Predictive simulation of rowing exercise using GPOPS-II

Milad Zarei and Antonie J. van den Bogert

Parker Hannifin Laboratory for Human Motion and Control (hmc.csuohio.edu)

Department of Mechanical Engineering, Cleveland State University

Introduction

A rowing exercise machine (Fig. 1) presents a specific geometrical and mechanical environment to the user. The design parameters affect how the user performs the exercise and which forces are generated in musculoskeletal tissues. These effects may be determined by predictive simulations based on optimal control.

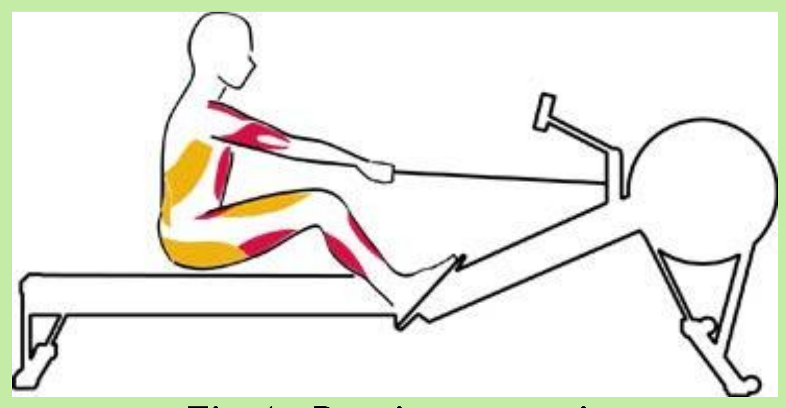

Fig 1. Rowing exercise

System dynamics

- Rowing machine model for the two phases of the movement (Fig. 2,3)
- An arm model with a Hill-based muscle model

Simulation of rowing:

- The motion must be periodic
- Cycle time is prescribed
- Duration of the phases is unknown
- Minimal effort is assumed

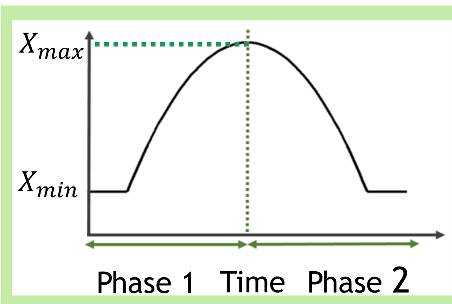

Fig 2. Motion profile

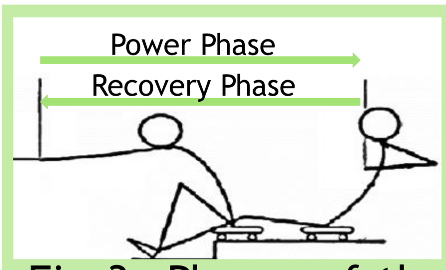

Fig 3. Phases of the rowing movement

Objectives:

- Develop a computational method based on musculoskeletal modeling and optimal control to predict how mechanical parameters alter human performance [1].
- Demonstrate the method by predicting movements and forces generated by the arm during periodic elbow flexion exercise.

Methods

System dynamics

Two phases:

- *1st phase*: Power phase (Fig. 4)

Resistance is provided by two springs, a damper and the total effective mass of the arm (m_h) and the flywheel in the rowing machine (m_r)

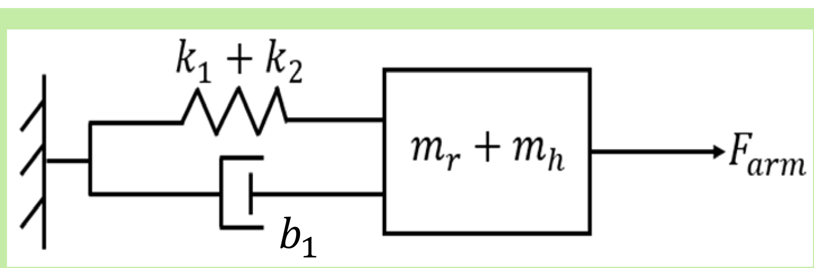

Fig 4. Phase 1

- *2nd phase*: Recovery phase (Fig. 5)

The resistance mechanism is disengaged, except for a weak spring which winds up the cable

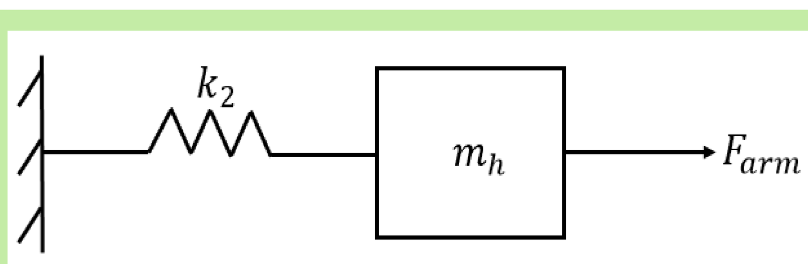

Fig 5. Phase 2

Hill-based model [2] (Fig. 6):

- Contractile Element (CE) represents standard force-length and force-velocity relationships
- Parallel Elastic Element (PEE) represents passive properties of muscle fibers and surrounding tissue
- Series Elastic Element (SEE) represents the tendon and any elastic tissue in the muscle itself that is arranged in series with the muscle fibers
- A small amount of damping (b) adds numerical stability
- Biceps muscle properties from [3]

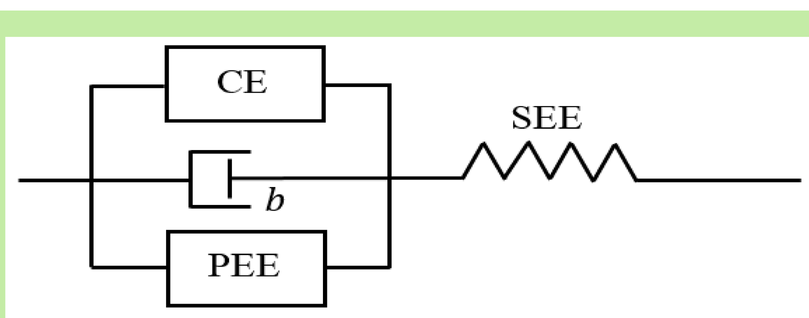

Fig 6. Hill-based model

Coupling between muscle and machine (Fig. 7)

- Arm length L
- Muscle moment arm d

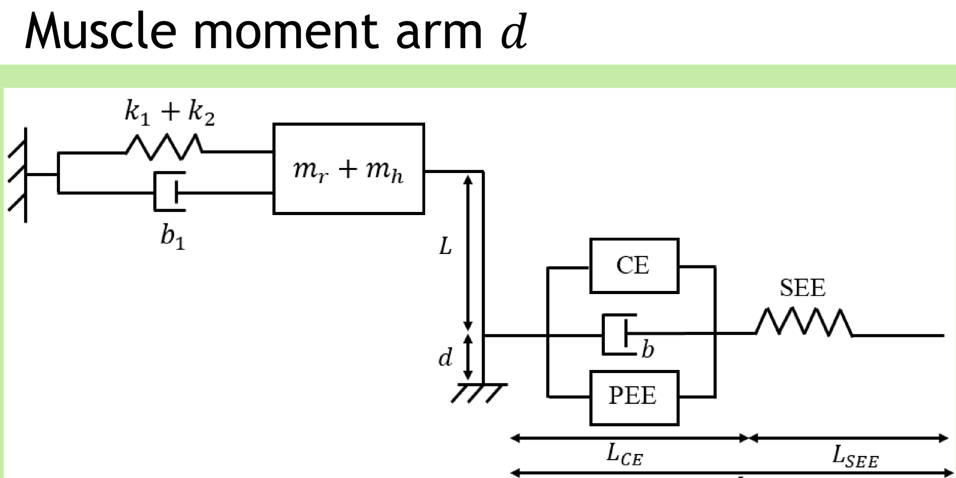

Fig 7. Dynamics of the muscle model in phase 1

Parameters	Values	Unit
m_h	10	Kg
m_r	20	Kg
k_1	5	N/m
k_2	30	N/m
b_1	5	Ns/m
L	0.6	m
d	0.04	m
L_M	0.288	m

Table 1.

All the model parameters are shown in the Table 1.

Simulation

The predictive simulation was formulated as an optimal control problem, to find the muscle excitation $u(t)$ that produces a periodic motion with an amplitude of 0.2 m with minimal effort.

Optimal Control Problem:

- 4 state variables (position, velocity, fiber length, and muscle activation): $[x_1\ \dot{x}_1\ L_{ce}\ \ a]$
- Rowing machine dynamics:
  1. Power phase: $\begin{cases} \dot{x}_1 = x_2 \\ \dot{x}_2 = \frac{1}{m_r+m_h}\left(\frac{d}{L}F_{SEE} - b\dot{x}_1 - (k_1+k_2)x_1\right) \end{cases}$
  2. Recovery phase: $\begin{cases} \dot{x}_1 = x_2 \\ \dot{x}_2 = \frac{1}{m_h}\left(\frac{d}{L}F_{SEE} - k_2 x_2\right) \end{cases}$
- Muscle dynamics:
  1. Excitation $\quad \dot{a} = (u-a)\left(\frac{u}{T_{act}} + \frac{1-u}{T_{deact}}\right)$
  2. Contraction dynamics

$$F_{CE}(a, L_{CE}, \dot{L}_{CE}) + F_{PEE}(L_{CE}) + b\dot{L}_{CE} = F_{SEE}(L_M - L_{CE})$$

- Cost function: $\int_0^{t_f} u^2(t)\, dt$
- Solved by GPOPS-II [4]

Results

GPOPS-II required about 60 seconds of computation time to solve the problem.

- The optimal phase 1 occurred in 2.48 s
- The optimal phase 2 occurred in 1.51 s
- The arm moves forward to the final position in phase 1 with positive velocity
- The arm goes back to the initial position with a negative velocity in phase 2
- Muscle fibers shorten in phase 1 and length in phase 2
- The arm generates more force in phase 1 than in phase 2

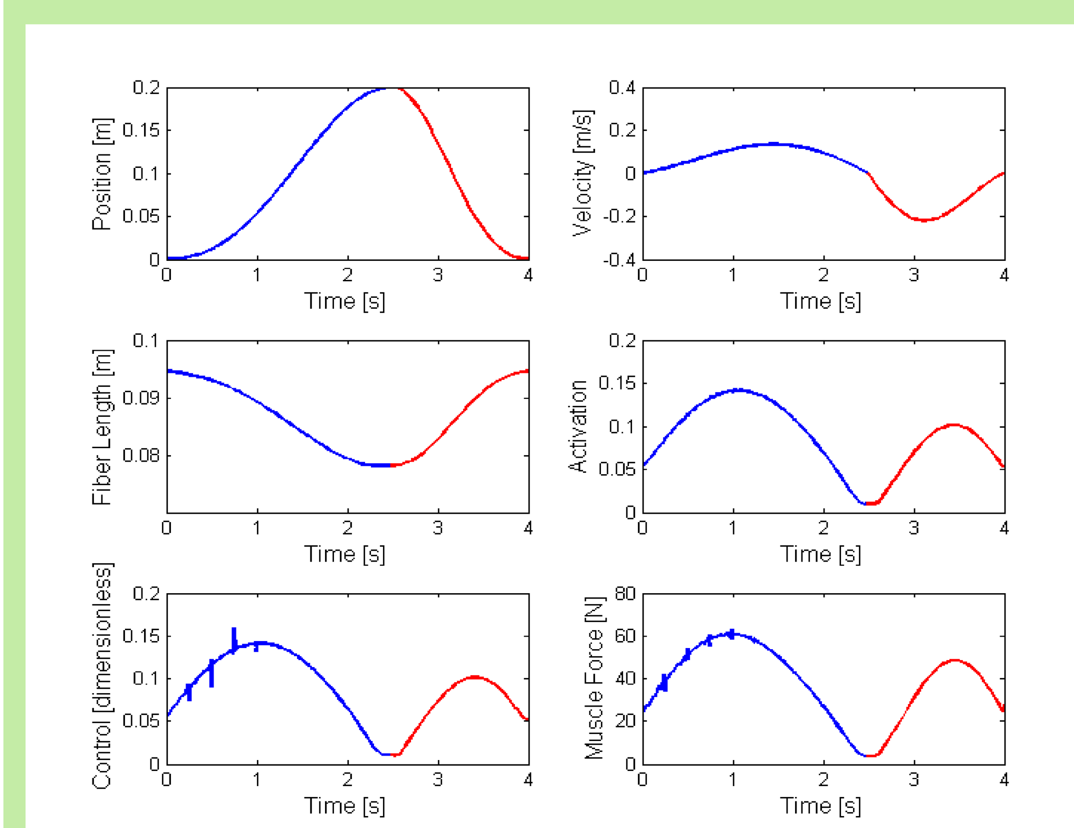

Fig 8. Position, Velocity, Fiber Length, Activation, Control, and Muscle Force for 2 phases

Conclusion

1. GPOPS was able to solve the optimal control problem.
2. The predicted motions and forces seem realistic.

Future work

More degrees of freedom will be added to the model to simulate full body rowing exercise.

References

1. van den Bogert, AJ, et al. *Proc Inst Mech Eng, Part P: J Sports Eng Technol* 226, 123-133, 2012.
2. van den Bogert, AJ et al. Procedia IUTAM **2**, 297-316, 2011.
3. Chadwick, EK, et al. *IEEE Trans Biomed Eng* 61, 1947-1956, 2014.
4. Patterson, MA, et al. A general-purpose MATLAB software for solving multi-phase optimal control problems, University of Florida (http://www.gpops2.com), 2014.

Acknowledgments: supported by the National Science Foundation under Grant No. 1344954 and the by the Parker Hannifin corporation