Developing advanced exercise machines

Smart Training

Researchers from Cleveland State University are developing new kinds of exercise machines for athletic conditioning, rehabilitation and exercise in space. dSPACE MicroLabBox is used to collect measurement data and operate the machine prototypes, which are capable of adapting to their users.

The use of exercise machines can be traced at least to Industrial Revolution times. Since then, these machines have evolved in their sophistication to include electronic displays providing key indicators such as levels of resistance, speed, and heart rate (figure 1). They are designed to emphasize strength (e.g., weight-lifting machines) or aerobic exercise (e.g., gym rowers and treadmills). While the amount of weight can be selected in a lifting machine, and resistance can be adjusted in a gym rower, the kind of opposition to motion (the mechanical impedance) is always the same.

The Aim: Individualized Mechanical Impedances

The motivation for this research project is that fixed impedances are not the best option for an efficient training. Rehabilitation machines should not merely resist motion, but also assist it. Moreover, therapists and doctors should be able to program machines to customize the balance between assistance and resistance within a single motion cycle, within a single session, or as part of a longer-term rehabilitation program. For astronauts in space, weight lifting must be emulated by powered means and any equipment flown into space is subject to severe mass and volume constraints. All these requirements indicate that the same hardware should be used for resistance and aerobic exercise. The research team has collaborated with the NASA Glenn Research Center and its Exercise Countermeasures Program to design

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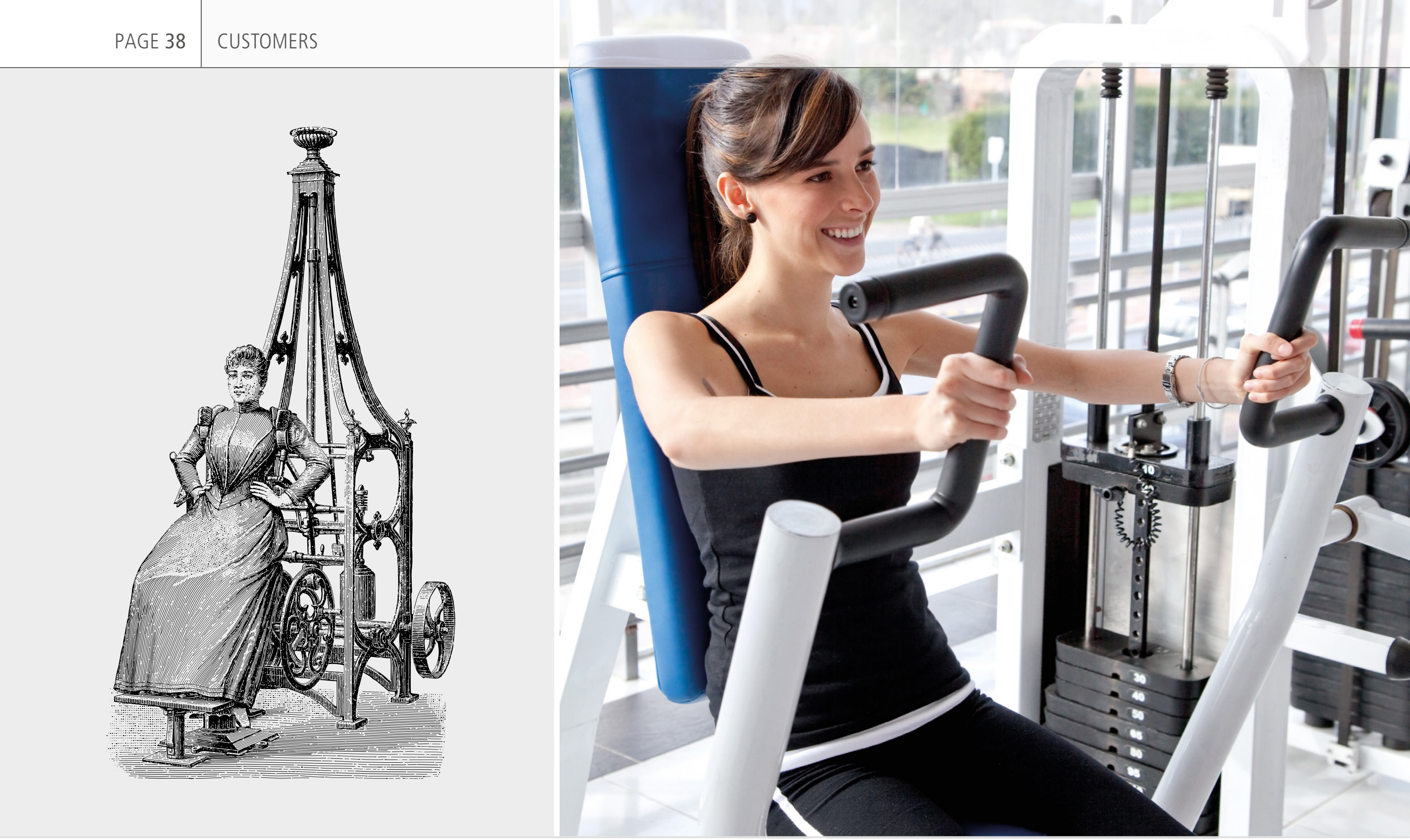

Figure 1: Exercise machines have evolved in their appeal and user interactivity, but their mechanical function remains essentially the same in many cases.

machines meeting these stringent specifications. The team also leveraged their expertise in energy regeneration control to demonstrate a scaled version of a rowing machine, which offered programmable impedances and was entirely powered by the subject performing the exercise. The self-sufficient power feature offers an additional advantage over other solutions, as the machine does not draw power from the space vehicle's grid, and may even be able to return some energy.

Characteristics of Advanced Exercise Machines

The above-mentioned application scenarios require characteristics for advanced exercise machines, where motors and control systems are used to generate continuously adjustable mechanical impedances:

- Use of a combination of direct sensing and model-based estimation to generate detailed real-time information about current human performance
- Use of current performance indications to modify its own mechanical characteristics to maximize a preselected, programmable objective
- Generation of optimal real-time cues for excercisers to modify their mechanical outputs
- Monitoring, managing and resolving conflicts between man and machine objectives with an overriding safety criterion (figure 2)

The Challenges

The new machines will vary their impedance over single motion cycles and over extended periods of time. The effects of such variations on the body – specifically on targeted measures of muscular strength – must be well understood. This understanding will come through modeling, which is the ultimate basis for determining the impedance variations that are beneficial. In an implementation, optimal impedance adjustments will be made based on information about the current status of the exerciser and the machine. A control system must make these changes effective on the machine by appropriately commanding its motors.

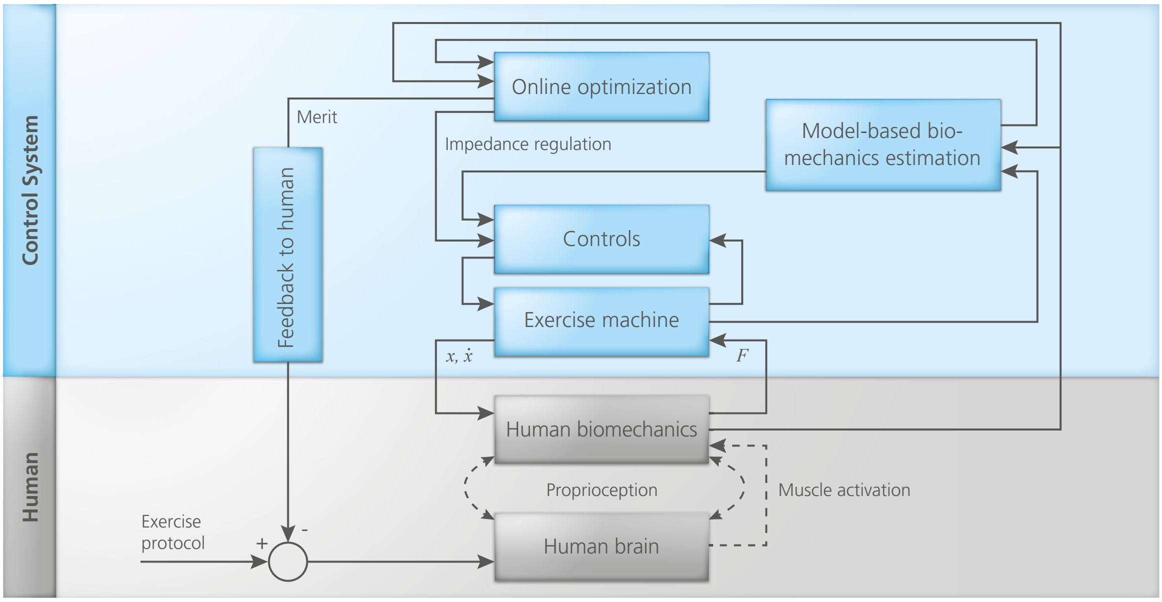

Figure 2: Functional block diagram for the advanced exercise machine concept. The system generates cues to modify human behavior during exercise. These changes, together with machine impedance variations, are generated by the system to achieve optimum performance.

Optimal Exercise

Exercise can be optimized for specific goals. For losing weight, the exercise should distribute the load optimally among as many muscles as possible so the endurance is maximized. In rehabilitation or bodybuilding, the goal might be to strengthen one muscle group. For muscles that cross more than one joint, such as the hamstrings, it is not immediately obvious how such exercise should be designed. Because individuals respond differently to a training stimulus, it is important to create custom exercise programs to fit individual needs. With controlled exercise systems, athletes can optimize their training performance while eliminating injuries by allowing only the loads suited to their specific physiology. Older individuals and rehabilitation patients could exercise safely to address musculoskeletal problems.

Biomechanical Modeling

In an advanced exercise machine, motion and force are continuously monitored by the control system. This data is used to estimate motions and forces in the muscles. This allows assessment of exercise and real-time feedback to the user about the training. In order to perform this assessment, a detailed mathematical model of musculoskeletal dynamics is required, combined with state estimation techniques that are robust enough to produce reliable results even when the data is noisy and incomplete and the model is not perfect. Models will be validated using motion capture and electromyography (EMG) recordings.

State Estimation

To control a system to achieve desired goals, the controller needs to first estimate some of the unobserved quantities of the system. These can include system parameters, unmeasured inputs, and the internal system status or state. With an exercise machine, these quantities could include the force applied by the user, friction parameters, muscle activation signals, and many others. For estimating unknown system quantities, the team is planning to rely on Kalman filtering in their

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> "With dSPACE MicroLabBox, it was easy to collect initial data and operate machine prototypes in real time. This made it possible to focus on the control algorithms themselves rather than the details of their implementation."

Hanz Richter, Cleveland State University

Figure 3: During a trial, dSPACE MicroLabBox (left picture) collects 16-channel electromyography (EMG) data and machine mechanical data at a sampling rate of 1 kHz. A separate system collects motion data using visual markers (shiny spots) and metabolic data. Data from all systems is synchronized by offline postprocessing.

exercise machine development, along with more advanced estimators such as unscented Kalman filtering and H-infinity filtering.

Optimization

To provide the greatest benefit to the user, several components of the exercise machine need to be optimized, including the machine design itself, the estimator, the control algorithm, and even the control objectives. Beside the fact that many system components will be unknown or unmeasurable, some of the system components may even change over time because of aging or because of changes in the external environment. The human model will certainly change over time, as different subjects use the machine. For optimization, the team will rely on fast evolutionary algorithms, which include a set of solutions to an optimization problem. As the potential solutions are tested and evaluated in real time, they exchange information with each other in carefully planned ways to maximize performance.

Real-Time Control via MicroLabBox

Model-based control algorithms must be specified that can effect optimal impedance variations, while guaranteeing safety for the exerciser. The team is relying on theories including passivity and extremum seeking control as part of their development framework. Real-time implementation requires a high-performance data acquisition and control system capable of handling multi-channel analog data at fast rates, while offering a high-level user interface. The team selected dSPACE MicroLabBox to collect initial data and ultimately operate machine prototypes in real time (figure 3). The experiment software ControlDesk allows preparing data collection and real-time control experiments quickly and efficiently, since existing MATLAB®/Simulink® simulation models can be converted easily into real-time interfaces. This allows researchers to focus on the control algorithms themselves rather than the details of their implementation.

First Trials on a Rowing Machine

The first phase of the project has focused on the rowing exercise. The objective was to gain extended insight about this exercise by using a conventional machine. This involves collecting machine-specific and human-specific data on the rowing exercise beyond what is currently available in the research literature. Machine-specific variables include the force on the pull chain and the velocities of the rotating components inside the machine, namely the chain sprocket and the flywheel (figure 4). Human-specific data is more extensive and can be divided into three groups: motion, muscle activation, and metabolic data. Data collection trials were performed in Prof. van den Bogert's Human Mo-

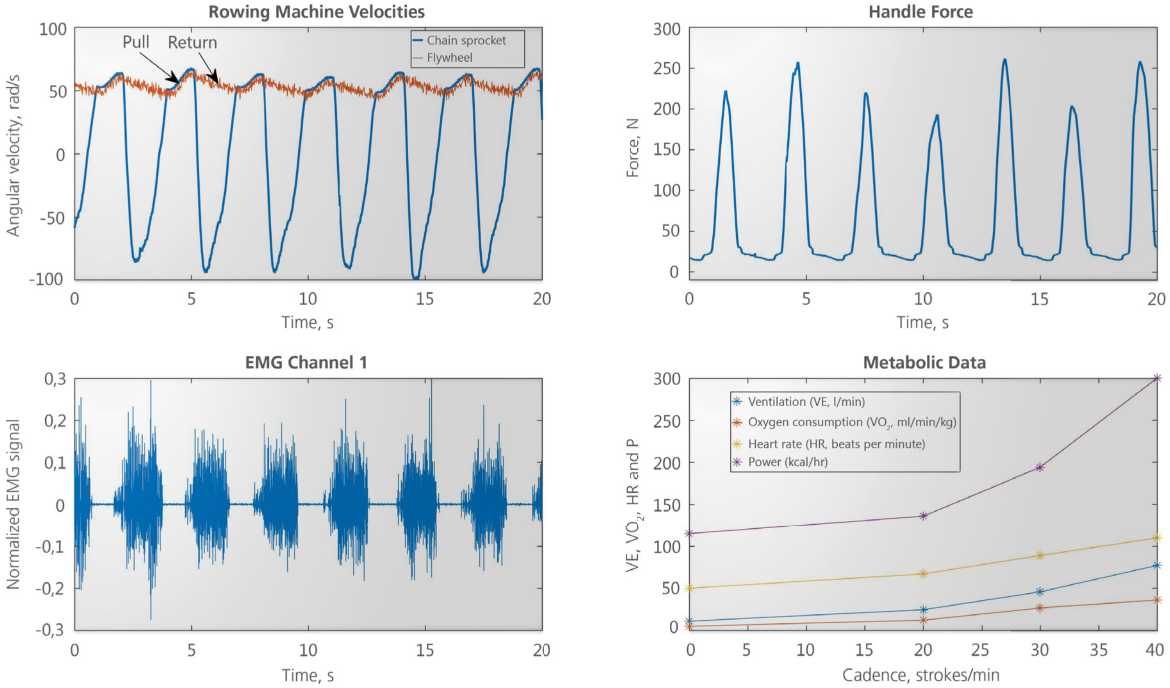

Figure 4: Sample data set (marker data not shown). The chain sprocket and flywheel have the same velocities during the pull and become decoupled in the return. Metabolic data is plotted for trials at various cadences (strokes/min) and rest.

tion and Control Lab. The lab is equipped with a 10-camera motion capture system (Motion Analysis Corp.) with Cortex software. A 16-channel wireless EMG/accelerometer system (Delsys) is used to collect muscle activation data. 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. Data arising from these trials will be used to build and validate biomechanical models and to design the motorized machines. ■

Hanz Richter, Cleveland State University

Figure 5: The research team (from left): Hanz Richter, PhD (Associate Professor, Mechanical Engineering), Antonie van den Bogert, PhD (Professor, Mechanical Engineering), Kenneth Sparks, PhD (Professor, Human Performance) and Dan Simon, PhD (Professor, Electrical Engineering and Computer Science, University's Associate Vice President for Research).