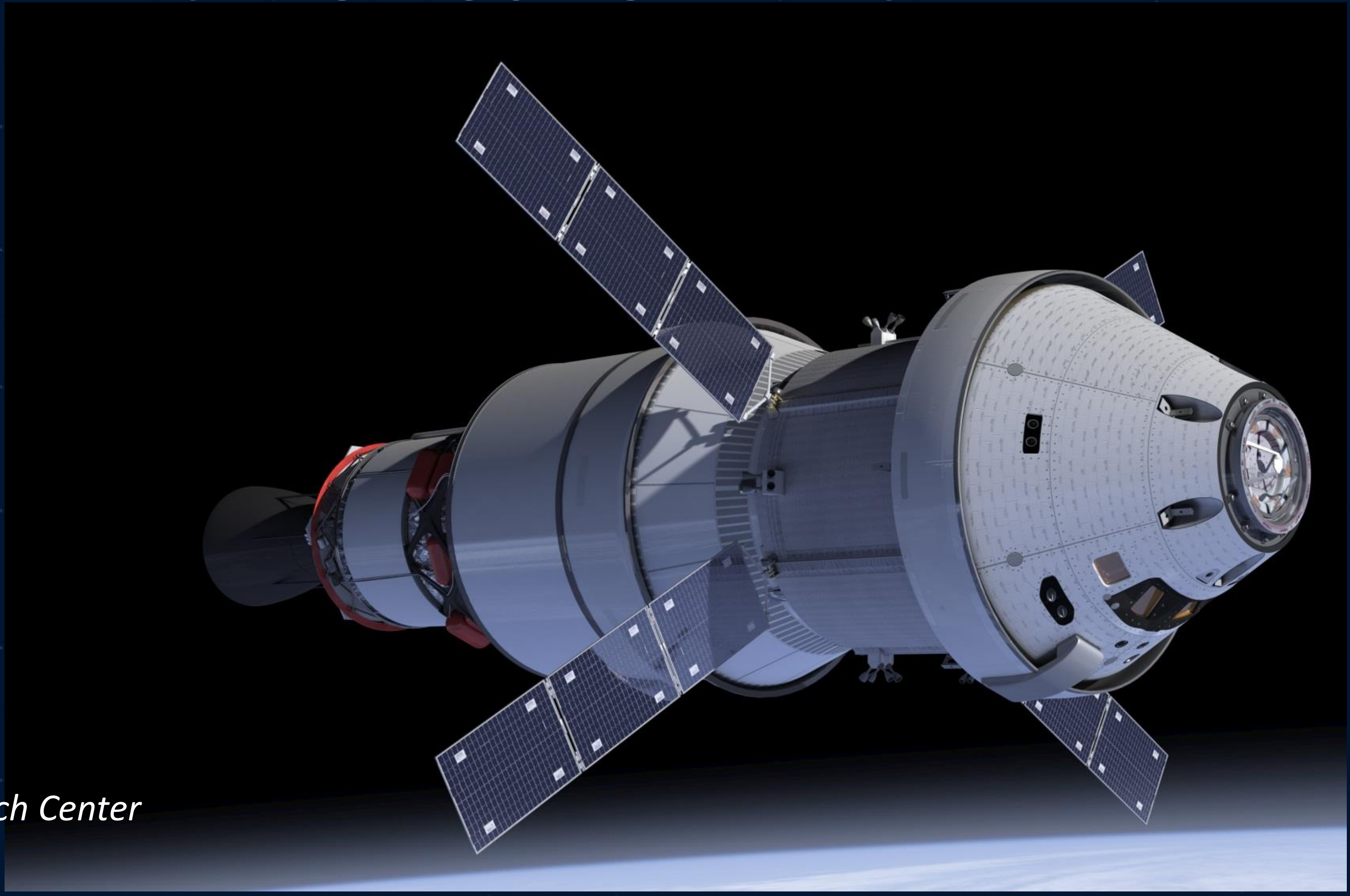
HRP Investigators Workshop – Feb, 2016

CLOSED LOOP CONTROL COMPACT EXERCISE DEVICE FOR USE ON MPCV



Chris Sheehan[1]

Justin Funk[1]

Nathan Funk[1]

Gilead Kutnick[1]

Brad Humphreys[1]

Douwe Bruinsma[2]

Gail Perusek[3]

[1]ZIN Technologies

[2]TDA Research

[3]NASA Glenn Research Center

Motor Driven Exercise Devices

- AEC-REQ-001 'Exercise Device for Orion EM-2 Functional Requirements'
    - 23.37 lbm
    - 13.5"-21.0" width x 13.5" height x 7.5" depth
    - 480W peak power draw from MPCV
    - Aerobic
        - Provide 450W average aerobic load, 30 min interval
        - Provide 750W peak power load, any interval that conforms to vehicle peak power draw
    - Resistive
        - Provide 400 lb peak load capability
    - Peak linear velocities per figure
- Motor technology offers
    - Excellent torque density
    - Excellent load accuracy
    - Custom impedance algorithms
    - Custom load versus position

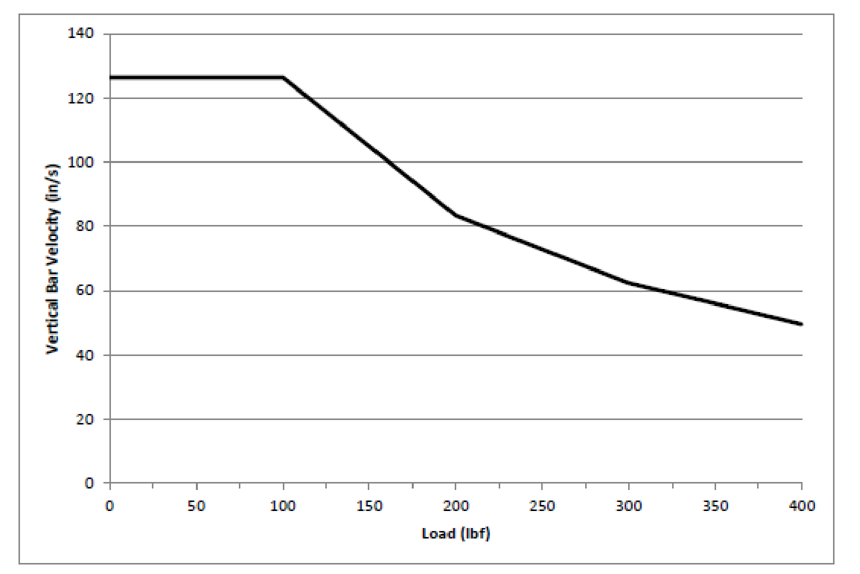


Fig. 1 Linear Velocity (in/s) versus Load Setting

ROCKY

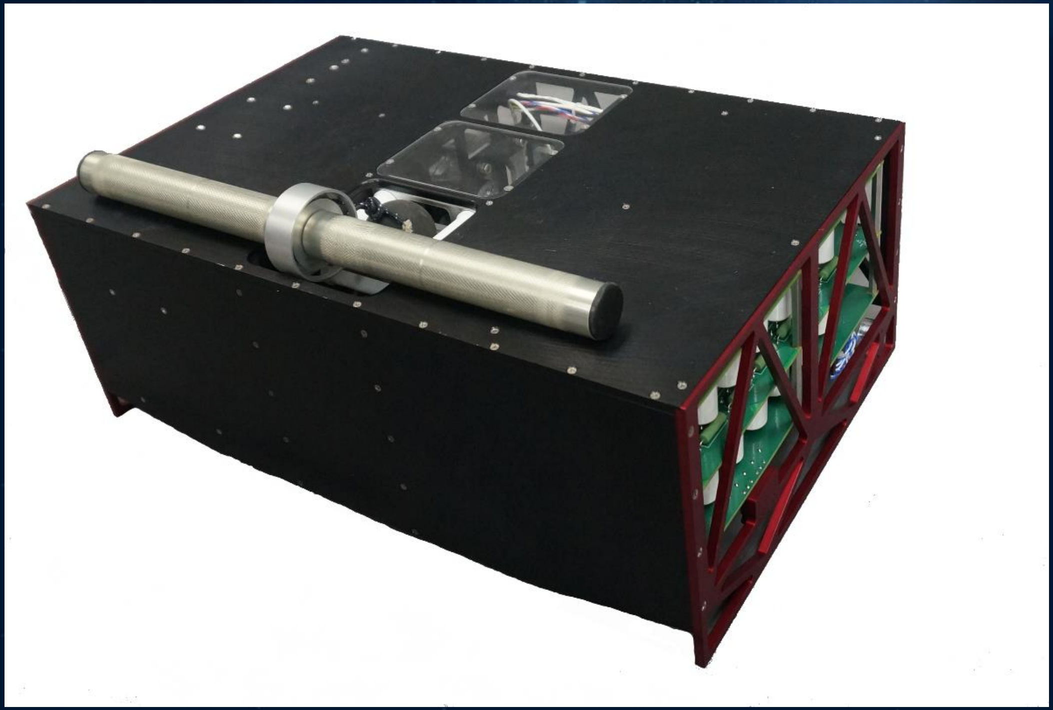
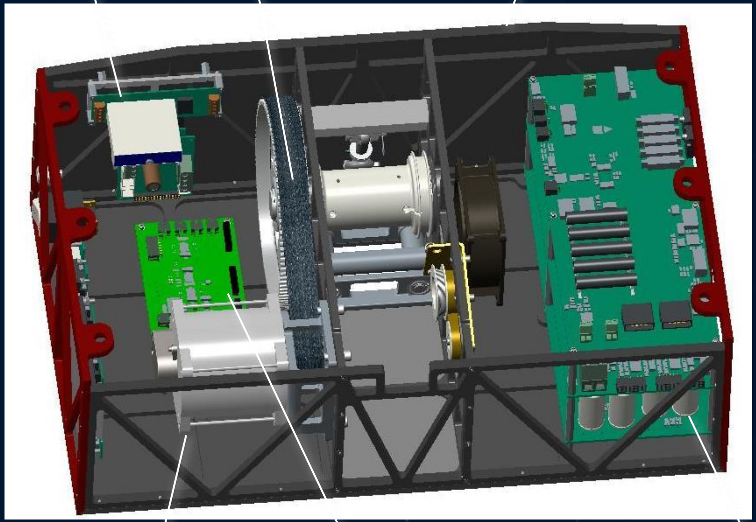


Fig. 2 Resistive Overload Combined with Kinetic Yo-Yo

ROCKY



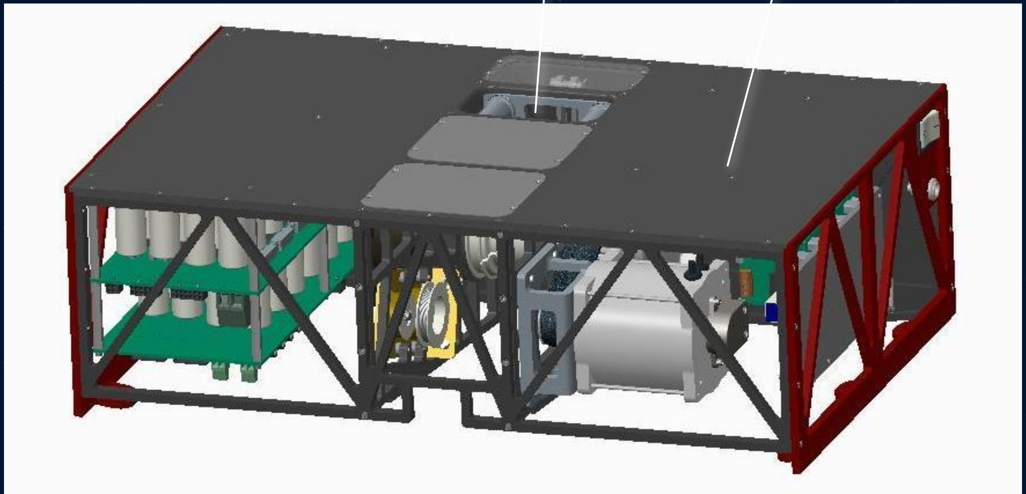


Fig. 3 Resistive Overload Combined with Kinetic Yo-Yo

ROCKY

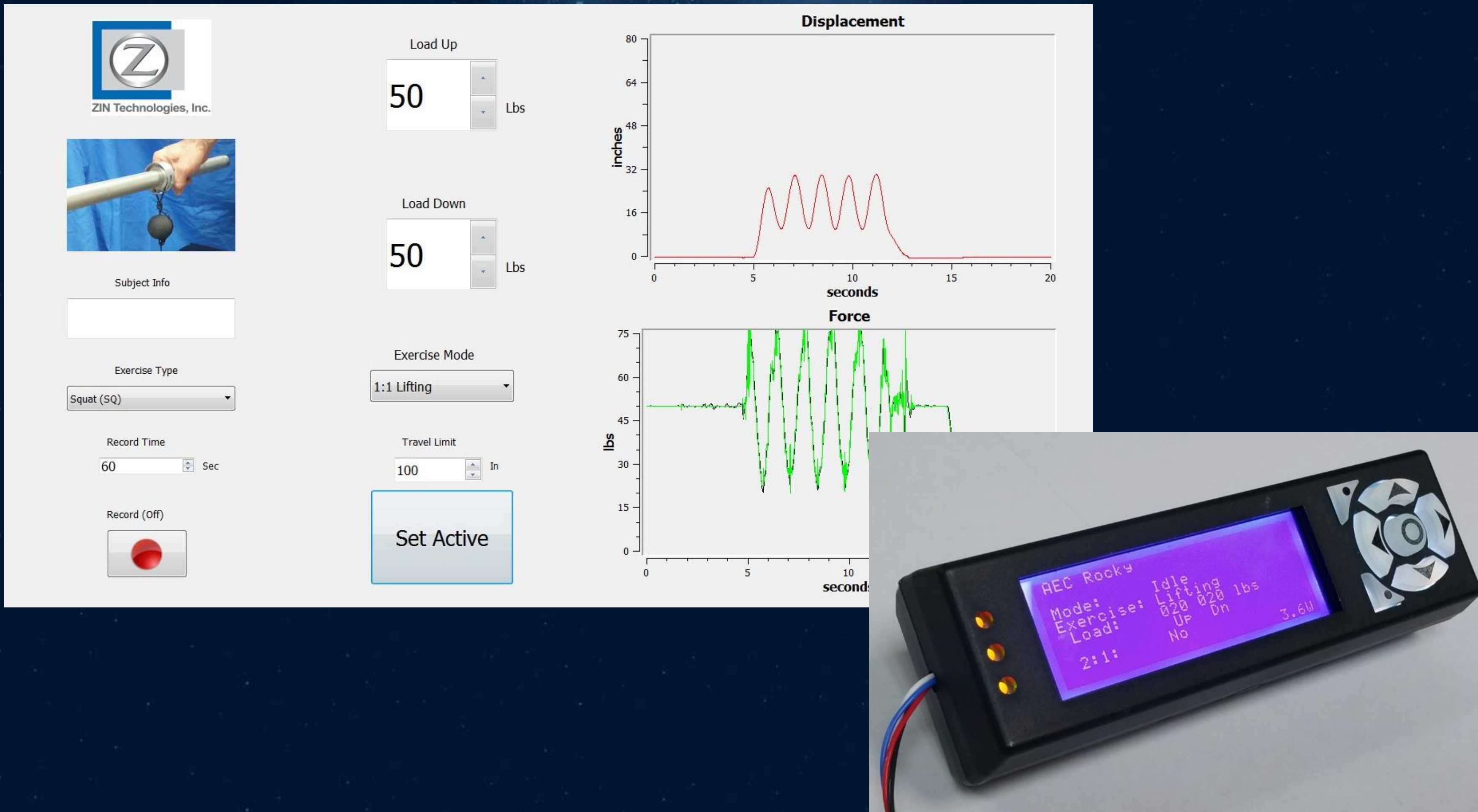


Fig. 4 ROCKY LabVIEW GUI and Standalone Hand Held Display

ROCKY

- **ROCKY is implementing aspects of TDA ‘Device for Aerobic and Resistive Training’ (DART) which was funded by NASA SBIR**
- **Phase III Tasks include collaboration with ZIN:**
  - Deliver bar with captive pulley (2:1) bar to enable high load and lower velocity exercise
  - Create updated rowing algorithm
  - Create updated load application algorithm
  - Overall assessment of weight reduction on system performance
  - Lessons learned

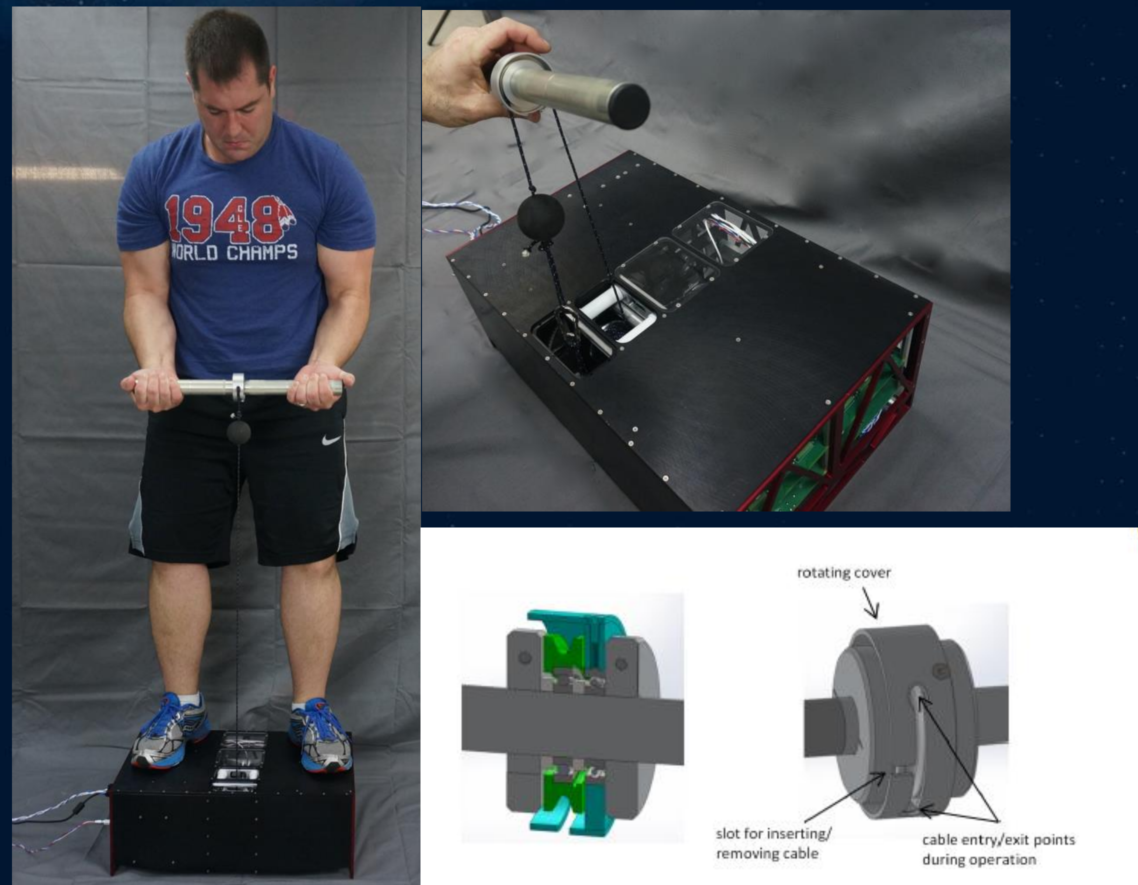


Fig. 5 1:1 and 2:1 Bar Set Ups and Captive Pulley with Rotating Cover

ROCKY

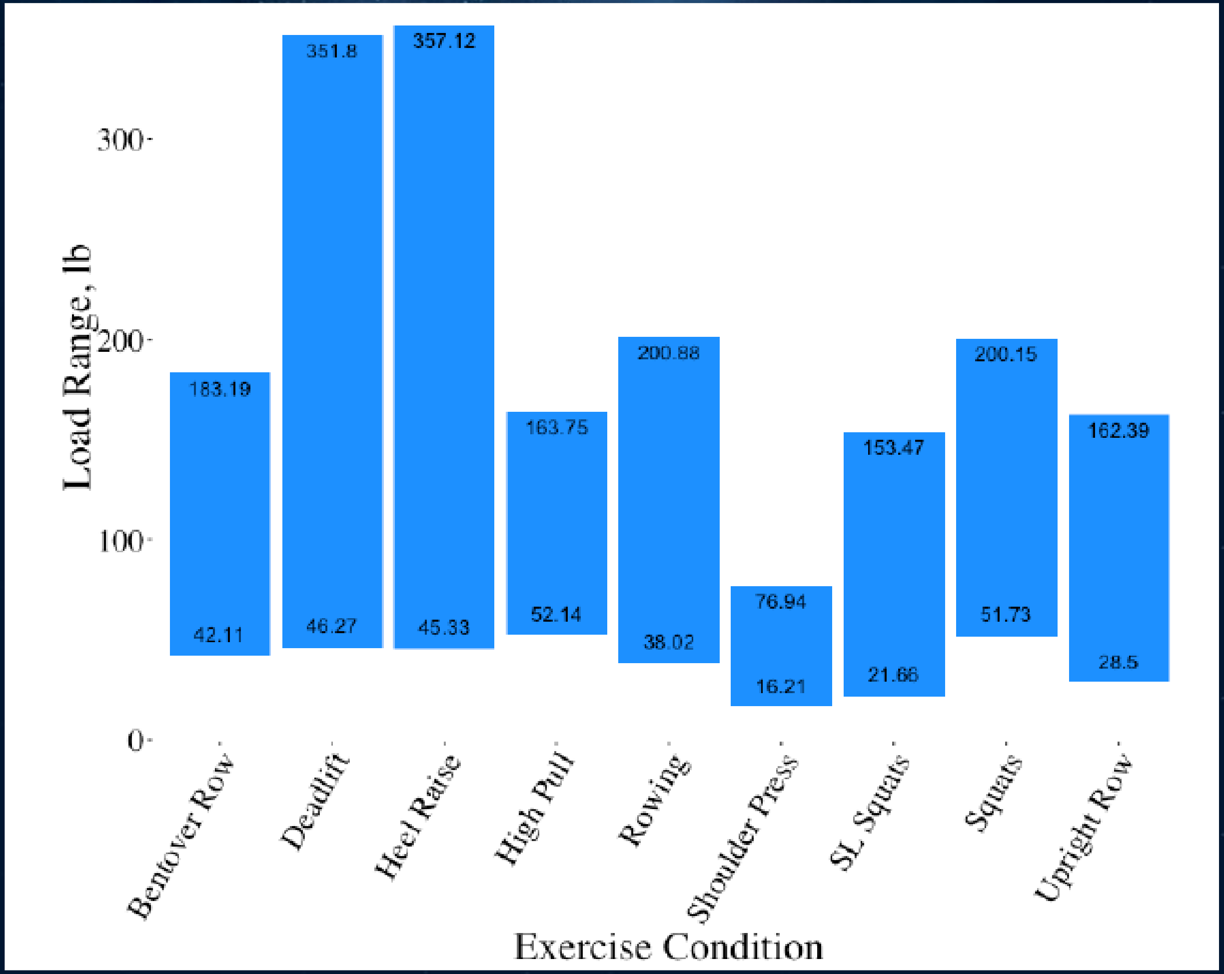


Fig. 6 Load Range versus Exercise Type (data courtesy of JSC Exercise Physiology and Countermeasures Lab – DeWitt and Fincke)

ROCKY

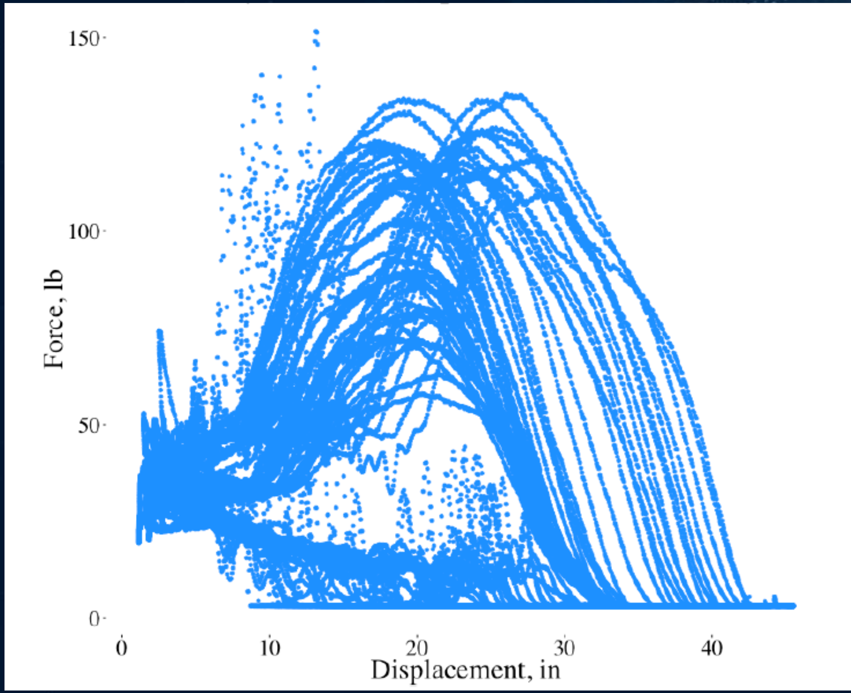


Fig. 7 Force versus Displacement (Rowing)

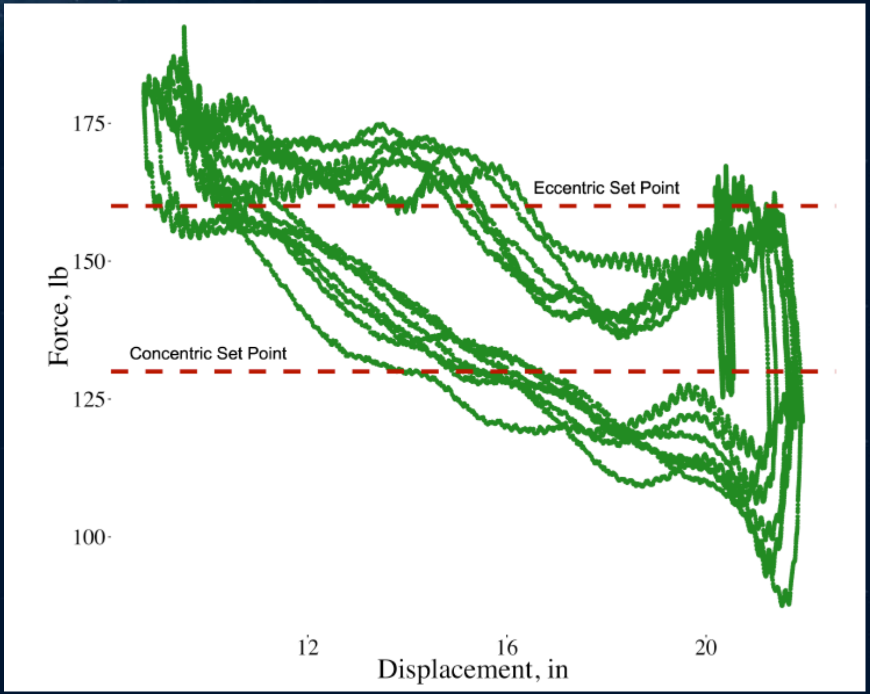


Fig. 8 Force versus Displacement (Squat)

Device was set at setting #5. The following features were noted:

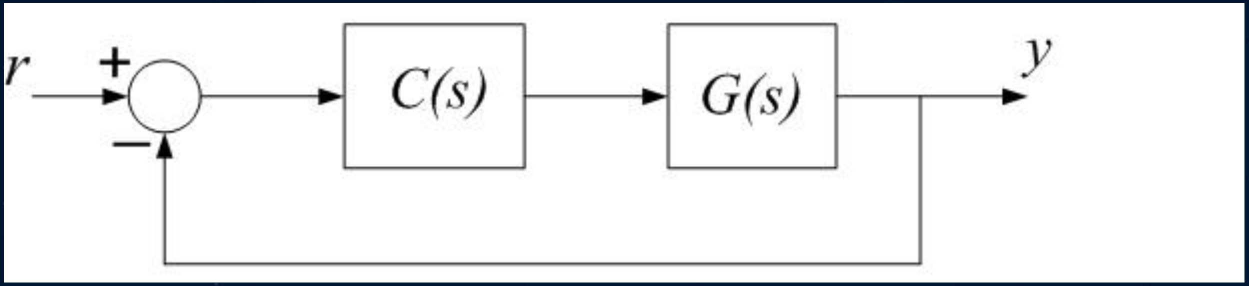
- Load is maximum in middle of the stroke (peaks between 100-150 lb)
- Very little return load
- Loading is consistent between strokes, although there is variation in stroke length for the subjects

Device was set at 130 lb concentric, 160 lb eccentric. The following features were noted:

- Load varied throughout completion of the repetition, with a decrease as displacement increased (possibly due to inertia of the bar
- Sharp change in load at the completion of the upward motion (peak displacement) as eccentric overload initiates

Motor Control Theory

- Open Loop
- Closed Loop
  - Proportional-Integral-Derivative (PID)
  - Linear Quadratic Regulator (LQR)
  - H-Infinity



PID Control

$$u(t) = \underbrace{ke(t)}_{\textit{Proportional}} + \underbrace{k_i \int_0^t e(\tau)d\tau}_{\textit{Integral}} + \underbrace{k_d \frac{de}{dt}}_{\textit{Derivative}}$$

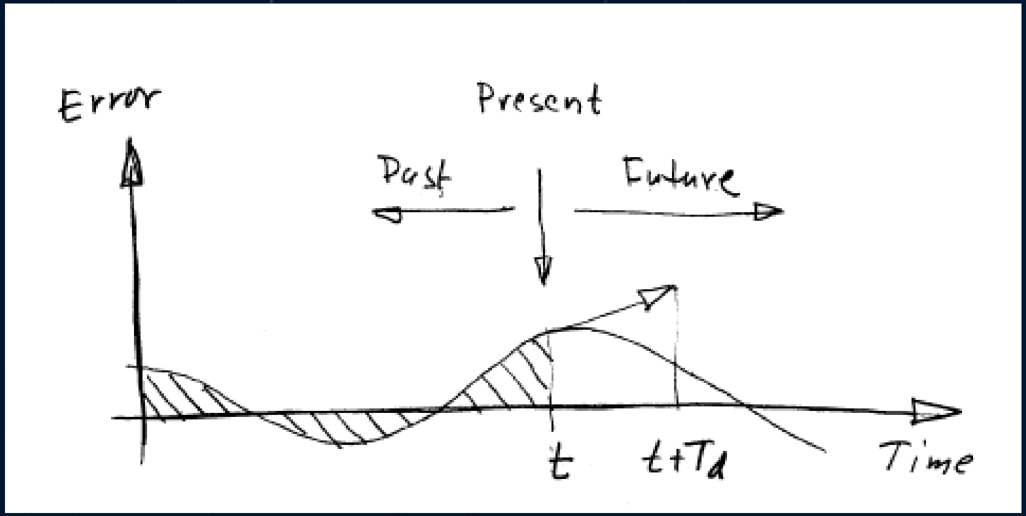


Fig. 9 PID Control

PID Control

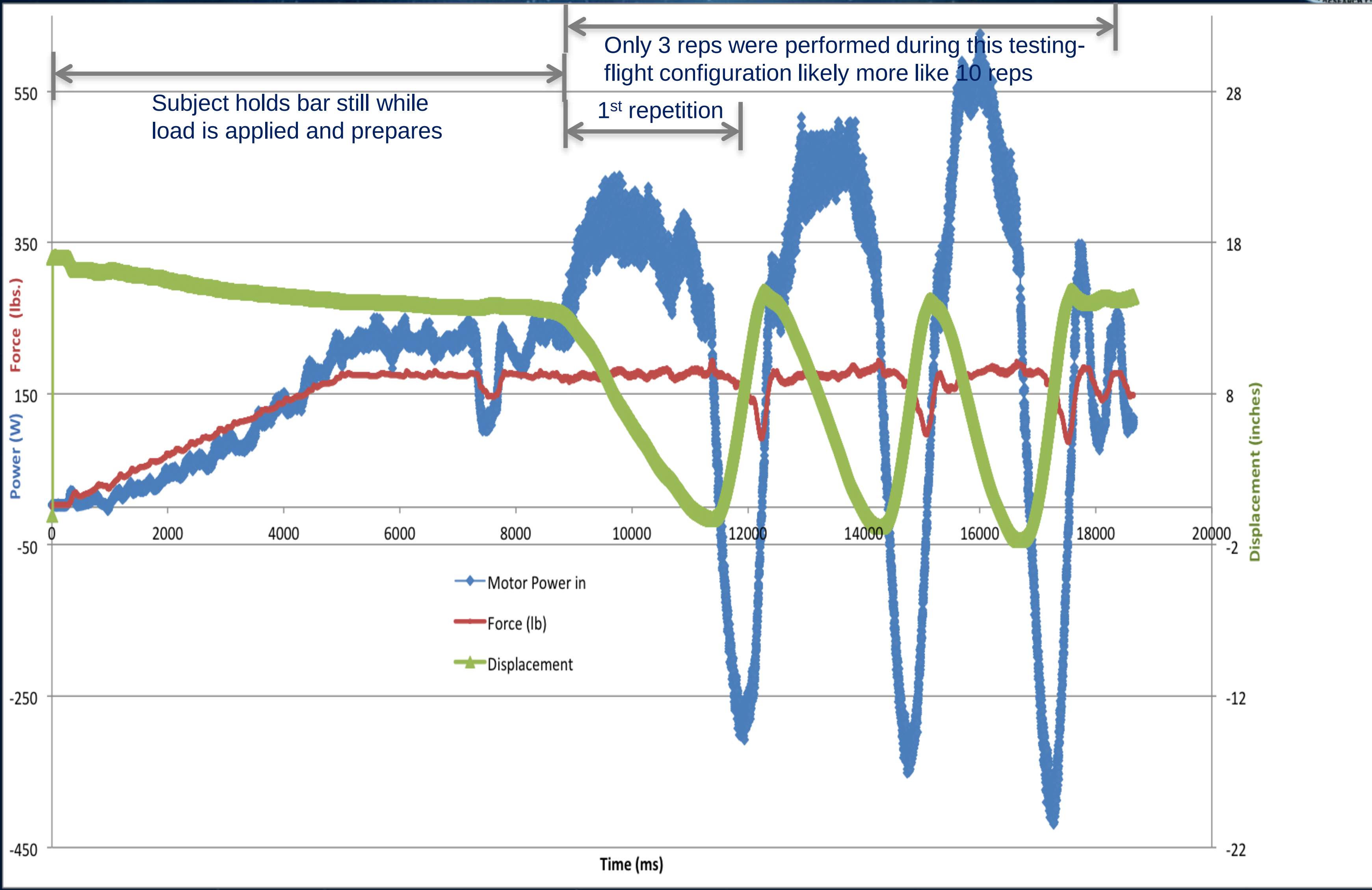


Fig. 10 ROCKY PID Control for Resistive Exercise

PID Control

- ROCKY Control
  - Aerobic control is PID around a velocity set point

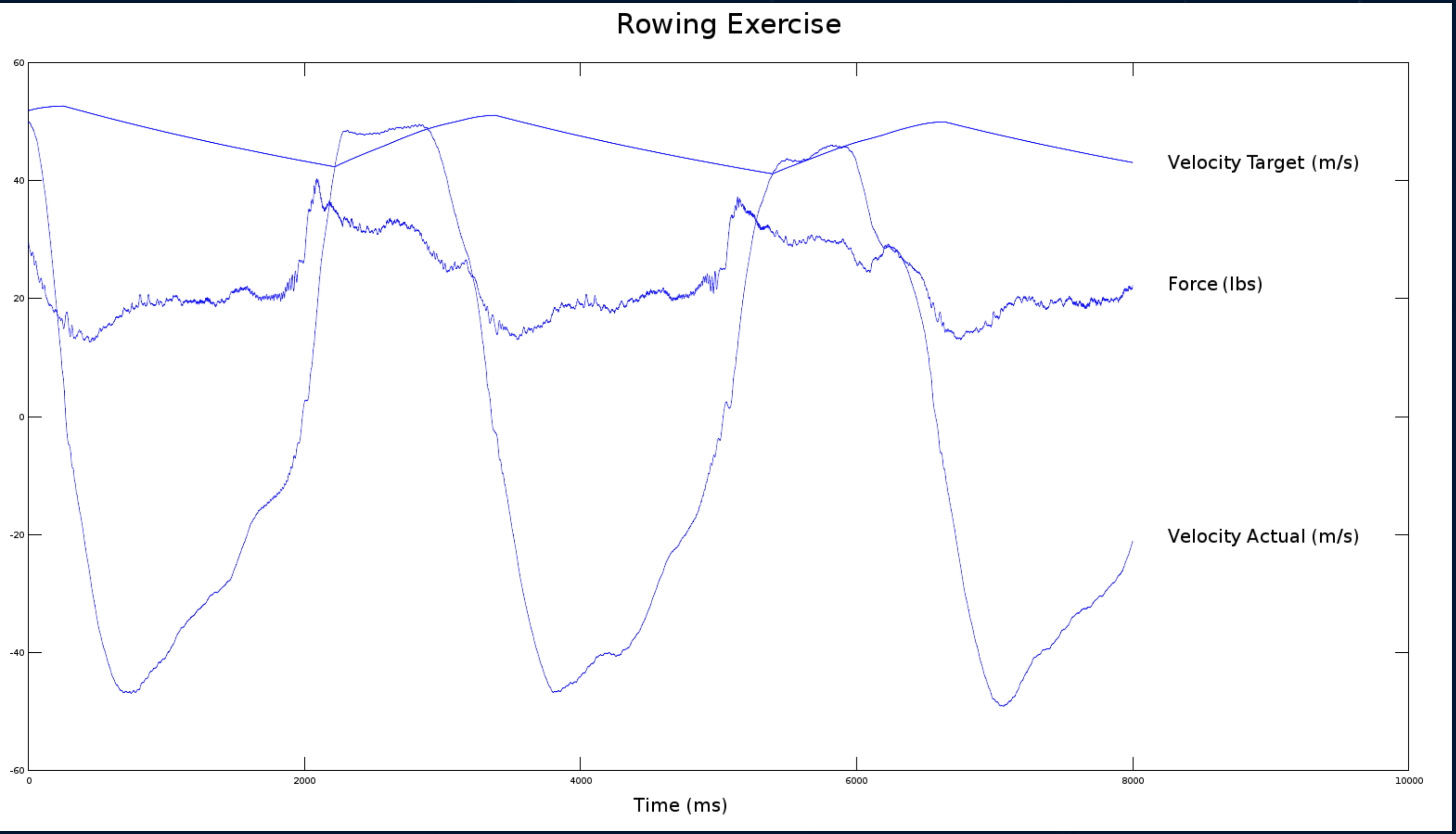


Fig. 11 ROCKY PID Control for Aerobic Exercise

LQR Control

- Classical optimal control theory has evolved over time to formulate LQRs which minimizes the excursion in state trajectories of a system while requiring minimum controller effort
  - The optimal quadratic regulator design is a reduction of the Algebraic Riccati Equation and is used to calculate state feedback gains for a chosen set of weighting matrices
  - These weighting matrices regulate the penalties on the deviation in trajectories of the state variables and control signal
  - Using a model to synthesize all internal states

$$\dot{x} = Ax + Bu$$

Given system

$$u = Fx$$

State feedback control to stabilize the system

$$J = \int_0^\infty [x^T(t)Qx(t) + u^T(t)Ru(t)]dt$$

Defined cost functional performance index

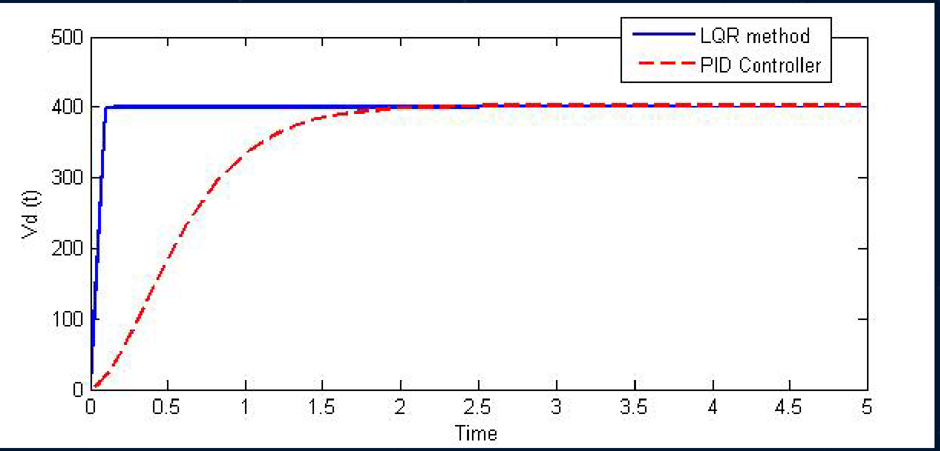


Fig 12 Highly Generalized Comparison of PID v. LQR Control Methods

H Infinity Control

- H_∞ control synthesis:
  - High disturbance rejection
  - High stability
  - High order controllers (complex and resource intensive)
- This controller design is generally based on minimization of a function (H_∞ norm of selected closed loop system)

$$\|F_1(M,K)_\infty = sup\underbrace{\bar{\sigma}}_{\text{Singular value of F(M,K)}}\overbrace{(F_1(M,K)}^{\text{Lower fractional transformation}}(j\omega))$$

Other Methods

- Semi-active Impedance Modulation with Ultracapacitors (H. Richter, A. van den Bogert, D. Simon)
  - Electromechanical system which can be programmed to produce any desired mechanical impedance
  - Dynamic relationship between force and velocity at the user is called impedance
    - Bungees = 'stiffness' impedance
    - Rowing = 'inertial' impedance
  - Energy regeneration and storage
  - Designed a small (100N, 0.5m/s capability) hand operated system which is:
    - Power neutral (excepting for small microprocessor batteries)
    - Highly configurable – the impedance perceived by the user can be arbitrarily defined and is enforced by the control system

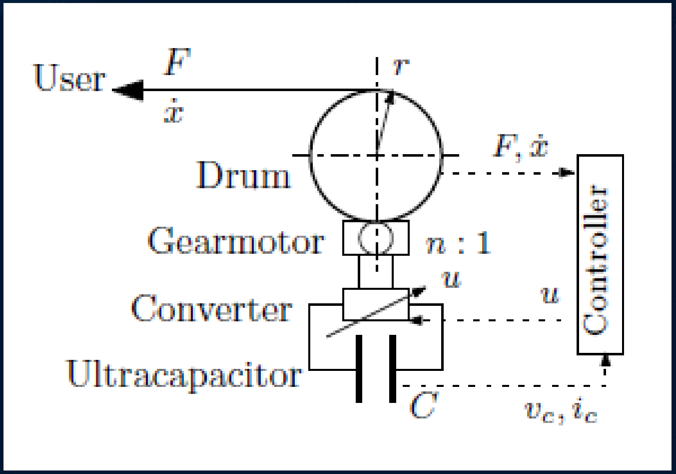


Fig 14. Advanced Rowing Ergometer Concept to Demonstrate Feasibility of Semi-Active Modulation to Match Commercial Ergometer F-V Characteristics

References

- Caltech Control & Dynamical Systems Class Notes (Chapter 8, PID Control), 2004
- ‘Comparison Performance Between PID and LQR Controllers for 4-leg Voltage Source Inverters’, A. Mohammadbagheri, N. Zaeri, M. Yaghoobi, 2011
- ‘H-Infinity Controller Design for a DC Motor Model with Uncertain Parameters’, L. Brezina, T. Brezina, 2011
- ‘Application of Multivariable Techniques to Design Experimentally a Flexible Satellite Attitude Control System’, J. de Castro, L. de Souza, 2010
- ‘Plant and Control Design for Advanced Exercise Machines with Energy Regeneration’, H. Richter, 2015