CPS Synergy: Cyber-Enabled Motions in Rehabilitation

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GENERALITIES

Aim

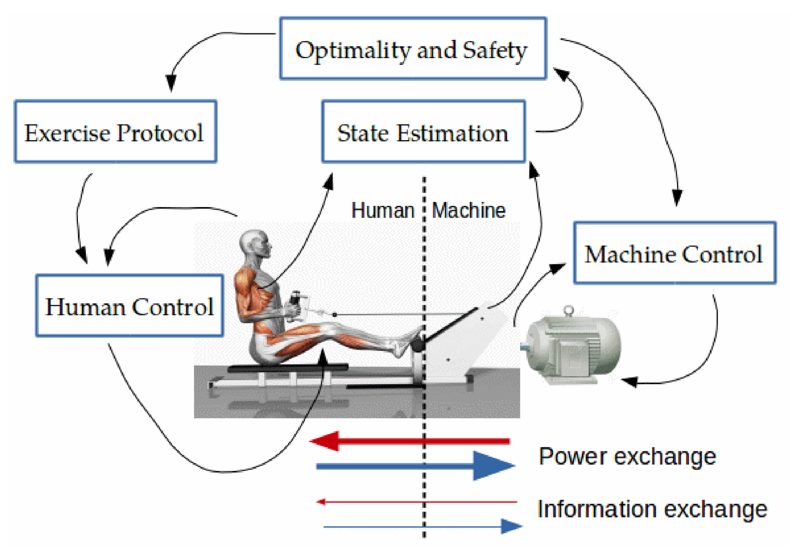
The project aims to advance both foundations and enabling technologies in the field of human-machine systems, with a focus on exercise and rehabilitation machines.

Beyond haptics

The analysis of human-machine systems is extended beyond haptics (*haptikos*: pertaining to touch). Haptics research does not explicitly consider the dynamics of power exchange between man and machine.

A human interacting with an advanced (actively-controlled) exercise machine is the ultimate cyber-physical system:

- Multi-level loop closures
- Large-scale, coupled musculoskeletal dynamics
- Conflicting objectives: human vs. machine controllers
- Uncertain dynamics and limited sensing



OBJECTIVES AND CHALLENGES

Working hypothesis: Physical training for athletic conditioning, rehabilitation or special environments (microgravity) can be improved (or made possible) by endowing machines with optimality-seeking adaptive behavior.

Specifically, the machine will be controlled to vary its mechanical impedance at the human interface, and optimal cues will be generated to direct the user to vary their motions.

What is optimal exercise? -This is one of the research questions. For instance, muscles can be ``addressed'' by spatio-temporal impedance modulation, thereby targeting specific muscle groups which are important for a sport or to manage an injury.

The specification of high-level control policies requires:

- A set of guiding optimality criteria
- Estimation algorithms based on biomechanical models and limited, minimally-invasive biomechanical sensing
- Online optimization of partially-known objective functions (as in extremum-seeking)
- Stability in the face interacting controllers with conflicting objectives, constraint handling and safety assurance.

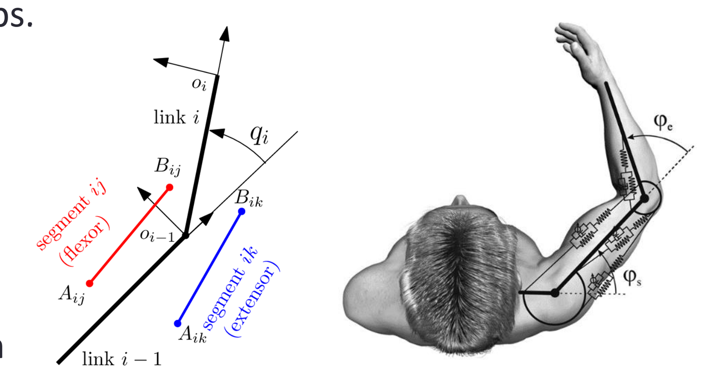
TEAM AND FACILITIES

- **Hanz Richter** (lead PI): system dynamics, control theory (directs Control, Robotics and Mechatronics Lab)
- **Dan Simon**: estimation theory, evolutionary optimization (directs Embedded Systems Research Lab), game theory
- **Ken Sparks**: human performance, exercise science, human subject testing (directs Human Performance Lab)
- **Ton van den Bogert**: biomechanical modeling, human motion and control, optimization (directs Human Motion and Control Lab)

MODELING AND FEEDBACK CONTROL OF MUSCLE-DRIVEN LINKAGES

Machine-side control, estimation and optimization subsystems require "working models" of the human musculoskeletal dynamics and its internal controls.

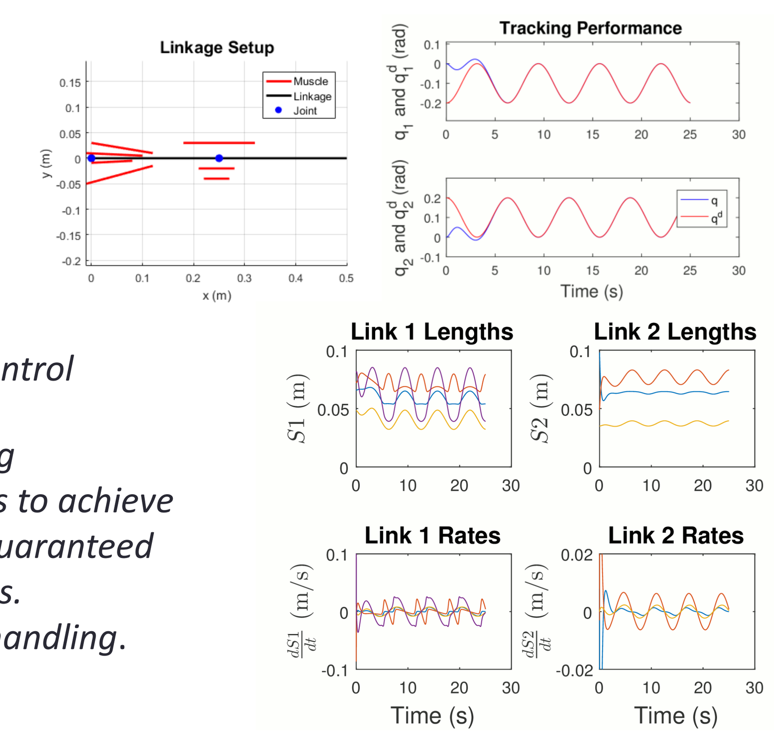
A systematic, scalable approach has been undertaken to produce dynamic models of muscle-driven multi-d.o.f. linkages representing human limbs.



Feedback controllers for trajectory following and impedance can be designed on the basis of these models.

While identification of actual (physiological) human controllers is not the aim, we seek controllers which retain several features of human control systems:

- Ability to comply with motion tasks: *asymptotic tracking or impedance regulation*
- Limited information about "load" and tolerance to change: *robustness/adaptation*
- Self-protection: *stability and constraint handling*
- Self-correction: *feedback, automatic regulation*
- Redundancy resolution, minimal effort: *optimal control*

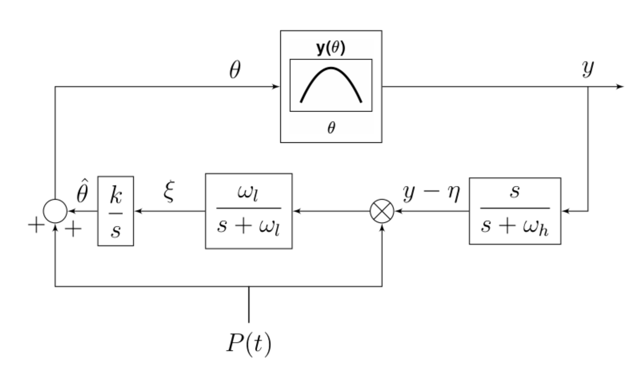


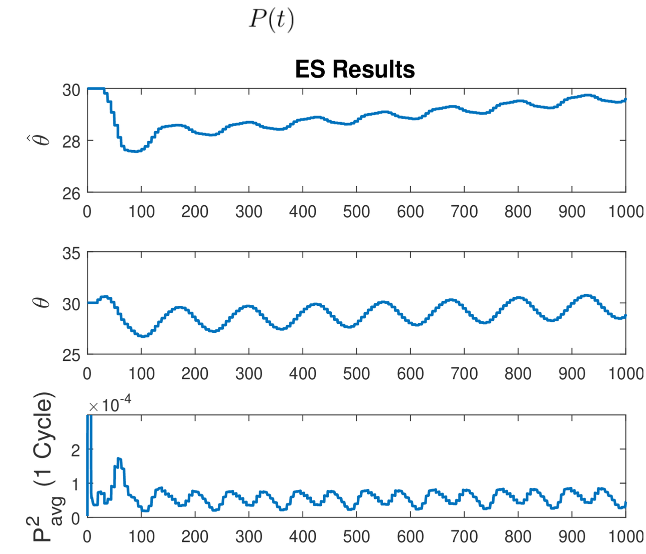
We have introduced new control techniques combining robotics-oriented modeling and biomechanical models to achieve asymptotic tracking and impedance regulation with guaranteed stability for redundant multi-link/multi-muscle systems. Model-predictive control is being used for constraint handling.

HUMAN PERFORMANCE OPTIMIZATION

We use muscle activations to define human performance indicators, which can be affected by machine interaction dynamics (mechanical impedance).

The aim is to generate autonomous impedance modulations to seek maxima for the selected performance indicator, for instance muscle power.





In a real-time human application, model information will be absent or limited. Sensing will be available as limited EMG (muscle activation), link motions and force at the interface only.

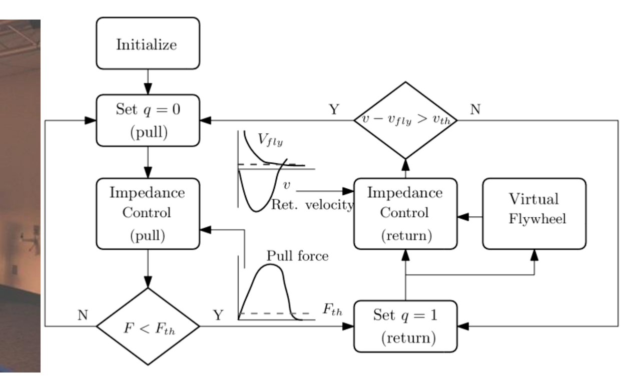
Extremum-seeking algorithms have been selected as the basis of our approach, with many outstanding challenges, mainly:

- ES meant for staic I/O maps, while power is highly dynamic. *We explore real-time mean square averaging.*
- ES assumes that extrema actually exist and that the search variables have been defined. *We have used human linkage/muscle dynamic modeling to investigate the existence of maxima relative to machine impedance parameters (stiffness, inertia, damping)*

THE *PHYSICAL* IN CYBER-PHYSICAL: ADVANCED EXERCISE MACHINE PROTOTYPES

Our CPS project emphasizes actual implementation of fundamental research in a real-time human-machine interaction setting. We use two platforms: a new powered rowing machine for aerobic exercise and a new 4 DOF exercise robot for resistance exercise (under design/construction).

Comprehensive baseline study of the rowing exercise and conventional machine (March 2016, CSU Human Motion Lab)



Top-level architecture of a robust hybrid impedance controller for the powered rowing machine (US patent application)

CSU student-athlete testing the final powered prototype, with EMG and motion capture (September 2017, CSU Human Motion Lab)

The powered rowing machine brings the following innovations:

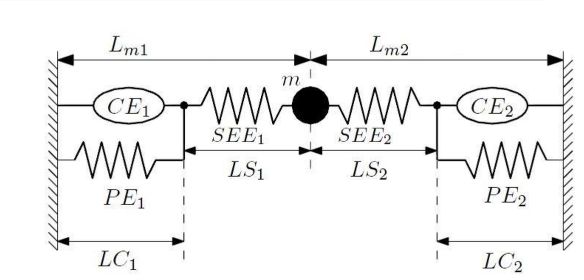
Basic human performance data recorded during trials in Sept.17

An eccentric/concentric power ratio of 1:1 was demonstrated.

- **Programmable impedance**: the mechanical impedance appearing at the user port can be selected arbitrarily and robustly attained (high versatility).
- **High eccentric capability:** the design eliminates the one-way clutch found with conventional designs, allowing for significant return stroke forces.

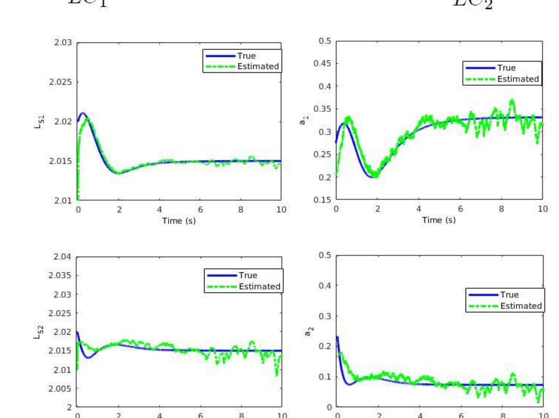
MUSCULOSKELETAL STATE ESTIMATION

Implementation of the proposed optimality-seeking algorithms in exercise and rehabilitation machines relies on the availability of key biomechanical variables. In a real-time human experiment, only a few measurements are possible, and reliable estimation must be used.



We consider Kalman filter and nonlinear estimation approaches such as the super-twisting observer.

Scenario: a model of the human linkage and actuating muscles is available, along with uncertain parameters and limited, noisy measurements (EMG at selected locations, joint motions and force/torque at the human-machine Interface.



Aim: obtain reliable estimates of muscle model variables conducive to an estimate of the selected performance index to be used in an optimality-seeking algorithm (e.g., ES)

Current results with a conceptual 2-muscle agonist-antagonist model indicate that unknown variables such as muscle activations can be reliably estimated, while noisy measurements can be refined by a full order of magnitude in the noise/signal ratio.

Current efforts are aimed at estimation algorithms suitable for larger human linkage-muscle systems and real-time estimation based on EMG data.