MUSCULOSCELETAL EFFICIENCY IN CYCLING AND HANDCYCLING

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Agenda

• Index of efficiency: Definition and relevance in cycling
• Musculoskeletal simulation of cycling
• Handcycling: the force generation abilities of the arms
• Simulation of handcycling
• Muscle-length and momentarms in 3D
Only tangential force contributes to propulsion
Pedal forces in cycling

Index of effectivenes (IE)

\[ IE = \frac{\int_{0^\circ}^{360^\circ} F_{\text{tangential}} \, d\alpha}{\int_{0^\circ}^{360^\circ} \sqrt{F_{\text{tangential}}^2 + F_{\text{radial}}^2} \, d\alpha} \cdot 100\% \]

Four Sectors of a cycle (right)

- **Push forward**
  - 315°
  - 45°

- **Pull up**
  - 225°

- **Push down**
  - 135°

- **Pull backward**
  - 6°
Sectors IE

\[
IE_{\text{unten}} = \frac{\int_{45^\circ}^{135^\circ} F_{\text{tangential}} d\alpha}{\int_{45^\circ}^{135^\circ} \sqrt{F_{\text{tangential}}^2 + F_{\text{radial}}^2}} \cdot 100\%
\]

IE at different power levels

Options to increase IE

Training

1. Technique specific Protocol
2. Biofeedback
3. SmartCranks

Hardware modifications

1. Elliptical chainrings
2. Variation of crank alignment
Relevance of IE in Cycling

Studies relating energy consumption and power output to better IE (no hardware changes)

Recreational cyclists:
1. Lafortune & Cavanagh 1983
   1. Ericson & Nissel 1988
   2. Coyle et al. 1991

Professionals:
1. Lafortune & Cavanagh 1983
2. Hillebrecht et al. 1998
3. Cavanagh & Sanderson 1986
Where is the problem?

Mechanics + Biology = Biomechanics

Index of Effectiveness
Hypothesis

For efficient cycling the musculoskeletal system requires radial forces
Summary

- Index of effectiveness (IE) is the relation of tangential forces to total forces applied to the pedal.

- IE can be subdivided into four sectors defined by the action of the cyclist.

- IE does not show any relation to efficiency or power production in professional or recreational cyclists.
Human model

- 4 rigid segments
- 8 Hill-type muscles [1]
- metabolic energy consumption [2]

Muscle metabolic energy [1]

\[ \dot{E} = \dot{H} + \dot{W} = \dot{A} + \dot{M} + \dot{S} + \dot{B} + \dot{W} \]

- \( \dot{E} \) = energy rate
- \( \dot{H} \) = heat rate
- \( \dot{W} \) = work rate
- \( \dot{A} \) = activation heat rate
- \( \dot{M} \) = maintenance heat rate
- \( \dot{S} \) = shortening heat rate
- \( \dot{B} \) = basal metabolic heat rate

\[ \dot{E} = f(F_{CE}, v_{CE}) \]
\[ = f(act, m, \exp(-t_{stim}/\tau)) \]
\[ = f(act, m, l_{CE}/l_{CE, opt}) \]
\[ = f(F_{iso, max}(l_{CE}), F_{CE}, v_{CE}) \]
\[ = f(m) \]
Bicycle model

- seating position [2]
- air resistance
- inertia of bike, rider and wheels
- free wheel clutch

Optimization of muscle activation

- Genetic algorithm
- Optimisation goal:
  a) reduction of metabolic energy consumption
  b) increase of index of efficiency
Validation Study

- Ergometer 280 W, 90 rpm
- 20 male amateur cyclists (28±7 y, 180±5cm, 76±8kg)

Validation of muscle activation

Simulation results

Pedal Forces

- $F_{\text{tan}}$ [N]
- $F_{\text{rad}}$ [N]

- IE optimal
- Energy optimal

35 km/h
280 W
90 rpm
Simulation results

Energy optimal

IE optimal
Comparison of energy consumption and IE

Energy [J]

Index of effectiveness [%]

Optimal energy consumption

Optimal IE

Optimal energy consumption

Optimal IE
why it is so efficient to push downward?

1. Anti-gravity muscles are much stronger than their antagonists

2. Long moment arms in top and bottom positions
   - high joint torques required
   - high muscle forces required
Conclusion

IE optimal pedalling technique results in 2.5 times higher energy consumption

Index of Effectiveness is not adequate to quantify the quality of pedalling technique
Summary

• Muscles energy consumption might be estimated using the Hill muscle model

• Optimization for energy consumption results in realistic muscle activations

• Optimizing for IE results in considerably high energy consumption
Arms are shorter than legs, current crank system simply adopted from cycling might not be suitable for the hand arm system.
push, pull (max. Isometric)
Device to measure isometric joint torques
Maximum isometric joint torques at the elbow and shoulder
Muscles torque potential

Böhm H., Krämer C., 2007, Computational Imaging and Vision (36)
Torque potential for rowing and cycling

- **circular**
- **linear**

Diagram showing torque potential at different angles (0°, 45°, 90°, 135°) for rowing and cycling.
Conclusions from the measurements

1. In rowing the ability to generate force is higher than in cycling.
2. In handcycling the maximal joint loads are lower than in rowing

Conclusion:
Combine both advantages in an elliptic drive
Hypothesis

• The elliptic drive concept enables the muscles to work in a better range of their force length relation, so that there is less activation required and less metabolic energy consumed than in a cyclic movement
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Human model

4 rigid segments
6 Hill-type muscles [1,2]
metabolic energy consumption [3]

Muscle lengths of biarticular muscles
Optimization procedure to obtain muscle activation

Starting position with initial guess for activation functions of six muscles (Boehm et al. JAB 2006)

Calculate the cyclic motion and the cost function

Optimizer changes the muscle Activation to get a global minimum of the cost function (Corana et al. ACM 13, 1987)

Stop when minimum is reached
Example M.brachialis
Optimization

- global Minimum
- Multidimensional Problem (48 Variables)

→ Simulated Annealing (Corana et al. ’87)
Simulated motion

cyclic drive (b/a=1)

• m, 32 y, 170 cm, 72 kg
• drive resistance 20 Nm
• crank length 18 cm

elliptical drive (b/a =0.5)
All muscles’ metabolic energy consumption

![Graph showing metabolic energy consumption for elliptic and cyclic drives. The graph plots the metabolic energy in Joules (J) against the angle in degrees (°). The red line represents the elliptic drive, and the blue line represents the cyclic drive. The graph shows an increasing trend in metabolic energy as the angle increases.](image)
Simulations

<table>
<thead>
<tr>
<th>Subject</th>
<th>Arm length</th>
<th>Muscles metabolic energy $(E_{\text{elliptic}} - E_{\text{cyclic}}) / E_{\text{cyclic}}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>m, 170 cm, 72 kg</td>
<td>58.0 cm</td>
<td>- 3.5 %</td>
</tr>
<tr>
<td>m, 180 cm, 79 kg</td>
<td>59.8 cm</td>
<td>- 3.8 %</td>
</tr>
<tr>
<td>m, 187 cm, 88 kg</td>
<td>64.2 cm</td>
<td>- 4.0 %</td>
</tr>
</tbody>
</table>

• The model suggest that the elliptic drive concept is more efficient
Krämer et al 2009, Ergonomics

Krämer et al 2009, European Journal of Applied Physiology
• Muscle length and moment arms in 3D are not known for complex arm movements such as forearm pronation and supination
The Visible Human Dataset

- high-resolution images
- segmentation of bones

Frontal view:

- Right arm
- Humerus

Horizontal view:
Triangulated surface meshes
Dijkstra algorithm

muscle length = shortest path from origin to insertion
Graphical user interface

virtual reality

command window
Extensor: m. triceps brachii

![Graph showing muscle length vs. flexion angle.](attachment:graph.png)

- Extended arm
- Flexed arm

Approximately 2 cm change in muscle length.
Flexor: m. brachialis

![Graph showing muscle length vs flexion angle](image)

- **Polynomial fit to Fagg 2003**
- **Dijkstra algorithm**

Extended arm vs flexed arm

$\approx 2\text{ cm}$
Conclusion

+ Allows calculation of individual muscle lengths during motion
+ Can be transferred to complex joint movements
+ Calculation is semi-automatic
+ Works well for muscles close to the bony surface
Muscle deformation by minimizing deformation energy

Summary

• Elliptical drive was suggested to be more efficient in handcycling

• 3d simulation requires a lot more work