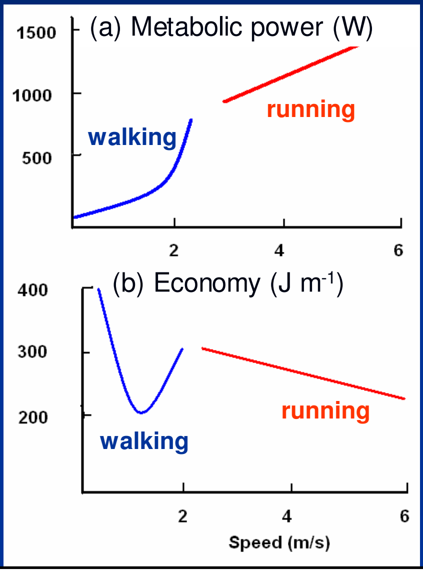
Mechanical energy fluctuations during walking of healthy and ACL reconstructed subjects

Sławomir Winiarski

University School of Physical Education, Wroclaw;
Biomechanics Dep.

SIMI

Metabolic Cost of Walking



slow walking is very economical,
up to about 2 m/s

minimum energy usage at intermediate walking speed, indicating optimum efficiency for gait

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=E(L,f,v)

$$E = b + m \cdot v^2 = 32 + 0{,}0050 \cdot v^2$$

Ralston (1958) Bobbert (1960)

$$E = \frac{E_0}{\left(1 - \frac{s^2}{s_u^2}\right)\left(1 - \frac{f^2}{f_u^2}\right)} \approx \frac{E_0}{\left(1 - \frac{v}{v_u}\right)^2}$$

Zarrugh (1974)

Zarrugh MY, Todd FN, Ralston HJ (1974) Optimization of energy expenditure during level walking. European Journal of Applied Physiology 33: 293–306.
Ralston HJ (1958) Energy-speed relation and optimal speed during level walking. Internationale Zeitschrift für angewandte Physiologie 17: 277–283.
Bobbert AC (1960) Energy expenditure in level and grade walking. Journal of Applied Physiology 15: 1015-1021.

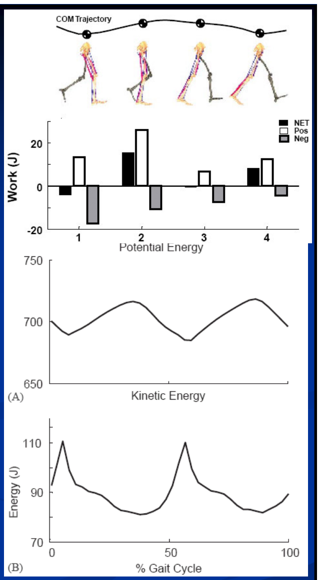
2. Mechanical energy

4 forms of Mechanical Energy:

- Gravitational potential m g y
- Elastic potential ½ k s^2
- Translational kinetic ½ m v^2
- Rotational kinetic ½ I ω^2

Total mechanical energy is sum of all four

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

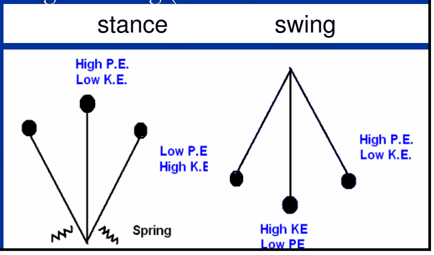


- Cavagna et al., 1977; Cavagna and Margaria,1966.
- Inman (1981) *Human Walking*
- Griffin (1999) Walking in simulated reduced gravity:mechanical energy fluctuations and exchange

Winter DA, Quanbury AO, Reimer GD (1976) Analysis of instantaneous energy of normal gait. Journal of Biomechanics 9: 253-257.

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)

$$E_{total}=\sum E_s=\sum\left(m_s\cdot g\cdot y_s+\frac{1}{2}m_s\cdot v_s^2+\frac{1}{2}I_s\cdot\omega_s^2\right)$$

- Body Center of Gravity Method (Single Rigid Body Method)

$$E_{total}=M\cdot g\cdot y_{cog}+\frac{1}{2}M\cdot \bar{v}_{cog}^{2}$$

- Inverse Dynamics and Joint Power Analysis Method Integral of Power with respect of Time Elftman (1939), Winter (1987)

Winter DA, Quanbury AO, Reimer GD (1976) Analysis of instantaneous energy of normal gait. Journal of Biomechanics 9: 253-257
Cavagna GA, Thys H, Zamboni A (1976) The sources of external work in level walking and running. Journal of Physiology 262: 639-657
Winter DA (1979) A new definition of mechanical work done in human movement . Journal of Applied Physiology 46: 79-83.

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;

$$W_{int.}=\Sigma\,|\Delta E_{total}|\,-\,W_{ext.}$$

Pierrynowski MR, Winter DA, Norman RW (1980) Transfers of mechanical energy within the total body and mechanical efficiency during treadmill walking. Ergonomics 23: 147-156.
Robertson DGE, Winter DA (1980) Mechanical energy generation, absorption and transfer amongst segments during walking. Journal of Biomechanics 139: 845-854.
Williams KR (1985) The relationship between mechanical and physiological energy estimates. Med Sci Sports Exercise 17: 317-325.
Elftman H (1939) Forces and energy changes in the leg during walking. American Journal of Physiology 125: 339-356.
Winter DA (1987) Mechanical power in human movement: generation, absorption and transfer. Med Sci Sports Exercise 25: 34-45.
Aissaoui R, Allard P, Junqua A, Frossard L, Duhaime M (1996) Internal work estimation in three-dimensional gait analysis. Medical and Biological Engineering and Computing 34(6): 467-471.

Energy Transfer Between Segments

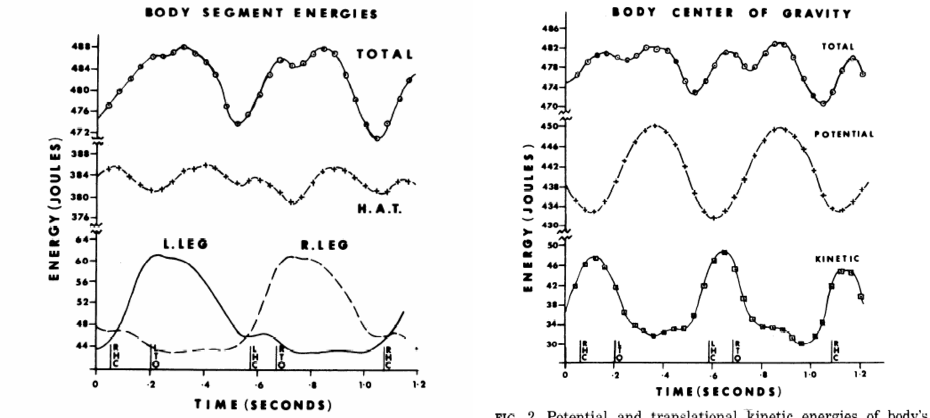


FIG. 1. Energy of leg and HAT segments of the body during leve overground walking. Total body energy reflects exchanges of energ between segments. See text for detailed discussion.

FIG. 2. Potential and translational kinetic energies of body's center of mass for same data as in Fig. 1. Total energy of body's center of mass reflects to a certain extent the kind of energy changes that are occurring within and between segments.

Winter DA (1979) A new definition of mechanical work done in human movement. Journal of Applied Physiology 46: 79-83.

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); **Test Group** - patients after ACL-reconstruction following physiotherapy process
  - 23 male (age 22,1±3,2); **Control Group** - with no visible locomotor impairment

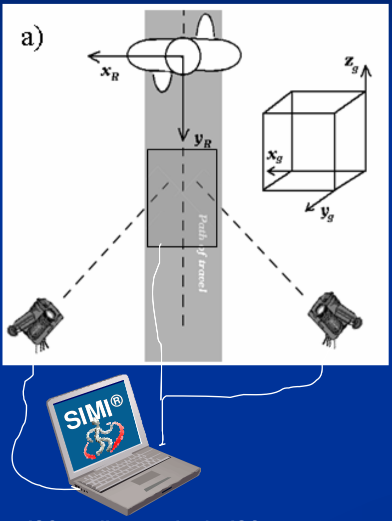
Test patients underwent original physiotherapy process [Czamara, 2002] after the isolated ACL reconstruction, which involved harvesting the tendon graft (ST or GR) and rigid fixation.

Three Stages of physiotherapy process:

1. 2–4 weeks postoperatively;
2. 5–8 weeks postoperatively;
3. 9–12 weeks postoperatively;

Instrumentation

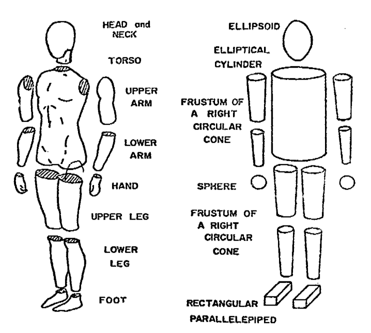
SIMI Motion Analysis System (Simi Reality Motion Systems GmbH, Unterschleissheim, Germany)



ISO quality standards: ISO 9001:2001

Anthropometric Model

- **Clauser's Model**
  - 14 rigid segments



Clauser's et al. Body Segment Parameters for 2-D Studies[1]

Segment name	Endpoints (proximal to distal)	Seg. mass /total mass (P)	Centre of mass /segment length ($R_{proximal}$)	(R_{distal})	C. of mass to ant. A/P size	Radius of gyration /segment length (K_{cg})	($K_{proximal}$)
Hand	stylion to metacarpale III	0.0065	0.1802	0.8198	0.5613	0.6019	0.6283
Forearm	radiale to stylion	0.0161	0.3896	0.6104	0.4863	0.3182	0.5030
Upper arm	acromion to radiale	0.0263	0.5130	0.4870	0.5100	0.3012	0.5949
Forearm & hand	radiale to stylion	0.0227	0.6258	0.3742	0.5240		
Upper extremity	(regression equation)[2]	0.0490	0.4126	0.5874			
Foot	heel to tip longest toe	0.0147	0.4485	0.5515		0.4265	0.6189
Foot	sphyrion to sole of foot	0.0147	0.4622	0.5378			
Leg	tibiale to sphyrion	0.0435	0.3705	0.6295	0.4247	0.3567	0.5143
Thigh	trochanter to tibiale	0.1027	0.3719	0.6281	0.5335	0.3475	0.5090
Leg & foot	tibiale to floor (sole)	0.0582	0.4747	0.5253	0.3325		
Lower extremity	trochanter to floor (sole)	0.1610	0.3821	0.6179	0.6313		
Trunk	chin-neck int. to trochanter[3]	0.5070	0.3803	0.6197		0.4297	0.5738
Head	top of head to chin-neck int.	0.0728	0.4642	0.5358		0.6330	0.7850
Head	glabella to occiput	(c. of m. to occiput/head length)			0.3996		
Trunk & head	chin-neck int. to trochanter	0.5801	0.5921	0.4079			
Total body		1.0000	0.4119	0.5881		0.7430	0.8495

Clauser, McConville, Young (1969) *Weight, volume and centre of mass of segments of the human body*, AMRL-TR-69-70, Wright-Patterson Air Force Base.
Chandler, Clauser, McConville, Young (1975) Investigation of inertial properties of the human body, AMRL-TR-74-137 Wright-Patterson Air Force Base.

Data Analysis

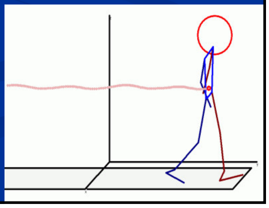
1. Registering the positions of CoG for each segment;
2. Calculating the position of BCoG for every frame;
3. Calculating the height and speed of BCoG;
4. Calculating the potential and horizontal kinetic energy of BCoG;
5. Normalization

$$h^{norm}_{BCoG} = \frac{h_{BCoG}}{L}$$

$$E^{norm}_{pot.} = \frac{mg \cdot h_{BCoG}}{m \cdot g \cdot L} = h^{norm}_{BCoG}$$

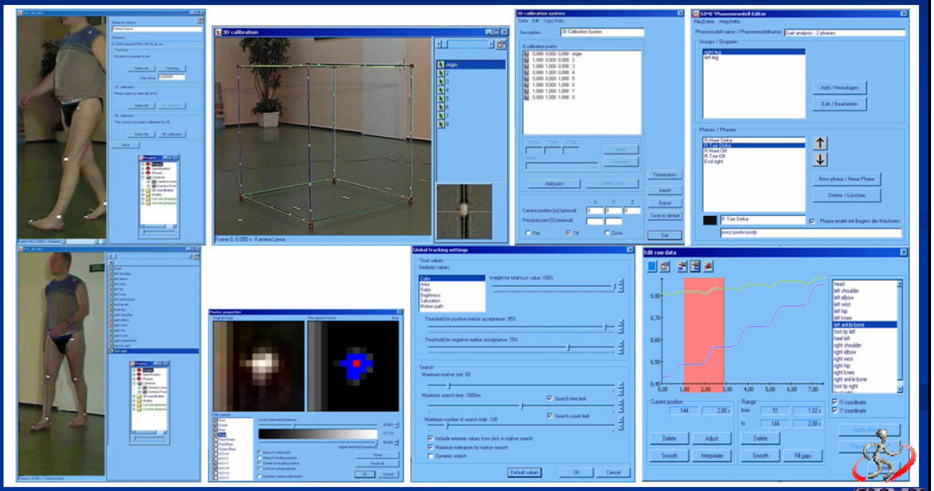
$$E^{norm}_{kinet.} = \frac{0{,}5 \cdot m \cdot \bar{v}^{2}_{BCoG}}{m \cdot g \cdot L} = \frac{\bar{v}^{2}_{BCoG}}{2gL}$$

$$E^{norm}_{total} = \frac{E_{pot.} + E_{kinet}}{m \cdot g \cdot L} = h^{norm}_{BCoG} + \frac{\bar{v}^{2}_{BCoG}}{2gL}$$



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

Data Evaluation

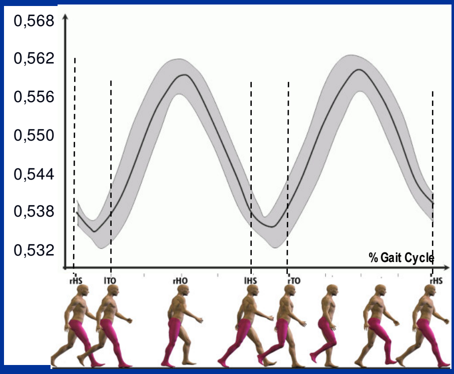


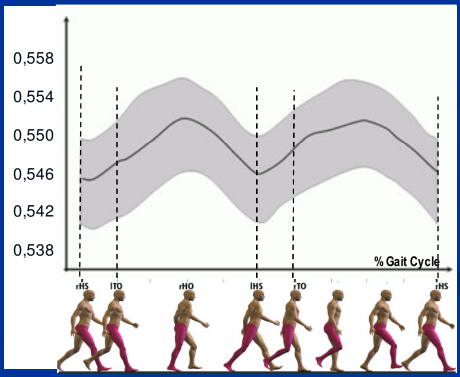
Results

- Potential energy, mean±SD, men

Normal (reference) group

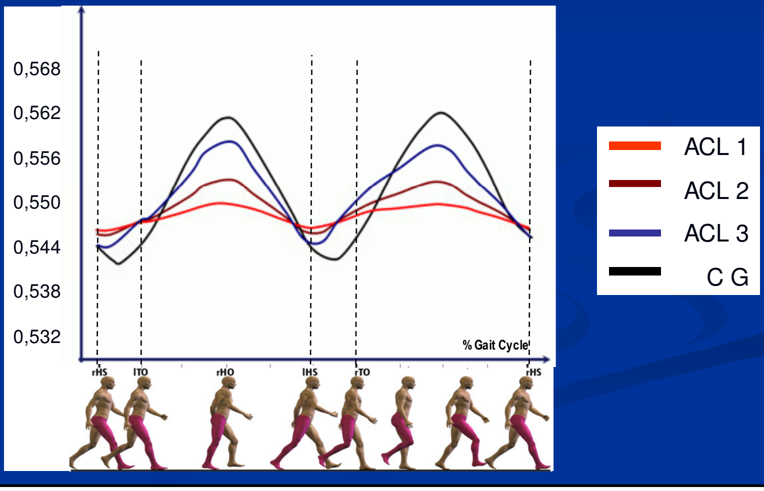
ACL-reconstructed group Stage 1





Results

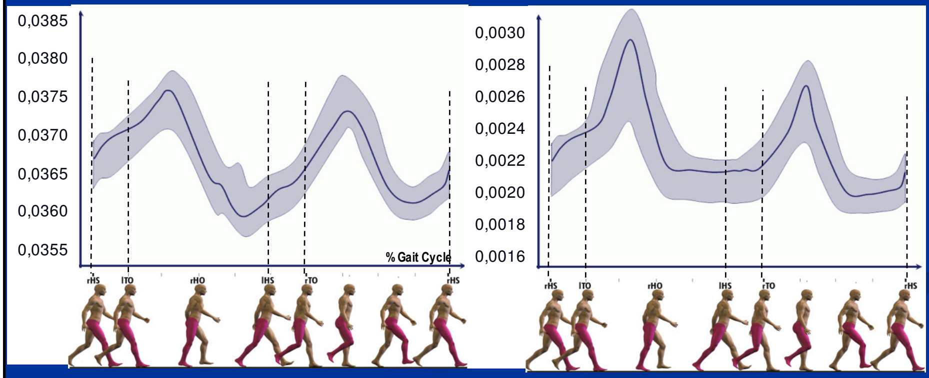
- Potential Energy in physiotherapy process



Results

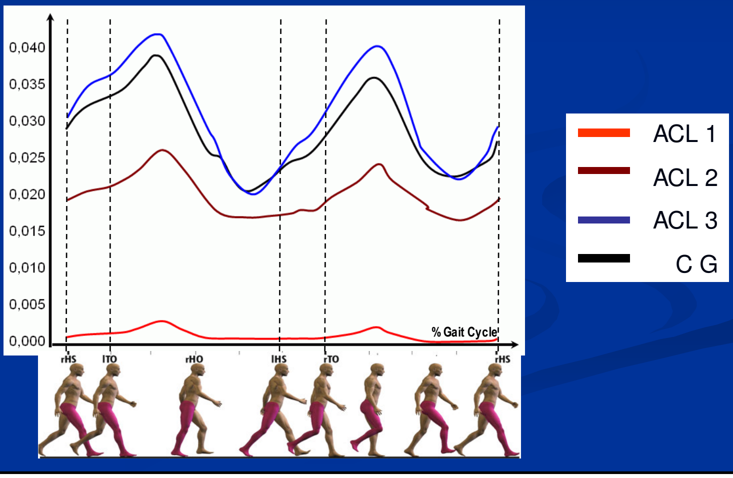
- Kinetic Energy, mean±SD, men

Normal (reference) group — ACL-reconstructed group Stage 1



Results

- Kinetic Energy in physiotherapy process



Conclusions

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