Mechanical energy fluctuations during walking of healthy and ACL reconstructed subjects

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Metabolic Cost of Walking

- (a) Metabolic power (W)
  - slow walking is very economical, up to about 2 m/s
  - minimum energy usage at intermediate walking speed, indicating optimum efficiency for gait

- (b) Economy (J m^-1)
  - Walking is very energy-efficient, because of various mechanisms that ensure the mechanical energy the body has is passed on from one step to the next
Sources of Energy

1. Metabolic energy

\[ E = b + m \cdot v^2 = 32 + 0.0050 \cdot v^2 \]

Ralston (1958) Bobbert (1960)

\[ E = \frac{E_0}{\left(1 - \frac{v^2}{v_0^2}\right)\left(1 - \frac{f^2}{f_0^2}\right)\left(1 - \frac{\omega^2}{\omega_0^2}\right)} \approx \frac{E_0}{\left(1 - \frac{v}{v_0}\right)^2} \]

Zarrugh (1974)


2. Mechanical energy

4 forms of Mechanical Energy:
- Gravitational potential \( m \cdot g \cdot y \)
- Elastic potential \( \frac{1}{2} k \cdot s^2 \)
- Translational kinetic \( \frac{1}{2} m \cdot v^2 \)
- Rotational kinetic \( \frac{1}{2} I \cdot \omega^2 \)

Total mechanical energy is sum of all four

Elastic potential energy is usually omitted because it cannot be measured accurately


- Cavagna et al., 1977; Cavagna and Margaria, 1966.
- Griffin (1999) Walking in simulated reduced gravity: mechanical energy fluctuations and exchange
Gait Mechanism: an Overview

- Pendulum-like movements of the limbs give rise to two phases: swing & stance;
- The forward momentum of the body gives it the necessary initial angular velocity of rotation;
- "Inverted" pendulum action also involves inter-conversion of potential and kinetic energy, but in this case (unlike a conventional pendulum) KE reaches a minimum at the midpoint of the motion, and PE is highest at that point;
- When reaching the endpoint of its "inverted swing" the stance leg does not swing back, as a real inverted pendulum would, because the foot is taken off the floor, the fulcrum transfers from the foot to the hip, and the leg swings again as a conventional pendulum.
- The legs move as conventional pendulums during the swing (with a little assistance from the hip flexors);
- This reduces the amount of muscle energy needed to move the swinging leg forward;
- Although the legs swing forwards much like pendulums, they are prevented from swinging backwards by footstrike;

Total Mechanical Energy Estimation - Methods

- Body Segment Energy Method (Multiple Rigid Body Method) Sum of all segmental total mechanical energies (Es)
  \[ E_{total} = \sum E_s = \sum \left[ m_i \cdot g \cdot y_i + \frac{1}{2} m_i \cdot v_i^2 + \frac{1}{2} I_i \cdot \omega_i^2 \right] \]
- Body Center of Gravity Method (Single Rigid Body Method)
  \[ E_{total} = M \cdot g \cdot y_{cog} + \frac{1}{2} M \cdot v_{cog}^2 \]
- Inverse Dynamics and Joint Power Analysis Method Integral of Power with respect of Time

Relation to Other Mechanical Variables

- **External Work** = change in body total mechanical energy:
  \[ W_{ext} = \Delta E_{total} = E_{total}(t_{final}) - E_{total}(t_{initial}) \]

- **Internal Work** = mechanical cost of moving the limbs during a cyclic motion; energy transfer from segment to segment;
  \[ W_{int} = \sum |\Delta E_{total}| - W_{ext} \]

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Energy Transfer Between Segments

**Fig. 1.** Energy of leg and HAT segments of the body during level overground walking. Total body energy reflects exchanges of energy between segments. See text for detailed discussion.

**Fig. 2.** Potential and translational kinetic energies of body’s center of mass during overground walking. Center of mass reflects to a certain extent the kind of energy changes that are occurring within and between segments.

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Aim of Work

- to explore the possibilities of employing the total mechanical energy into estimating the mechanical cost of transport in normal and pathological human gait

Material

- total of 130 bare-foot subjects
  - 53 male (age 31.5±9.7);
  - 23 male (age 22.1±3.2);

Test Group - patients after ACL-reconstruction following physiotherapy process

Control Group - with no visible locomotor impairment

Test patients underwent original physiotherapy process [Czamara, 2002] after the isolated ACL reconstruction, which involved harvesting the tendon graft (ST or GR) and rigid fixation.

Three Stages of physiotherapy process:
1. 2–4 weeks postoperatively;
2. 5–8 weeks postoperatively;
3. 9–12 weeks postoperatively;
**Instrumentation**

SIMI Motion Analysis System (Simi Reality Motion Systems GmbH, Unterschleissheim, Germany)


**Anthropometric Model**

- Clauser’s Model
  - 14 rigid segments


Data Analysis

1. Registering the positions of CoG for each segment;
2. Calculating the position of BCoG for every frame;
3. Calculating the height and speed of BCoG;
4. Calculating the potential and horizontal kinetic energy of BCoG;
5. Normalization

\[
E_{\text{norm}}^\text{pot} = \frac{mg \cdot h_{\text{BCoG}}}{m \cdot g \cdot L} = h_{\text{BCoG}}^\text{norm}
\]

\[
E_{\text{norm}}^\text{kin} = \frac{0.5 \cdot m \cdot v_{\text{BCoG}}^2}{m \cdot g \cdot L} = \frac{v_{\text{BCoG}}^2}{2gL}
\]

\[
E_{\text{total}}^\text{norm} = E_{\text{pot}}^\text{norm} + E_{\text{kin}}^\text{norm} = h_{\text{BCoG}}^\text{norm} + \frac{v_{\text{BCoG}}^2}{2gL}
\]

Hof (1996); Sutherland (1996); Stansfield i wsp. (2001); Stansfield i wsp. (2006)

Data Evaluation
Results

- Potential energy, mean±SD, men

Normal (reference) group    ACL-reconstructed group  Stage 1

Potential Energy, mean±SD, men

Results

- Potential Energy in physiotherapy process
Results

- Kinetic Energy, mean±SD, men

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<th>% Gait Cycle</th>
<th>Normal (reference) group</th>
<th>ACL-reconstructed group</th>
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Results

- Kinetic Energy in physiotherapy process

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<th>ACL 3</th>
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Conclusions

- Normal energy curves similar to Winter (1979), Griffin (1999) and Gider et al. (1995);
- Kinetic Energy is ca. 9 times lower than Potential Energy for the Control Group;
- Potential Energy, Kinetic Energy and Total Mechanical Energy rise during physiotherapy process;
- Potential Energy is rising during physiotherapy process due to rising amplitude of BCoG trajectory;
- Potential Energy on stage 3 of physiotherapy is significantly lower than in control group;
- Mechanical Cost is lower for ACL-reconstructed group than for control group;
- On the stage 3 of physiotherapy Mechanical Cost is still lower than in control group due to the significant lower amplitude of BCoG trajectory;