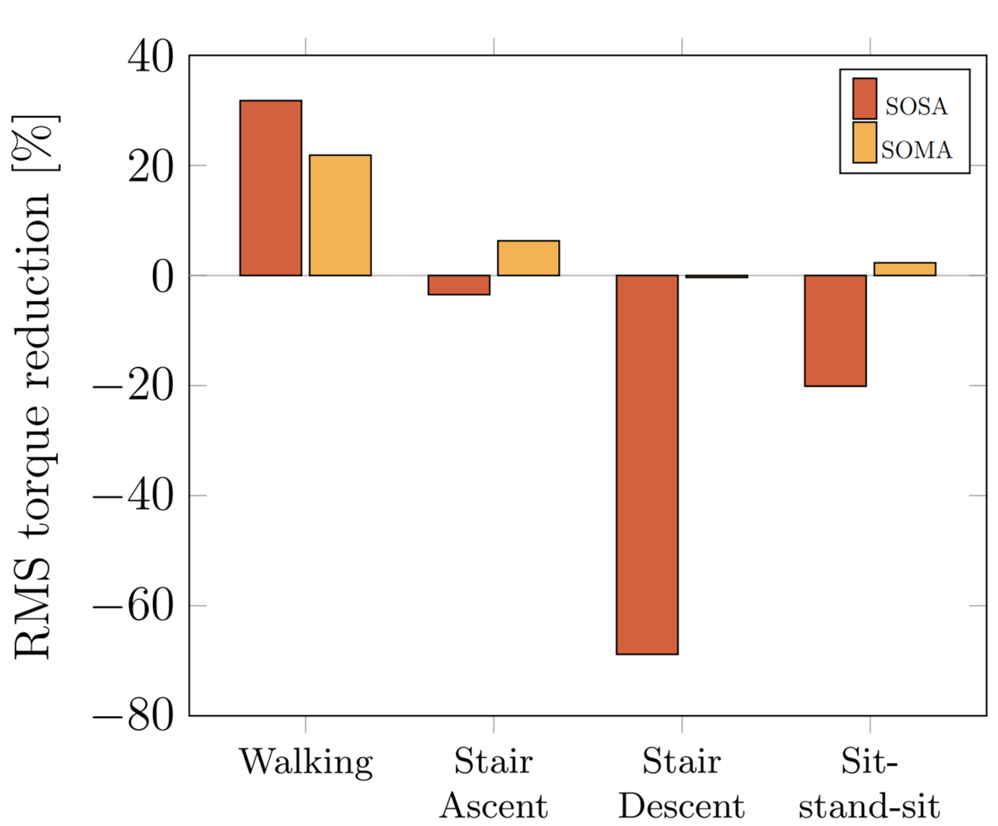


$$\boldsymbol{\tau}_m = \boldsymbol{\tau}_c - \frac{1}{r}(-k\boldsymbol{q}_s + \mathbf{1}\tau_p)$$

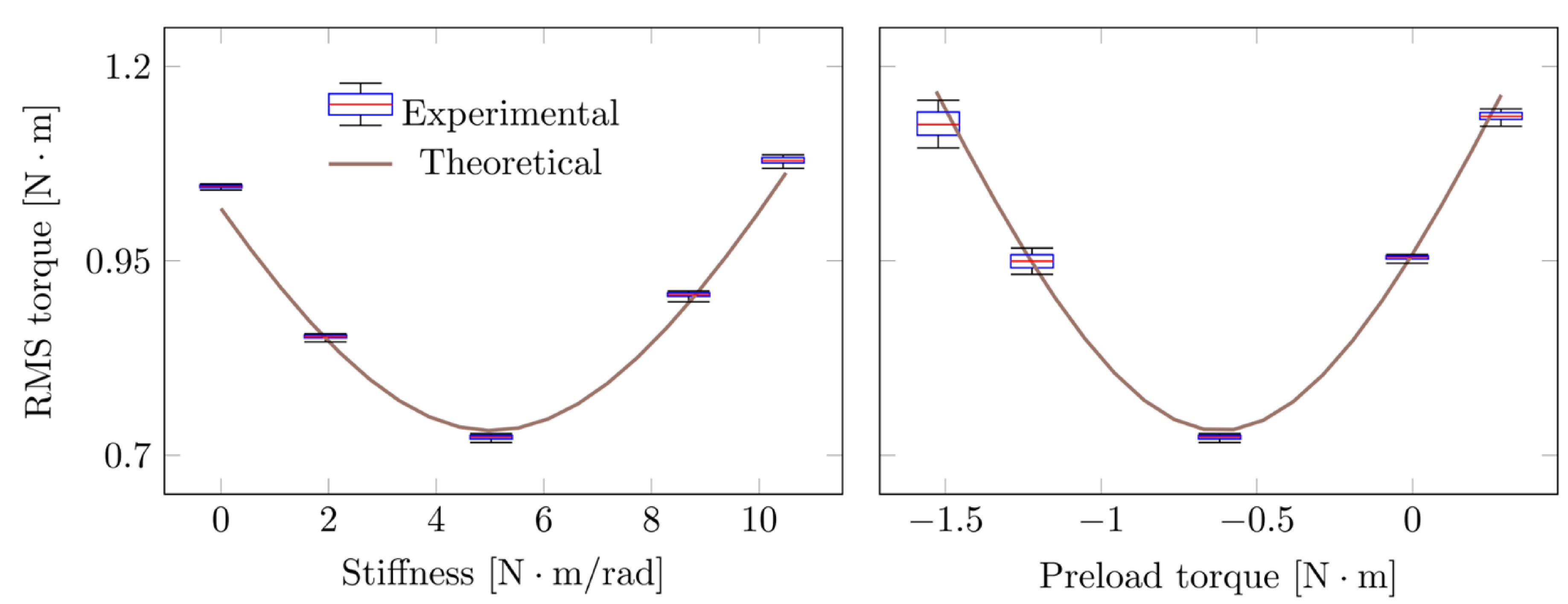
$$\boldsymbol{\tau}_c = I_m\ddot{\boldsymbol{q}}_m + b_m\dot{\boldsymbol{q}}_m + \mu\,\text{sign}(\dot{\boldsymbol{q}}_m) - \frac{\boldsymbol{\tau}_l}{r}$$



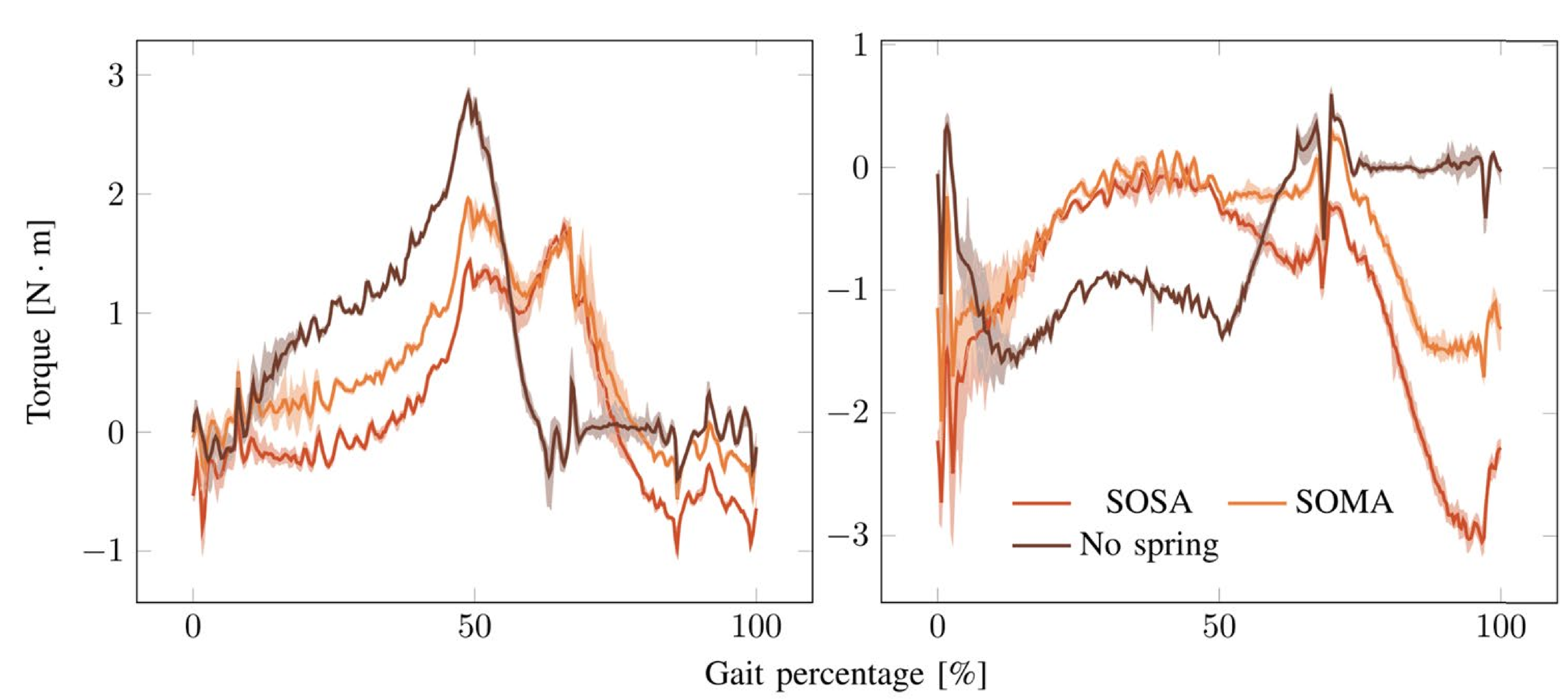
Dynamometer to simulate a prosthetic ankle



Spring optimized for a single activity (SOSA) vs. spring optimized for multiple activities (SOMA)



RMS torque during one walking stride as a function of PEA stiffness and preload. Experimental validation that RMS torque is a convex function of spring stiffness and preload.



Torque of an actuator without the spring, with a spring optimized for walking (SOSA), and with a spring optimized for multiple activities (SOMA) during **walking (left) and stair descent (right)** for 50 strides.

Solution: A Globally Optimal Design for Multiple Activities

Key features:

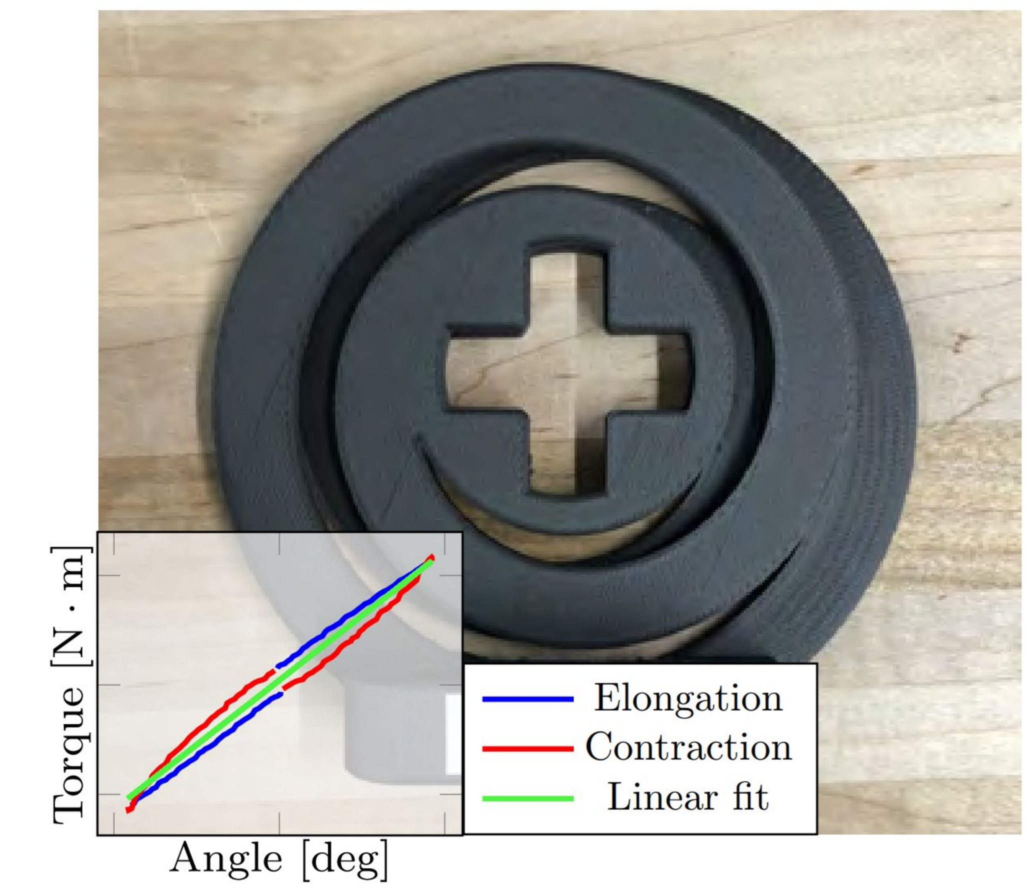
- RMS torque reduction for multiple tasks.
- Convex optimization framework.
- Solutions computed within polynomial time.

Single activity:

$$\min_{k,\tau_p} \; \|\boldsymbol{\tau}_m\|_2, \quad \text{s.t.} \quad k > 0$$

Multiple Activities:

$$\begin{aligned} \min_{k,\tau_p} \; & \|\boldsymbol{\tau}_{m,1}\|_2 \\ \text{s.t.} \; & k > 0 \\ & \|\boldsymbol{\tau}_{m,2}\|_2 \leq \|\boldsymbol{\tau}_{c,2}\|_2 \\ & \vdots \\ & \|\boldsymbol{\tau}_{m,x}\|_2 \leq \|\boldsymbol{\tau}_{c,x}\|_2 \end{aligned}$$



Spring optimized for

single activity	multiple activity
5.02 N · m/rad	3.28 N · m/rad

Scientific Impact:

- Parallel elastic actuators reduce motor torque for multiple tasks
- Convex optimization framework
- Torque-oriented design paradigm contrary to the traditional energy-oriented approach

Open Source Leg
www.opensourceleg.com

Societal Impact:

Users will experience lower metabolic cost during walking, stair ambulation, and sit-stand transitions due to a lighter prosthesis enabled by a globally optimal parallel spring that reduces motor torque requirements.

Educational Impact:

Dissemination with the Northern Indiana Amputee Support Group