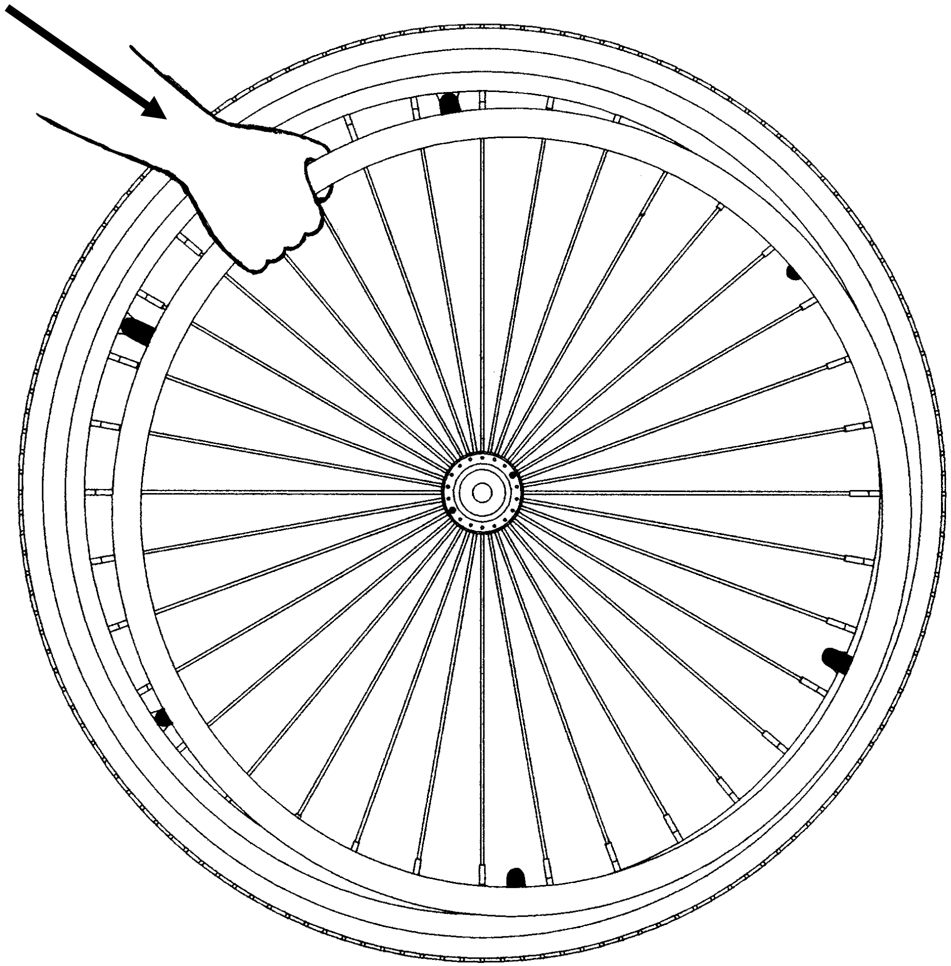
A Model-Based Approach to Determine the Effect of Handrim Compliance on Propulsion Efficiency

Mark Richter[1], Peter Axelson[2], Rory Cooper[3]

[1]Stanford University, [2]Beneficial Designs, Inc., [3]University of Pittsburgh

Compliance allows handrim to displace relative to the wheel



Motivation

- High incidence of upper extremity injury among manual wheelchair users (Sie, 1992)
- Association found between certain propulsion characteristics and incidence of injury (Boninger, 1999) (Koontz, 2000)
- Use of a compliant handrim found to reduce some of those loading characteristics associated with injury (Richter, 1999)

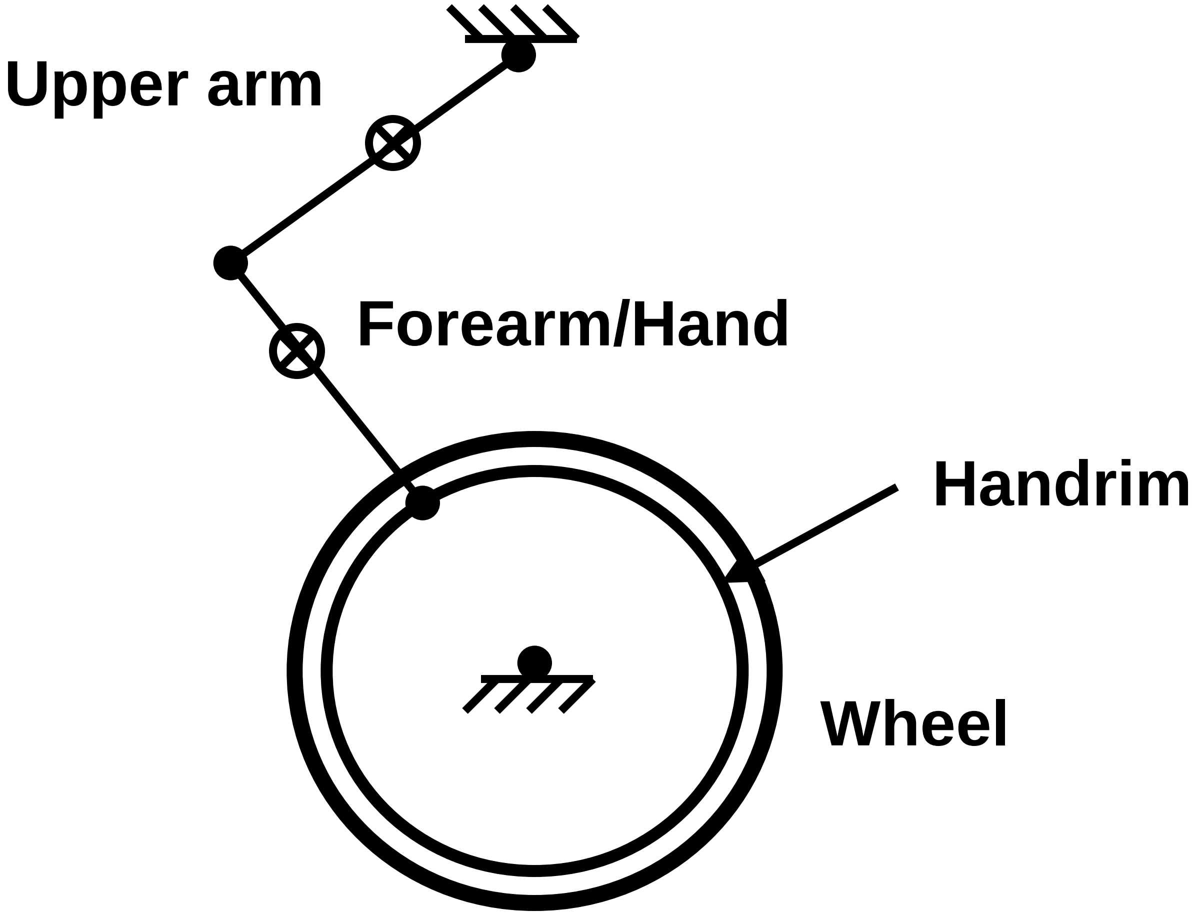
Motivation

- Use of a compliant handrim was found to reduce metabolic demand during propulsion (Richter, 1999)
- Is the impact energy better utilized by being stored in the compliant fasteners and then released during the push?
- Does the reduced kinematic constraints on the arm allow the user to optimize his/her propulsion stroke?

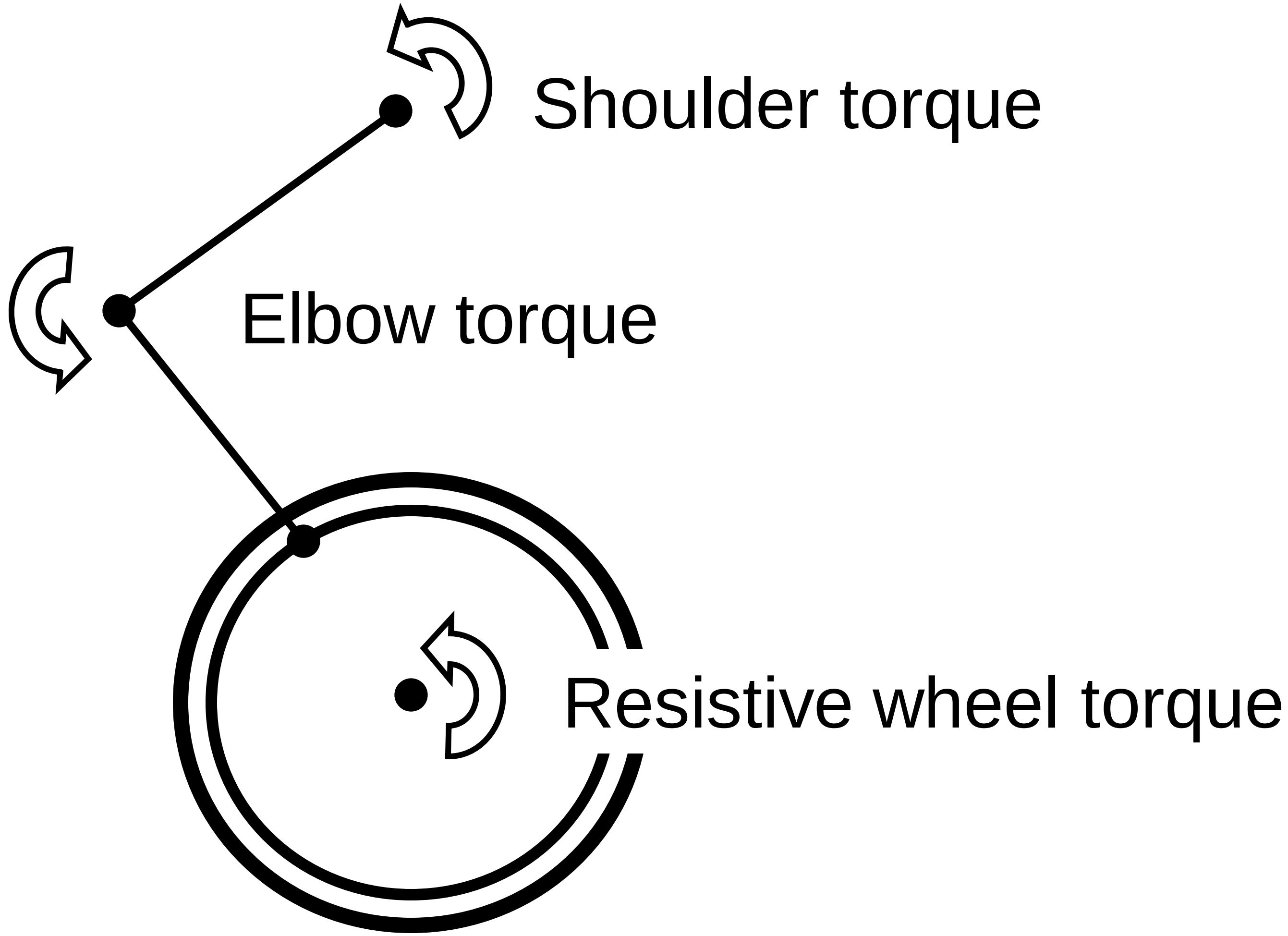
Dynamic compliant handrim propulsion model (DCHPM)

- Dynamic model allows investigation of wide spectrum of variables
  - Compliance characteristics (k,b)
  - Propulsion environment (% incline)
  - User characteristics (size, weight)
  - Wheelchair characteristics (wheel/handrim diameters & shoulder positioning relative to wheel)

DCHPM includes 4 rigid bodies



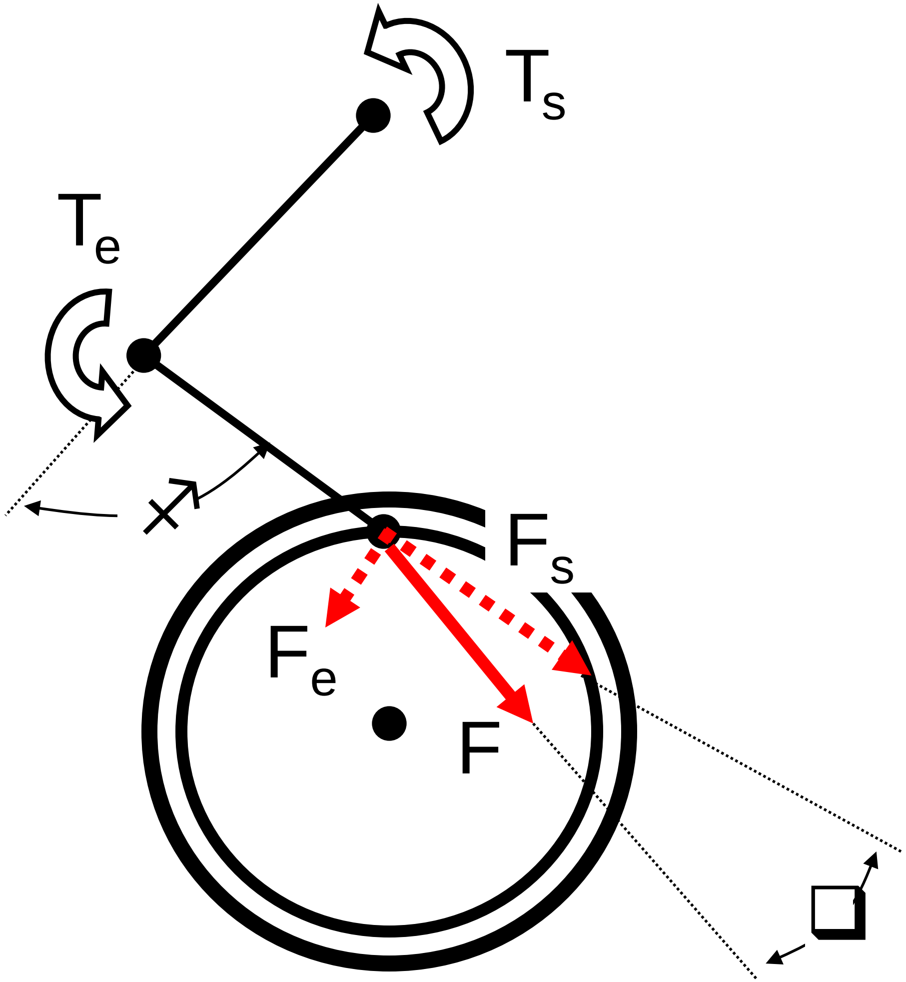
DCHPM external torque


Shoulder torque

Elbow torque

Resistive wheel torque

Joint torque combination required to produce input force on handrim



F_s = |F| cos[❑]

F_e = |F| sin[❑]

T_s = F_s LUA cos[90-♐]

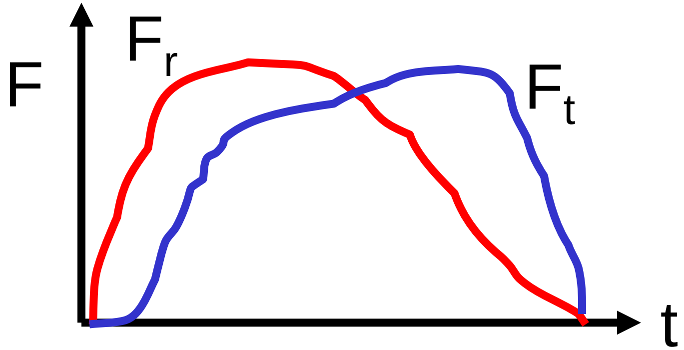
T_e = -F_e LFA

where;

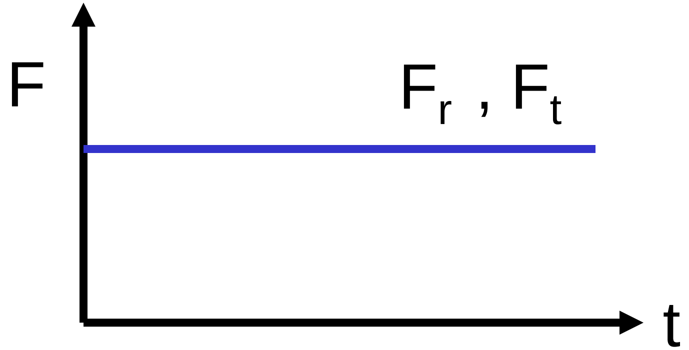
LUA = Length of upper arm

LFA = Length of forearm

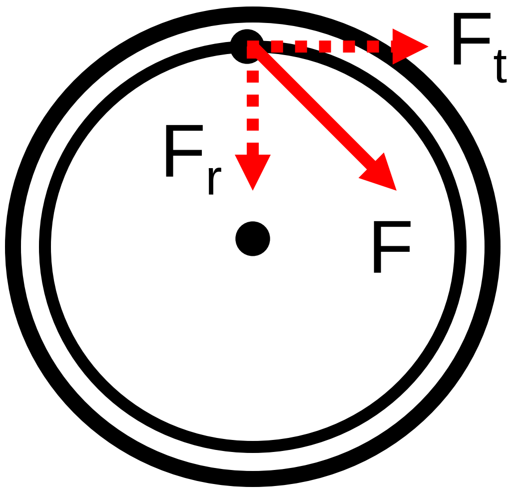
Simplification: constant input force on the handrim



Measured



Model



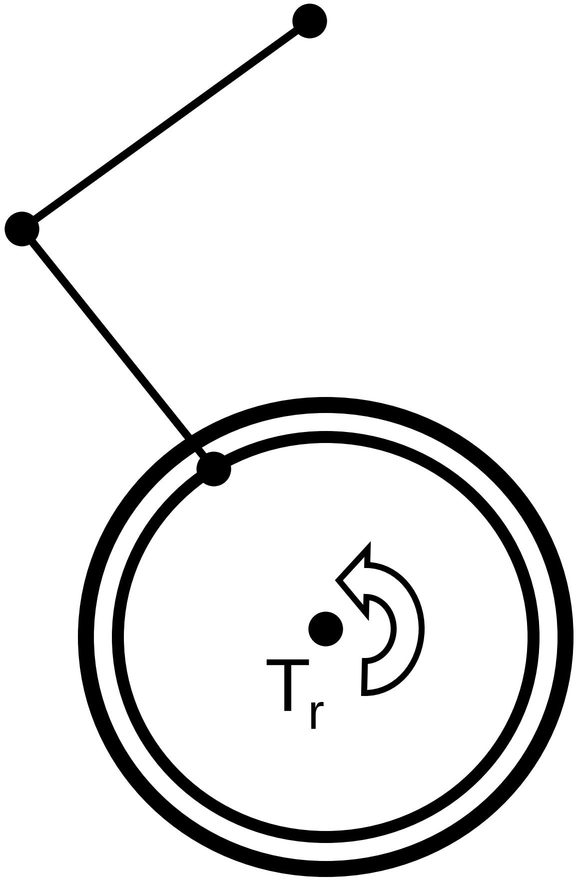
F_r = radial force component

F_t = tangential force component

$|F_r| = |F_t| = 45$ N

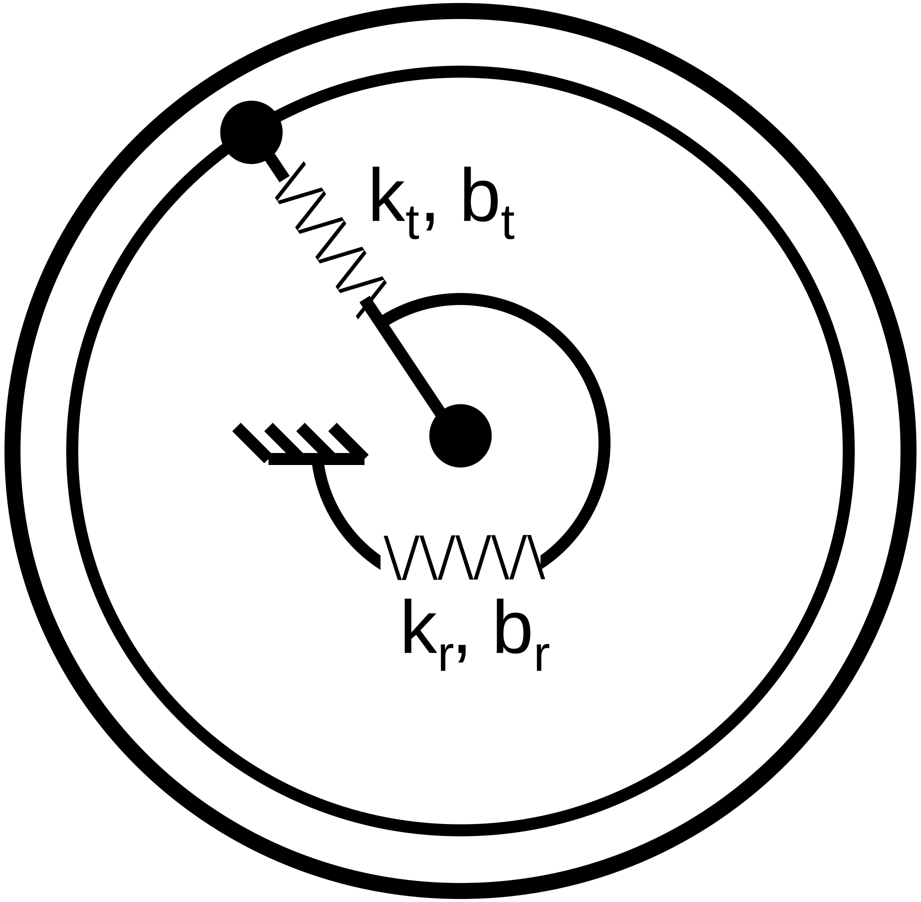
$|F| = (F_r$^2 + F_t^2)^0.5

Resistive wheel torque is a function of rolling resistance, air drag and the degree of incline



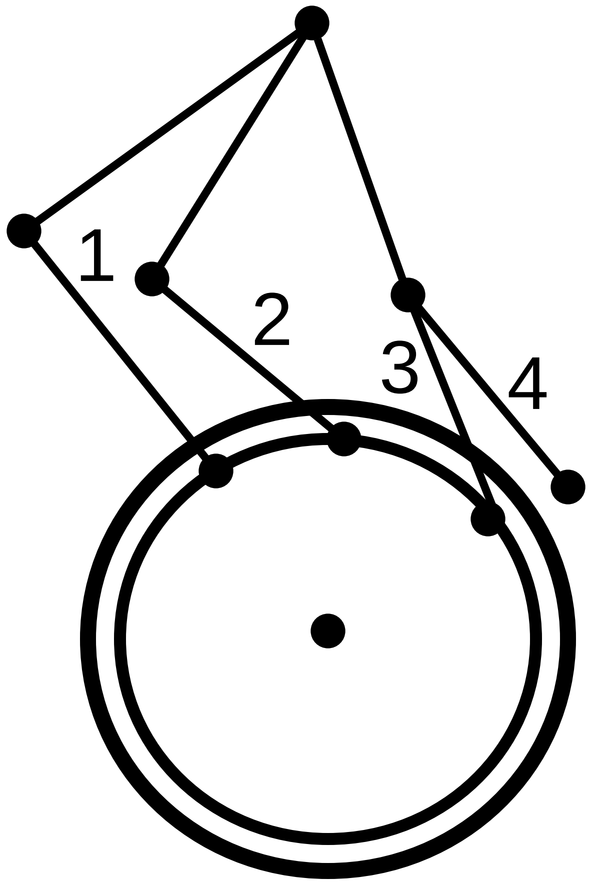
- Deceleration of the wheelchair, a_{wc}, found to be linear (Theisen, 1996)
  - a_{wc} (2% incline) = $-0.531\ m/s^2$
- $T_r = 1/2\ m_{wc}\ a_{wc}\ R_w$
  - where m_{wc} = mass of w/c + user and R_w = radius of the wheel

DCHPM compliance characteristics



- k_t = translational spring constant
- b_t = translational damping constant
- k_r = rotational spring constant
- b_r = rotational damping constant

DCHPM phases



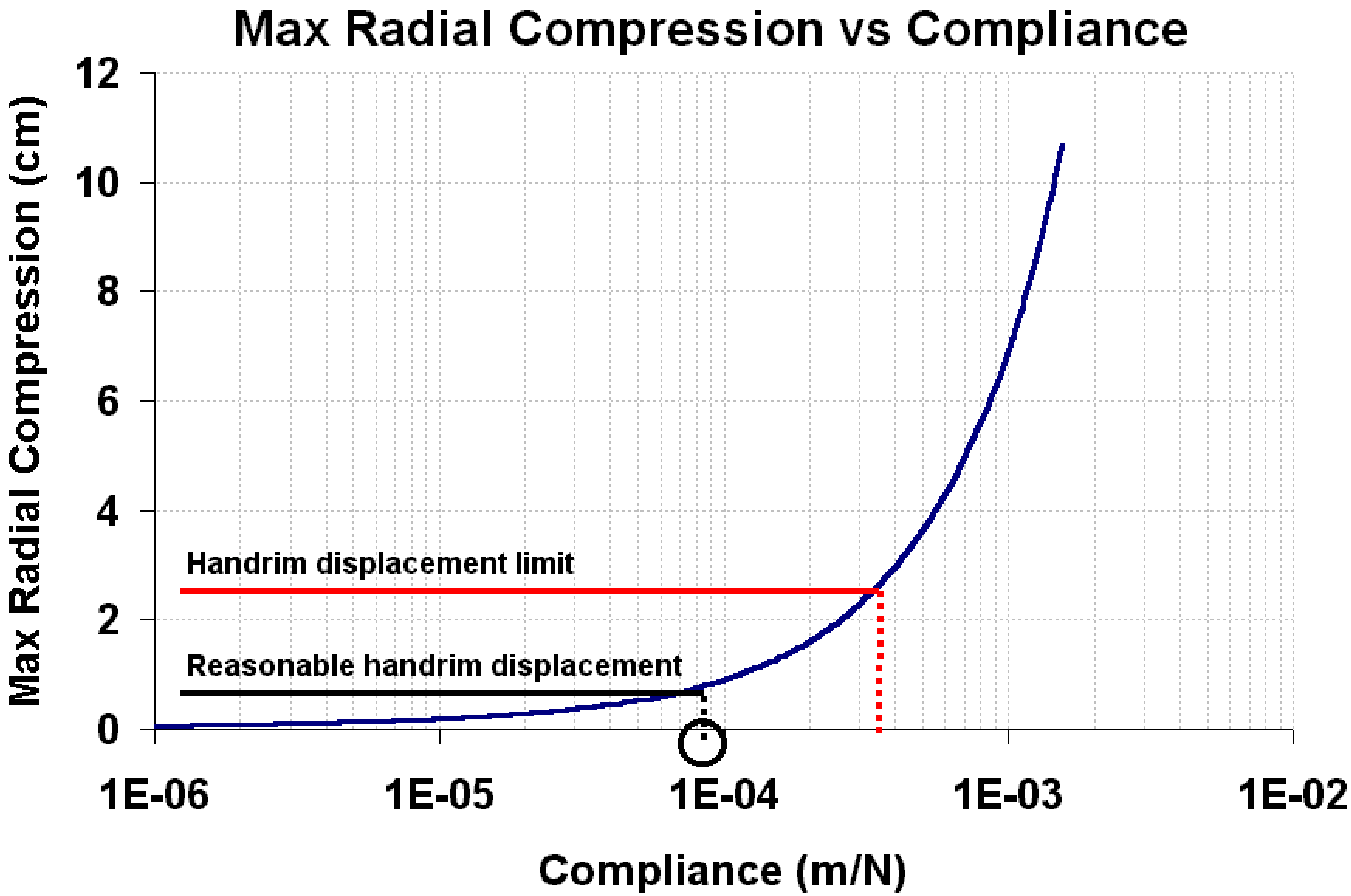
- 1 = Impact phase
- 2 = Drive phase
- 3 = Hold phase
- 4 = Release phase

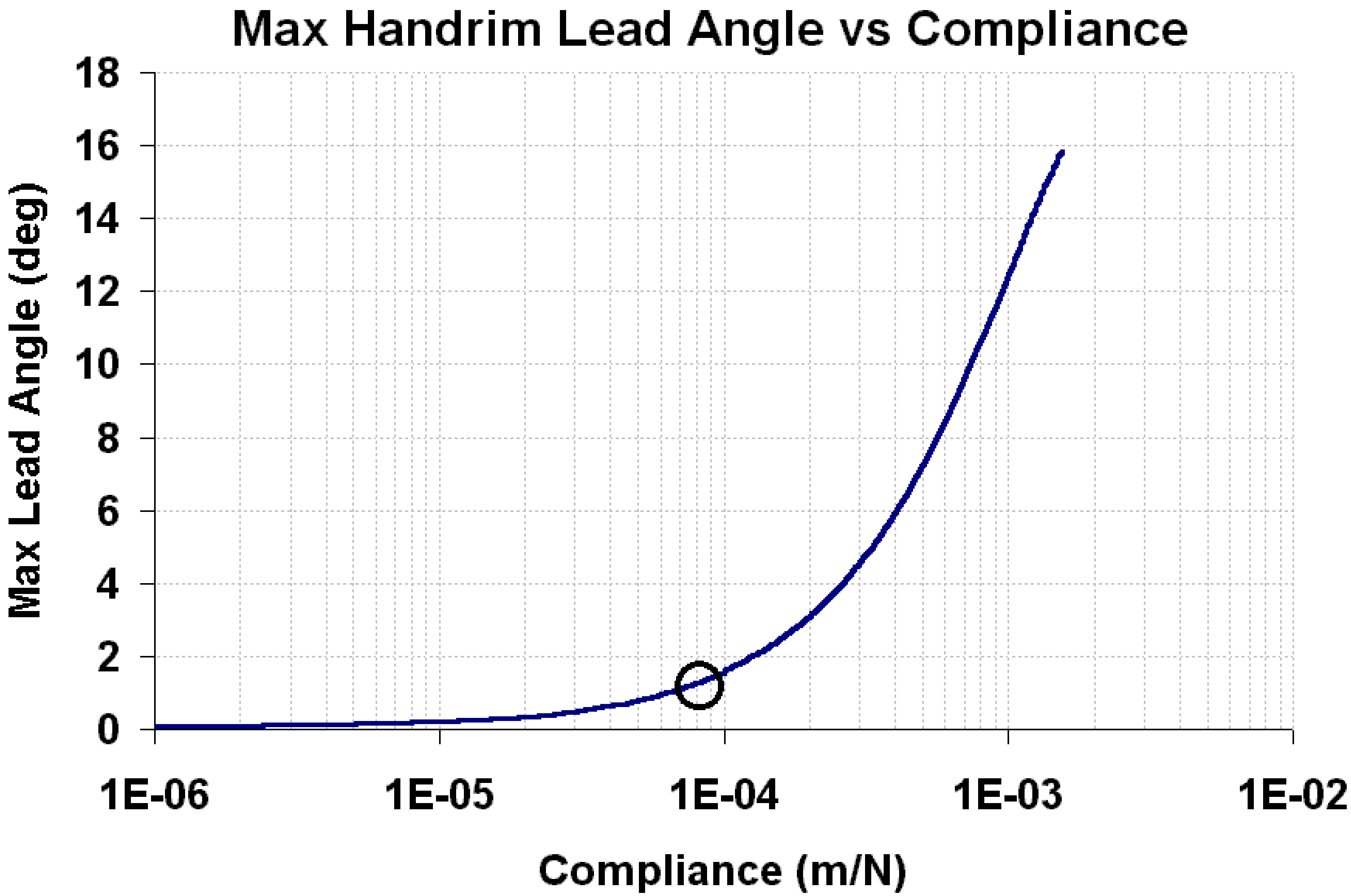
Model development

- Penalty potential constrains the hand to the handrim, results in a 5 DOF system
- EOM developed using Lagrange
- System of 5 EOM solved for second time derivatives of generalized coordinates
- 5, 2nd order ODEs reduced to 10 1st order ODEs
- ODEs integrated numerically

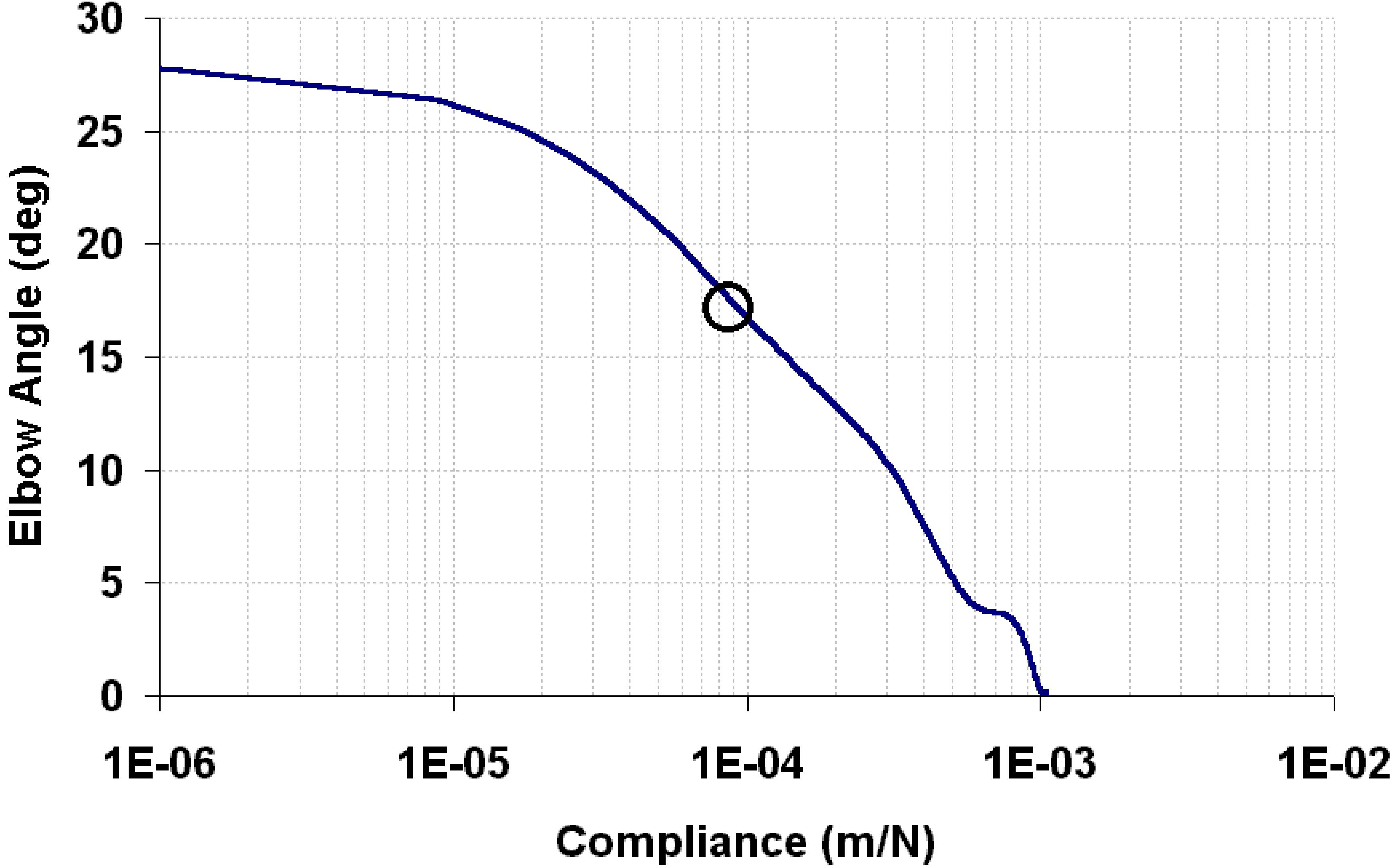
Analysis: simulation scenarios

- Propel at minimum of 1.7 mph on a 2% incline (2.5 rad/s)
- Vary compliance isotropically, equal radial and tangential behavior
- Fixed damping ratio, ⌘ = 0.5
- Impact vs. no impact
- Pure rotation
- Pure translation


Max Radial Compression vs Compliance
Max Radial Compression (cm)
12
10
8
6
4
2
0
Handrim displacement limit
Reasonable handrim displacement
1E-06
1E-05
1E-04
1E-03
1E-02
Compliance (m/N)


Max Handrim Lead Angle vs Compliance
Max Lead Angle (deg)
0
2
4
6
8
10
12
14
16
18
1E-06
1E-05
1E-04
1E-03
1E-02
Compliance (m/N)

Elbow Angle at Release vs Compliance



Analysis: efficiency

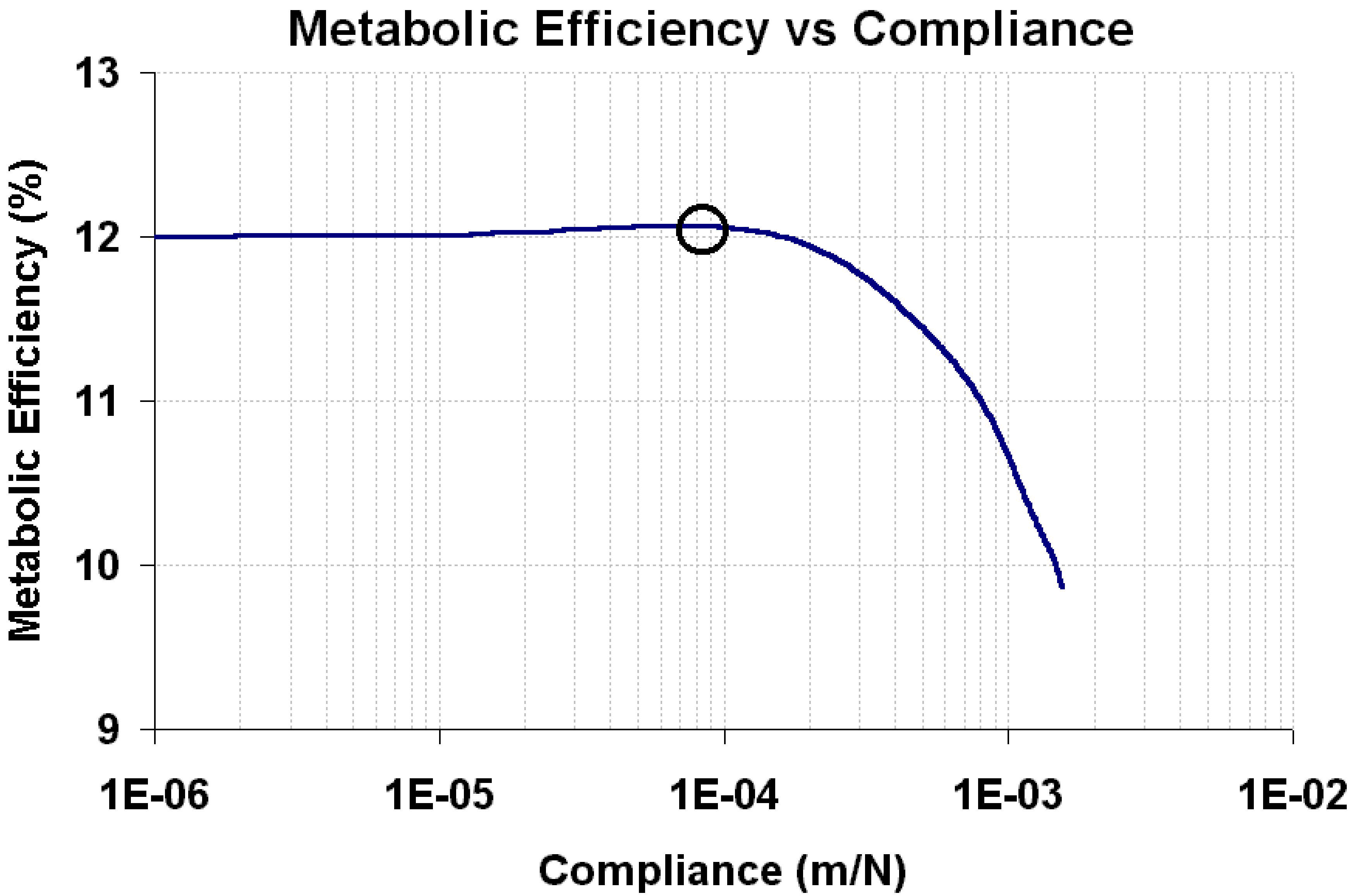
- Efficiency
  - ♒ = 100 (W_o/ W_i)
    - W_o = output work
    - W_i = input work

Analysis: output work

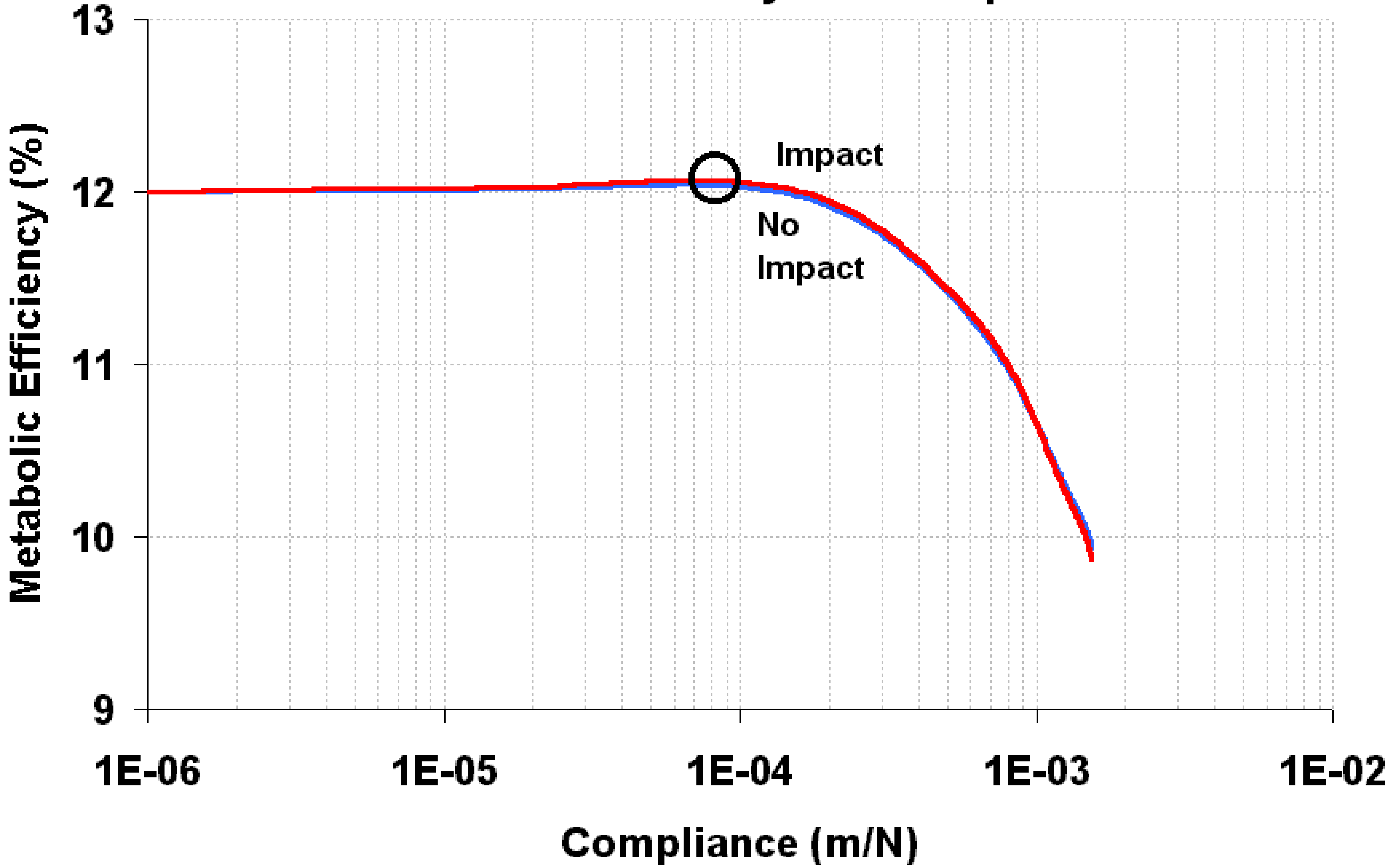
- Output work
  - W_o = ⇩P_o dt
    - Integral taken over the cycle
    - P_o = instantaneous power output
- Instantaneous power output
  - P_o = T_a (d❑$_w$/dt)
    - T_a = torque on the wheel and d❑$_w$/dt = the angular velocity of the wheel

Analysis: input work

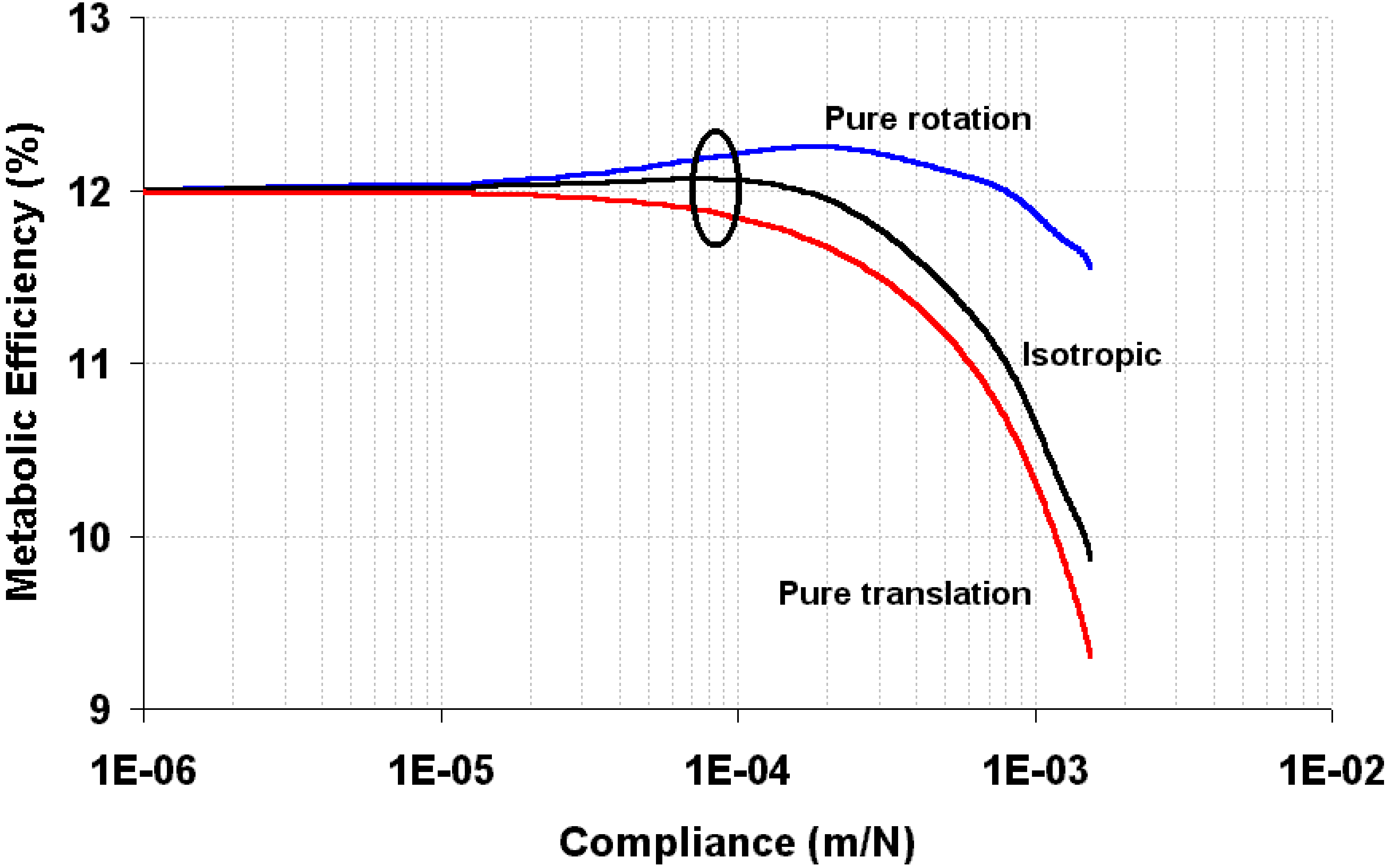
- Input work
  - $W_i = MF*(\Downarrow T_s dt + \Downarrow T_e dt)$
    - T_s = torque on the shoulder
    - T_e = torque on the elbow
    - MF = metabolic factor, estimated value used to scale torque*seconds to joules - set such that model results with rigid handrim approximate experimental measures (Veeger, 1996)


Metabolic Efficiency vs Compliance
Metabolic Efficiency (%)
13
12
11
10
9
1E-06
1E-05
1E-04
1E-03
1E-02
Compliance (m/N)

Metabolic Efficiency vs Compliance



Metabolic Efficiency vs Compliance



Discussion

- Model uses constant handrim force
- Users may be optimizing joint torque to maximize efficiency, model does not
- Muscle energy is a function of muscle tension, length and shortening velocity
  - Joint torque alone is not adequate to describe muscle tension, length and muscle shortening velocity
- Co-contraction theory: co-contraction of muscles may decrease with handrim compliance, not accounted for in model

Future work

- Model improvement/validation
  - Compare model results to experimental results
  - Improve input force characteristics
  - Possibly add muscles to the model
- Use the model to study effect of incline, user weight, anthropometrics, compliance and speed of propulsion

Acknowledgements

- Funding for compliant handrim research was co-provided by the National Institute of Child Health and Human Development and the National Center for Injury Prevention and Control (NCIPC), Centers for Disease Control and Prevention (CDC) through SBIR Phase I Grant # 1 R43 HD36533-01