CPS Synergy: Cyber-Enabled Motions in Rehabilitation

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GENERALITIES

Aim

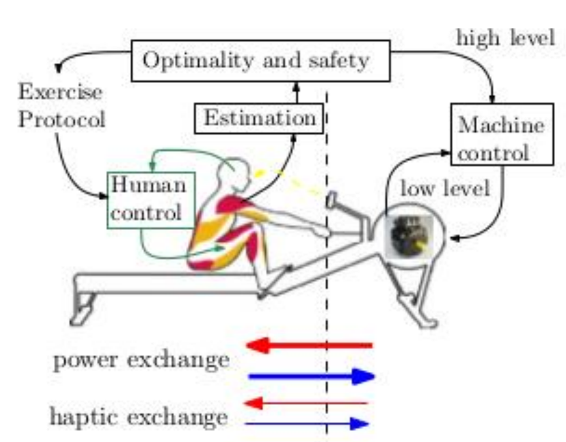
The project aims to advance both foundations and enabling technologies in the field of human-machine systems, with a focus on exercise and rehabilitation machines.

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 even 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 constitutes optimal exercise 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:

- 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

Human and machine dynamic models are essential to our objectives. According to the sub-problem being considered, several approaches to modeling and mathematical/numerical methods become relevant.

Machine-side control, estimation and optimization subsystems benefit from "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.

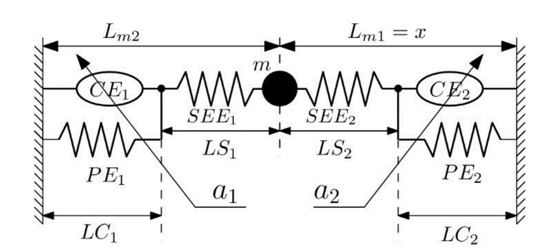
Feedback controllers for trajectory following and impedance can be designed on the basis of these models.

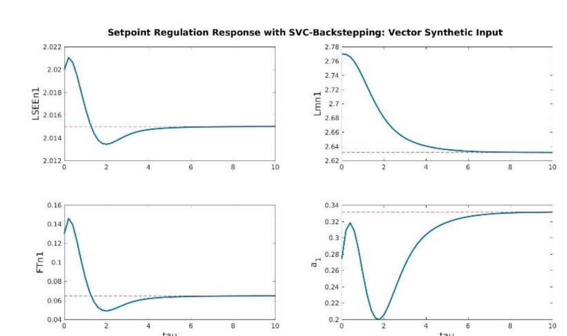
While identification of actual (physiological) human controllers is not the aim, we seek controllers which retain several features of human control systems:

- Ability to accurately follow motion tasks: *asymptotic tracking*
- 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 used backstepping control techniques to achieve asymptotic load regulation with guaranteed stability in the two-muscle system. Model-predictive control is also being explored for constraint handling.

Agonistic-Antagonist System with 2 Hill Muscles and Activation Inputs





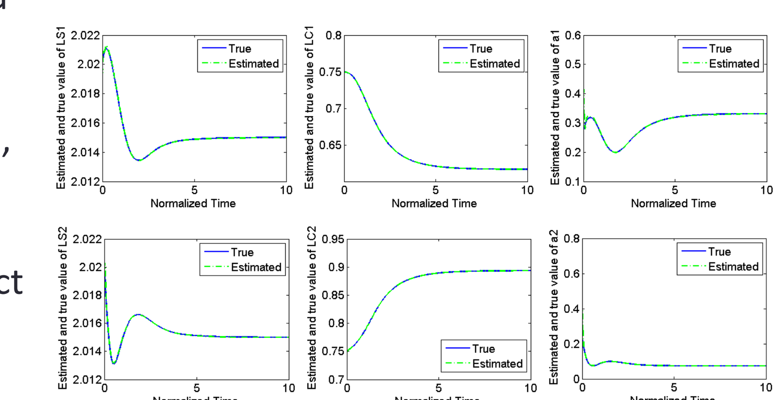
Setpoint regulation with backstepping control (one muscle response shown).

ESTIMATION

We develop two state estimation approaches based on the two-muscle agonistic-antagonistic model:

- **Extended Kalman filter** – based on linearization, approximately optimal (within linearization errors) assuming that noise statistics are known
- **Sliding mode observer** – uses high gains to reject unknown noise

Results with Extended Kalman Filter

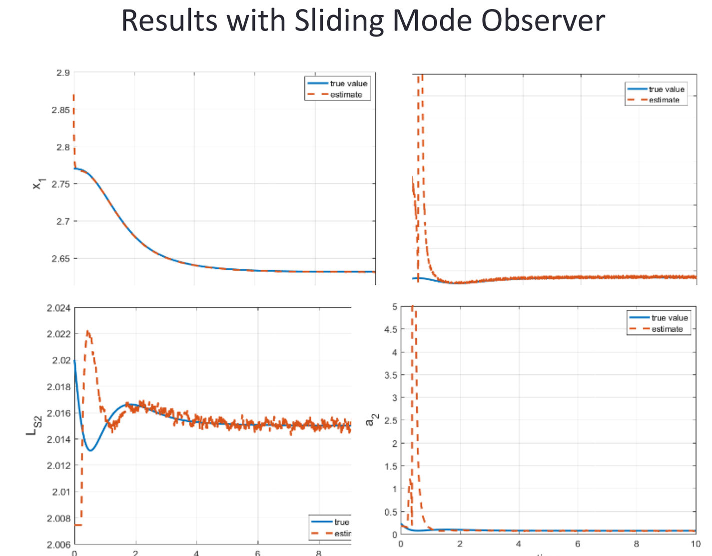


The filters do an almost perfect job of estimating the tendon lengths and CE, assuming that the total muscle length is available for measurement. Note that the filter does an almost perfect job of also estimating the muscle activation levels a_i (shown in the right plots) even though those quantities are not directly measured.

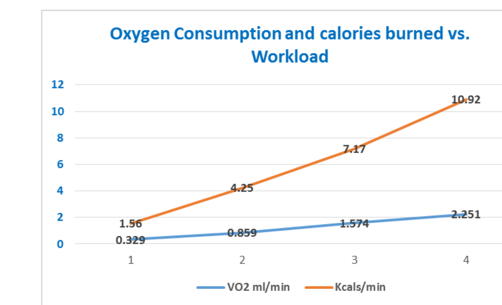
In addition, the sliding mode observer offers improved performance when the initial conditions of plant and estimator are significantly mismatched.

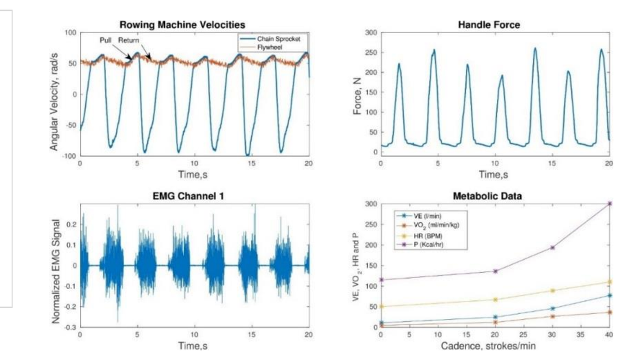
Fundamental questions to be answered are concerning observability, robustness and scalability.

Results with Sliding Mode Observer



HUMAN AND MACHINE DATA COLLECTION



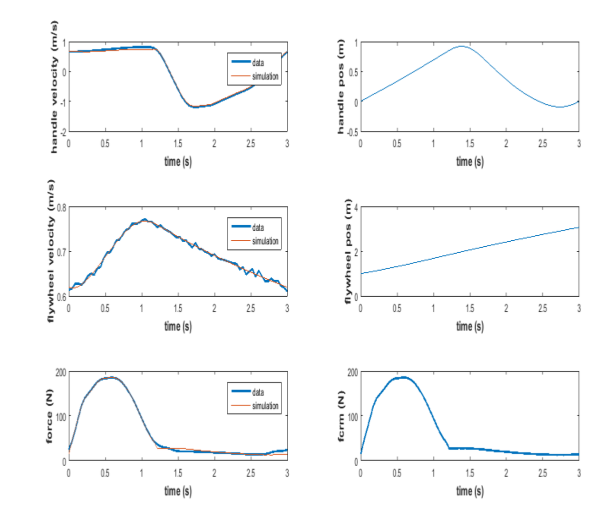


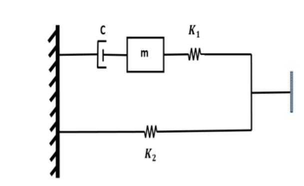
Our team has selected the rowing exercise as a testbed to drive and validate our results.
A comprehensive series of tests was conducted in Summer 2016, where machine velocities and forces, as well as extensive physiological data (16-point EMG, oxygen, heart rate and motion marker data at 28 locations) were recorded in nine different experimental conditions.

The results, available in a GitHub repository, are the most comprehensive data set on rowing that has been made available.

The data was used for system identification of a conventional rowing machine, a necessary step in the development of our variable-impedance, motorized prototype.

A dynamic model was formulated, and the system parameters were found by fitting the simulation to the experimental data. This was done by direct collocation with periodic boundary conditions for the trajectories.





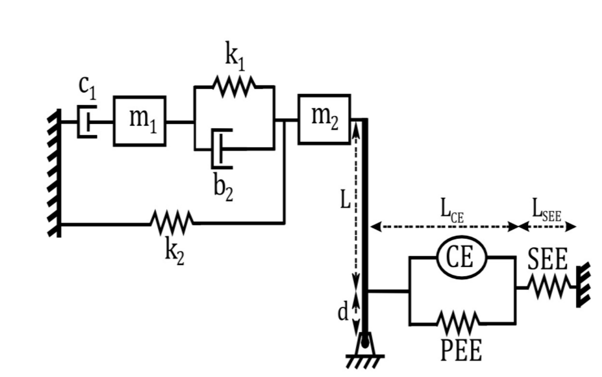
The parameters of a lumped-parameter model of the Concept 2 machine were accurately identified and validated against experimental data. An impedance-controlled motorized machine will be able to replicate this behavior for control system concept-proofing.

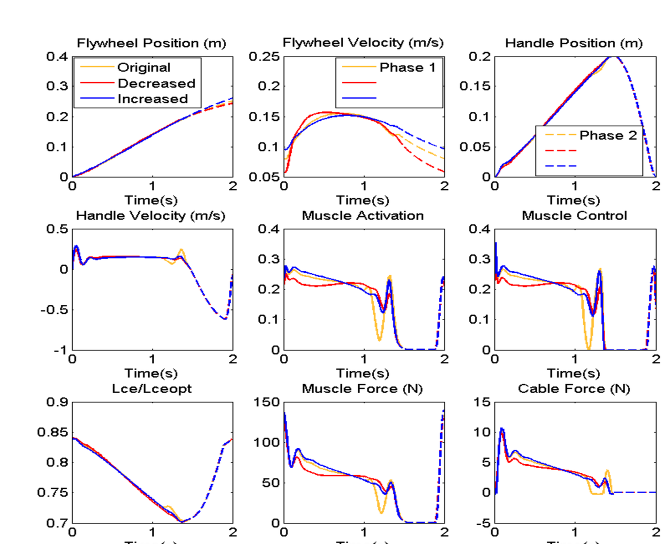
PREDICTIVE SIMULATION OF EXERCISE

Realistic simulations are needed to design novel exercise devices. Such simulations must include the forces generated by the human. These forces, however, will depend on how the user performs the exercise.

One possible approach is to perform a predictive simulation, in which we assume that the user performs the specified exercise with minimal effort. This is a trajectory optimization problem, requiring a dynamic model of the human-machine system and an assumed cost function that governs human behavior

The task simulated below is "forearm rowing", performed by only one muscle, (biceps) represented by a 3-element Hill model, shown to the right of the arm, which acts as a lever to transmit muscle force to the rowing machine, shown on the left.





These results show the predicted trajectories obtained by varying the flywheel inertia. The optimal muscle control Strategy is to maintain mostly constant activation during the pull phase, with a sudden jerk at the end to initiate the return motion via the elastic shock cord. In a real human, this would probably not occur because there is an antagonistic muscle, the triceps, which can do this more efficiently.

Models of larger portions of the musculoskeletal system with agonistic-antagonistic actuation can be obtained by similar methods.