Cyber-Enabled Repetitive Motions in Rehabilitation

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Abstract

The project seeks to invent cyber-enabled exercise machines (CEEMs), which are characterized by: i. intrinsic safety, ii. an extended use of sensing and estimation of biomechanical data, iii. real-time adaptation and guidance to the user to achieve optimal exercise. Optimality criteria will be developed on the basis of collective activation of target muscle groups. The CEEM hierarchical control system will contain machine and biomechanical sensing, estimation, online optimization and impedance modulation subsystems. The optimizer will use model information and sensed data to generate: 1. updates to the machine port impedance, 2. reference trajectories for the machine and 3. cues to the user to modify her mechanical output. Optimality is obtained whenever the user is able to follow the system-generated cues. Otherwise, a safe suboptimal state should ensue. Training adaptations are expected to be superior with CEEMs in comparison with fixed-impedance machines. This will be confirmed with human subject tests and two prototypes to be developed as part of the project.

Intellectual Merit

Recent innovations in exercise machines are characterized by an increased use of sensing and computation. The project will provide a solid foundation to invent machines which simultaneously guide the user and adapt themselves towards optimal exercise. Optimality is sought relative to muscular activation of target muscle groups. This approach is entirely new and contrasts with the use of power as an optimization objective, which has been used in two decades of exercise machine optimization and control research. The development of CEEMs will spur new cyber-physical foundational research encompassing biomechanical modeling and sensing, estimation theory, human performance, control theory and optimization. In addition, human subject tests will be conducted at the CSU Human Performance Laboratory using two CEEM prototypes: a two degrees-of-freedom planar machine and a rowing machine.

Broader Impacts

The project will advance cyber-physical systems at both foundational and applied levels. The invention of CEEM systems will bring benefits to the research community, will support and enhance the university's engaged learning mission and will have an impact on casual and athletic physical conditioning methods and results. CEEMs can be used by athletes to maximize training for optimal performance. CEEM-based training can also help eliminate training injuries by programming custom loads. CEEM systems could also be utilized by beginners and older populations wanting to improve strength, and for rehabilitation of patients with musculoskeletal problems. Due to its high degree of reconfigurability, CEEM technology could also be used in space stations and capsules to supplant the characteristics of Earth-based exercise.

Goals and Objectives

The project has the following broad goals:

1. Development of foundational cyber-physical science and technology in the field of human-machine systems
2. Development of new approaches to modeling, design, control and optimization of advanced exercise machines
3. Application of the above results to develop two custom-built machines: a rowing machine and a 2-degree-of-freedom planar machine
4. Dissemination and outreach

The following research tasks have been planned to accomplish the above goals:

A. Design concepts for CEEMs and offline optimization of machine parameters
B. Modeling and simulation of coupled biomechanics-machine systems
C. Extended and Unscented $\mathcal{H}_\infty$ estimation and stability
D. Real-time musculoskeletal state estimation
E. Exercise machine control and adaptation via impedance and passivity methods
F. Online micro evolutionary optimization
G. Validation, human subject testing, dissemination and outreach with two custom-built CEEM prototypes.

Background

Exercise machines have evolved from purely mechanical devices to systems which incorporate sensing and, to a lesser extent, control. The typical state-of-the-art gym machine can read heart rate as a basic indicator of activity, in addition to mechanical variables shared by the user and the machine, such as velocity or amount of resistance.

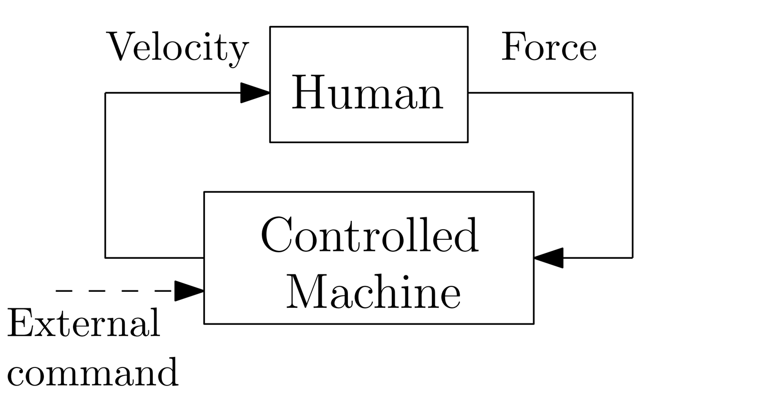

Figure 1: General human-machine system

These indications are provided to the user to modify his own activity to comply with a desired exercise session plan. The user must then adjust machine settings manually. Some machines adjust incline or resistance automatically, in a feedback loop designed to maintain heart rate in a target zone.

The proposed project has the goal of designing, optimizing and controlling exercise machines which extensively sense or estimate biomechanical variables, automatically adjust their own resistance and provide enhanced information to the user.

The purpose of enabling such functions in an exercise machine is, in a general sense, to optimize machine-based physical conditioning. Specifically, the project seeks to maximize activation of target muscle groups.

CEEM Hierarchical Structure

The interaction between human, machine and computation, and the presence of multi-level loop closures requires that these machines be analyzed with a cyber-physical systems optic. In Fig. 2 a dashed line divides the human from the controlled machine. On the human side, a control loop exists whose behavior may not be modified; however knowledge about some of its properties is available and useful to design the machine and its control systems.

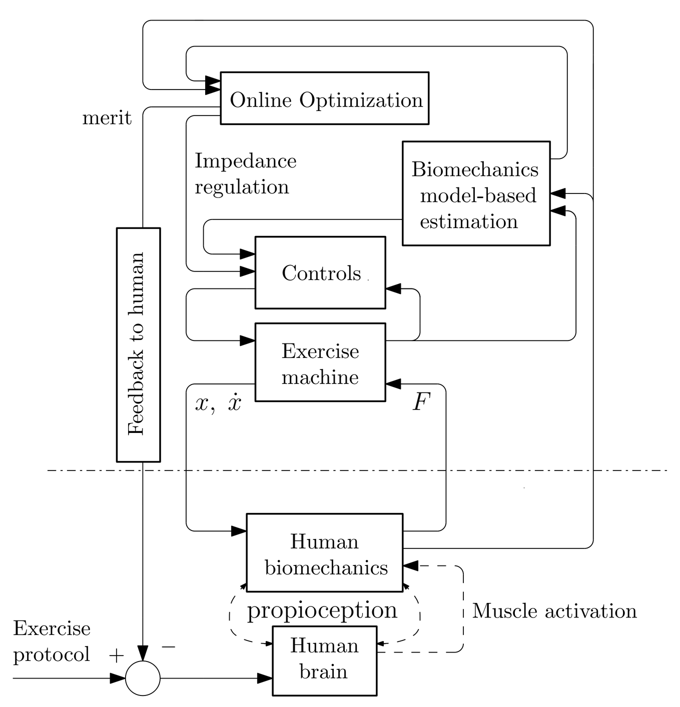

Figure 2: Proposed Cyber-Enabled Exercise Machine architecture

- Humans are intrinsically capable of accurately following a command (i.e., the system-generated cues) that does not exceed constraints associated with fatigue, overload or perceived danger.
- CEEMs will be designed to guide the user to perform optimal exercise, in particular by maximizing their muscular activations.

This will be accomplished by managing information and power exchanges in real time and bi-directionally. One direction of information flow is given by the biomechanical feedbacks required by the CEEM to operate and self-optimize. As shown in Fig. 2, this includes mechanical sensing at the interaction port and estimation of inaccessible variables such as actual muscle activations.

The opposite direction of information flow is presented to the user as cues to modify their mechanical output. Simultaneously, optimally-determined impedance settings and reference trajectories are enacted by the CEEM's control system. During exercise, the *actual* trajectories of the machine and the human must be algebraically linked, and are ultimately determined by human volition.

- Optimality is obtained when the human is able to follow the system-generated cues. The system should adopt a safe suboptimal condition whenever the user does not comply with the protocol. Passivity-based methods and impedance control will be used as a theoretical underpinning for our control algorithms.

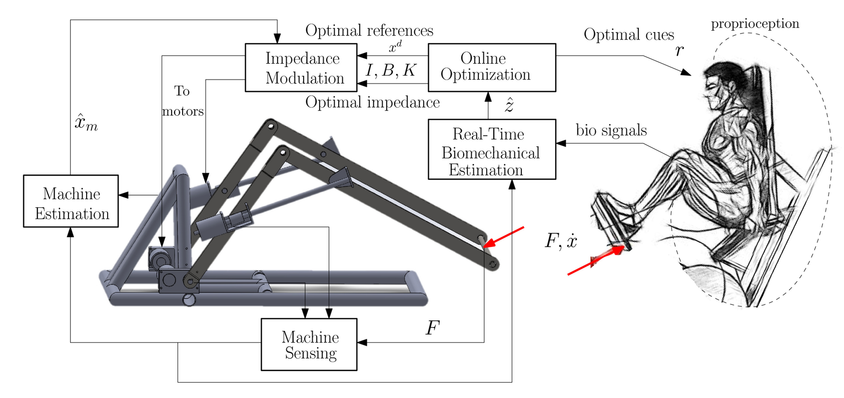

Figure 3: 2 DOF Resistance CEEM and its hierarchical control system

PI Team and Experimental Facilities

The project involves experimental work, including data collection, model validation, rapid control prototyping and human subject tests. A comprehensive data collection effort concerning the rowing exercise is being conducted at the beginning of the project.

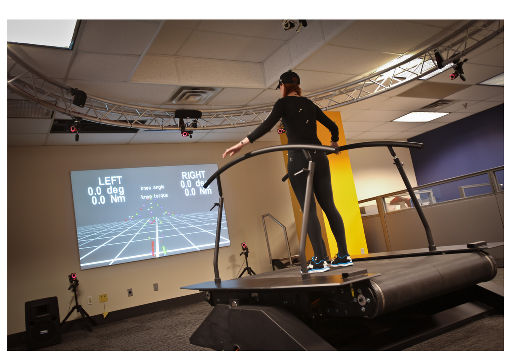

Figure 4: Osprey 10-Camera Motion Capture System with Cortex Software at the Human Motion and Control Lab

- A commercial rowing ergometer will be instrumented to measure machine-specific variables such as force and velocity at the human interface, and human-specific variables.
- The rower will be installed in CSU's Human Motion and Control Lab, directed by Prof. van den Bogert. The lab is equipped with a 10-camera motion capture system (Motion Analysis Corp.), a V-Gait instrumented treadmill with software controlled pitch and sway actuators (Motek Medical), (Fig. 4) a 16-channel wireless EMG/accelerometer system (Delsys), and D-Flow software (Motek Medical) for real-time control of experiments and data processing.

Software tools for musculoskeletal modeling and simulation include OpenSim, Autolev, Matlab, IPOPT, SNOPT, GPOPS, and in-house code (Matlab and C++) for predictive simulation via direct transcription of musculoskeletal dynamics and optimization criteria.

Prof. Sparks directs the Human Performance Lab. The lab is equipped with telemetry and ambulatory-based equipment, including a portable metabolic system (Cosmed K4b2) for quantification of oxygen use during exercise. Electromyography data will also be collected, as well as other physiological variables indicating exercise conditions, such as heart rate and perceived exertion. The team has acquired a dSPACE MicroLabBox system to handle synchronous data collection with a large channel count, as well as future real-time control tasks. Hardware development work and prototyping will be conducted at the Control, Robotics and Mechatronics Lab and the Embedded Systems Lab, directed by profs. Richter and Simon, respectively.

Figure 5: Sparks' Human Performance Lab and Concept2 rowing machine

Activities: Oct-Nov 2015

The team has focused on: i.recruiting, ii.final IRB procedures, iii. purchase of dSPACE MicroLabBox, iv. preliminary theoretical work on admittance replication with controlled electromechanical systems, v. optimal identification of rowing machine admittance.