Human-in-the-loop real-time optimization of exercise trajectory and resistance

CPS Synergy: Cyber-Enabled Motions in Rehabilitation

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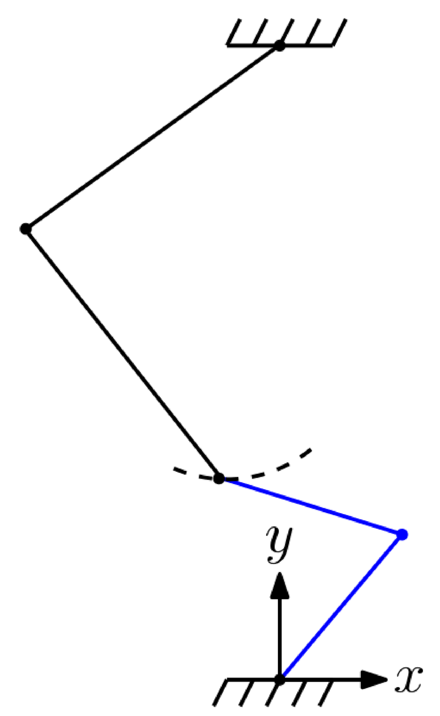
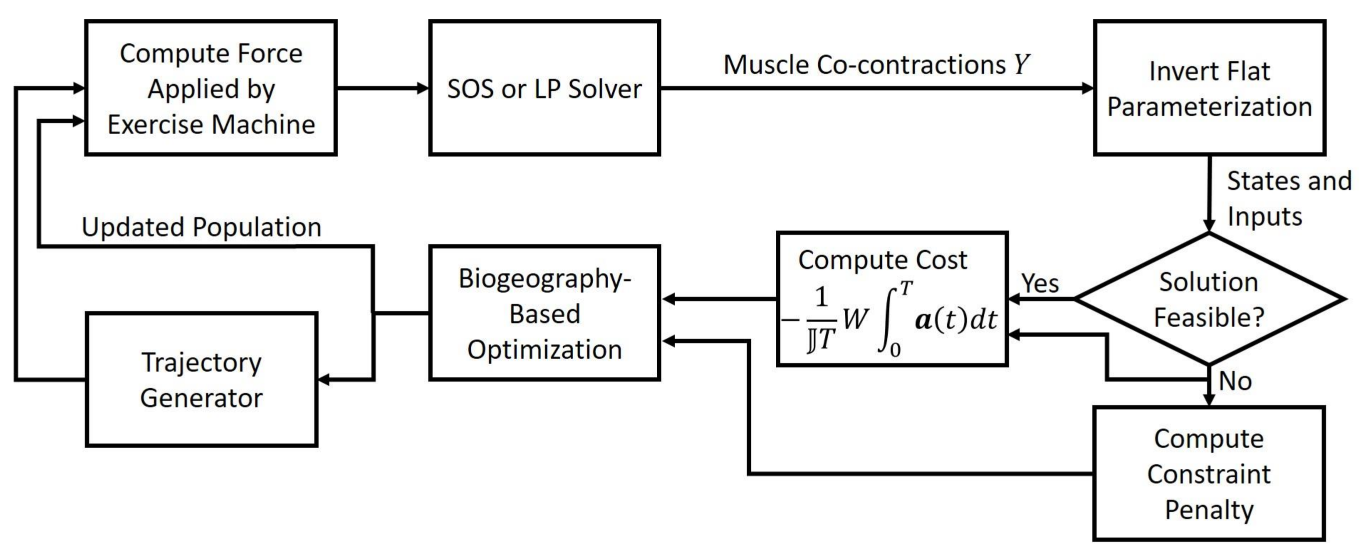
Human-Machine Interaction Modeling and Evolutionary Optimization

- Machine / musculoskeletal system interaction simulations inform optimal exercise or rehabilitation protocols to be implemented.
- A new approach based on differential flatness in combination with semidefinite programming (SOS polynomial optimization) produces extremely fast solutions which are biomechanically meaningful [1].
- We consider a prototype exercise or rehabilitation concept where a planar 2 DOF exercise machine is coupled to a human arm (blue). Interaction forces result from the machine's selectable impedance and its reference trajectories.





- The human is assumed to accurately track some ellipse, regardless of the required effort. Cartesian impedances are set against the deviation from the machine's reference (a circle) and the ellipse. *Both the ellipse parameters (tilt and eccentricity) and the impedance parameters are to be optimized.*
- The objective function is a weighted sum of muscle activation integrals over one period. Weights reflect training / rehab needs.
- Biogeography-Based Optimization was used, with 5 Monte Carlo trials with 50 candidate solutions over 200 generations to optimize shoulder muscles.
- Endpoint force limited to 45 N magnitude
- Anterior deltoid emphasis weights:

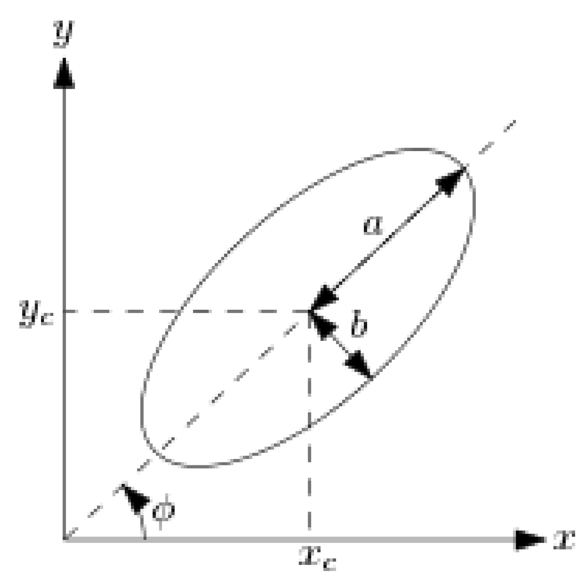
$$W = [1\ -1\ -1\ -1\ -1\ -1]^T$$

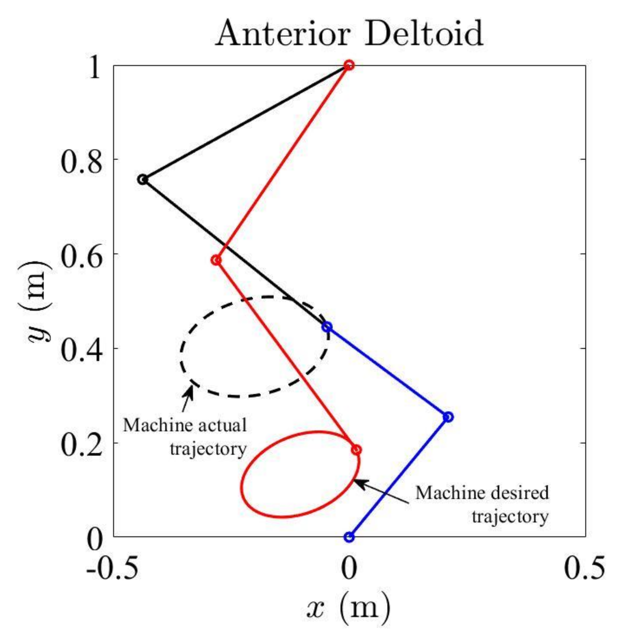
- Posterior deltoid emphasis weights:

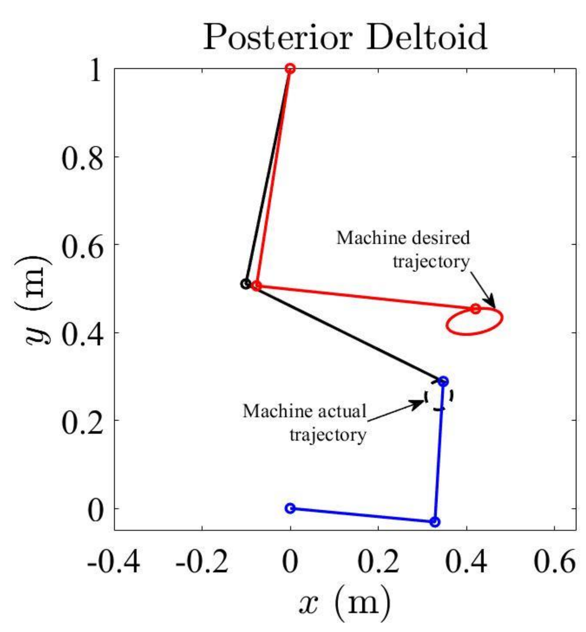
$$W = [-1\ 1\ -1\ -1\ -1\ -1]^T$$

[1] Richter, H. and Warner, H., Motion Optimization of Musculoskeletal Dynamics: A Flatness-Based Sum-of-Squares Approach, *IEEE Trans. Autom. Control*, (in review) 2019

Simulation Results



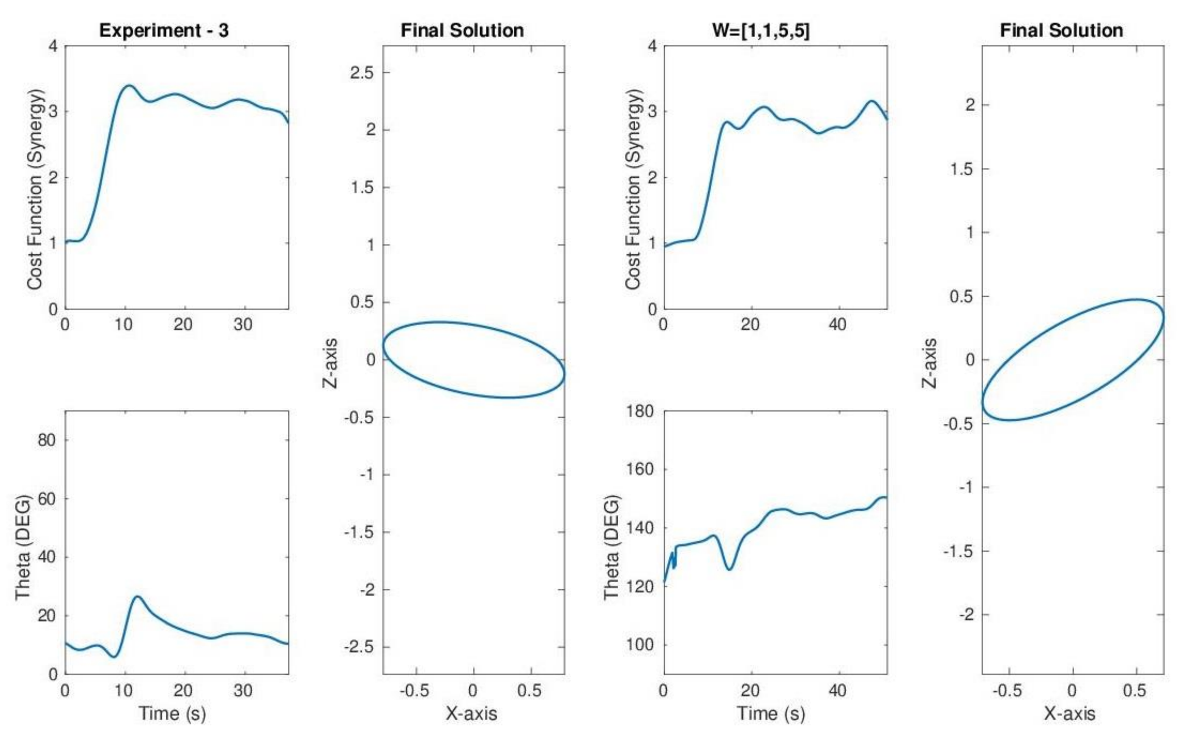




	a_a (m)	b_a (m)	a_d (m)	b_d (m)	xc_a (m)	xc_d (m)	yc_a (m)	yc_d (m)	ϕ_a (rad)	ϕ_d (rad)	f (Hz)	Direction	I_x (kg)	I_y (kg)	B_x (kg/s)	B_y (kg/s)	K_x (N/m)	K_y (N/m)
Ant. Deltoid	0.15	0.10	−0.2	0.40	0.23	0.13	0.08	−0.1	0.13	0.38	0.25	CW	77.2	139.6	85.70	64.02	267.1	11.79
Post. Deltoid	0.03	0.02	0.33	0.25	1.36	0.02	0.06	0.41	0.42	1.75	0.18	CCW	48.58	84.48	288.5	196.0	3.501	122.3

Results demonstrate strong influence of exercise trajectories and impedances on the distribution of muscular effort, justifying the experimental phase.

Real-Time Model-Free Optimization with Extremum Seeking Control



- The concept was implemented in real-time using a 4 DOF haptic robot (Barrett WAM arm).
- Only gravity compensation was used in the WAM. Human effort is due to overcoming the muscle's own passive resistance and weight as the ellipse is tracked.
- Extremum Seeking control was used to modify ellipse parameters to maximize a weighted measure of muscle effort.
- The objective function was computed with a moving average, based on EMG sensor data.