The 'use' of Energy in Sport Biomechanics

Objectives

• Quickly review some history and methods
• Review general energy equations
• Discuss their potential role for sports biomechanics
• Go through examples on equipment, sport techniques, muscle mechanics, etc.
Where do ‘we’ come from?

Sports biomechanics used to be rather descriptive
- But that was not Unexpected...
Historical perspective

Technical realisation: camera obscura
Also described and used by Aristotle, Kepler
First technical drawings by Leonardo DaVinci (1490)

Multiple exposure

Eadweard Muybridge (1830 – 1904)
Conceptual Models in Biomechanics

Partial heights model
(transferable to many movements)
(Hay, 1978)

Partial heights model: factors

Basic factors in pole vaulting
Resolve the contributors

Kinematic descriptors:
- knee angle, hip angle etc. → ?
- at key instances during execution ?
- segmental velocities (angular and translatory)
- anatomical model → implications for muscle action

Rough but easy: energies - segmental or 'just' the whole body

Energy in a purely 'physics' sense

Mechanical energy:
\[ E_{\text{kin}} = 0.5 \, m \, v^2 \]
\[ E_{\text{pot}} = m \, g \, h \]
\[ E_{\text{rot}} = 0.5 \, I \, \omega^2 \]
\[ E_{\text{el}} = 0.5 \, k \, \Delta x^2 \]

Total body energy:
\[ E_{\text{tot}} = \sum_{i=1}^{n} E_{\text{kin} \, i} + E_{\text{pot} \, i} + E_{\text{rot} \, i} ; n = \# \text{ of segments} \]
Example: Running with and without shoes

Oxygen consumption: + 4 - 5 % when running with shoes
(6 - 7 min in a marathon!)

Total work: $10^7$ J
Shoe mass: 100 g
Lifting height: 0.2 m
Maximal speed of foot during swing: 10 m/s
Step length: 2 m => 20 ksteps
  - Additional work due to gravity
  - Additional work to accelerate the shoe

Additional Energy needed

Add. Work [%] vs. Max foot speed [m/s] for different shoe masses (100g, 200g, 300g, 400g)
Application to the whole body

What do we need to know or have?

___________?
___________?

COM calculation from segment positions

\[ x_0 = \frac{\sum m_i \times x_i}{M} \]

\[ y_0 = \frac{\sum m_i \times y_i}{M} \]
**CoM velocity?**

\[
E_{\text{kin\_tot}} = \sum m_i v_i^2 + \text{potential Energy}
\]

\[
E_{\text{pot}} = \sum m_i g h_i
\]

Question: Is the total Energy equal to CoM based calculations?

**Rotational Energy contribution?**

\[
E_{\text{rot\_tot}} = \sum I_i \omega_i^2
\]

**Example**

Leg: \( m_{\text{leg}} = 0.0465 \text{ BM} \)

\( V_{\text{leg\_sprint}} = 20 \text{ m/s} \)

\( I_{\text{leg}} = 0.064 \text{ kg m}^2 \)

\( \omega_{\text{leg\_sprint}} = 500 \degree/\text{s} \)
Energy in a purely ‘physics’ sense

Mechanical energy:

Total body energy:

\[ E_{\text{tot}} = \sum_{i=1}^{n} E_{\text{kin}i} + E_{\text{pot}i} + (E_{\text{rot}i}) \quad n = \# \text{ of segments} \]

Energy of a pole vaulter

(after putting down the pole)

(Schade et al., 2000)
Application to high jump

In high jump the initial energy has to be transformed into jump energy.

There is no linear relationship between approach velocity and vertical take-off velocity. (Dapena et al., 1990)

Transformation is coupled with a decrease in total energy during the last ground contact. (Brüggemann & Arampatzis, 1991)
Purpose

• To examine the approach and take-off strategies of high jumpers at the world class level.

• To determine how to estimate the optimal take-off behavior from given initial characteristics.

Methods
Data Acquisition and Analysis

- four stationary PAL video cameras (50 Hz), two for each side, synchronised
- calibration with 2 x 2 x 3 m cube
- digitisation with Peak Motus (19 points)
- calculation of body angles, CM position, CM velocity and total energy by „fast information program“ using DLT

Digitised Frames
Calculations

\[ H = H_1 + \frac{v^2 \sin^2 \alpha}{2g} \quad (1) \]

\[ H = \frac{E_{p2}}{g} + \frac{E_{k2} \sin^2 \alpha}{2g} \quad (2) \]

where:

\[ E_{k2} = \frac{E_{\text{kin2}}}{m} ; \quad E_{p2} = \frac{E_{\text{pot2}}}{m} \]

\[ T_{in} = \frac{\alpha}{E_{\text{dec}}} \quad (3) \]

And: \( E_T = \text{total Energy} \)
The effective height ($H$) can be expressed as a function of:
initial energy, energy loss and transformation index.

$$H = \frac{E_{p2}}{g} + \frac{(E_{T1} - E_{\text{dec}} - E_{p2}) \sin^2 (T_{\text{in}} E_{\text{dec}})}{g}$$

(4)
Cluster Analysis

Parameters | Group1 (n=16) | Group2 (n=10)
--- | --- | ---
Initial energy [J/kg] | 35.15 (1.38) | 39.04 (2.06) | *
Energy decrease [J/kg] | 4.26 (0.99) | 9.23 (2.06) | *
Transformation index [°/J/kg] | 12.05 (3.34) | 5.47 (1.01) | *
Final energy [J/kg] | 30.88 (1.14) | 29.81 (0.74) |
Take-off angle [°] | 48.83 (1.99) | 48.67 (2.94) |
Two groups were identified that showed both varying initial conditions and jumping strategies.
Group1 showed a lower horizontal velocity and therefore, a lower initial energy prior to the last ground contact.

Group2 had a markedly increased initial energy and demonstrated a lower transformation index.

Formula: $T_{in} = \exp(-c \times E_{dec})$

$R^2 = 0.98$
With that:

Parameter [m/s] | Group1 (n=16) | Group2 (n=10)  
----------------|---------------|---------------
Horizontal TD velocity | 7.11 (0.29) | 7.83 (0.43) | *  
Decrease in h. velocity | 3.22 (0.30) | 4.05 (0.56) | *  
Horizontal TO velocity | 3.89 (0.27) | 3.77 (0.22) |  
Vertical TO velocity | 4.44 (0.11) | 4.29 (0.26) |
Both of the identified strategies resulted in comparable effective heights.

The faster approaching athletes could not benefit from their higher energy produced during the run-up.
• Since body orientation at touch-down shows no significant differences a possible explanation could be an different muscle stiffness.

• The influence of changes in muscle stiffness has to be further investigated.

• For both groups the optimum energy loss that leads to the maximum vertical velocity after the take-off can be estimated.
Training concepts may be developed to increase performance at both the world class level and in sub-elite jumpers.
Summary - I

Relationships between kinematic parameters and jump performance are usually not very strong. Therefore, predictions are almost impossible. Energy approach provides much simpler analysis and can be used on a daily basis (?). Muscle stiffness/joint stiffness has to be included.
Force Platforms Use

To identify the magnitude and direction of ground reaction force (i.e., force and moments applied to the platform).

Calculation of the point of force application

Vertical Jump
Predictors of Jump Height

Jump type - CMJ > SJ

Leg Strength - Moderate effect
- Explains less than 30% of variation (Dowling & Vamos, 1993)

Peak force late in movement sequence (Dowling, 1992)

Max power output in propulsion phase - strong predictor (Dowling & Vamos, 1993)
- Dependant on knee and ankle power (Arampatzis et al, 2001)

Overall goal - increased jump height (Ford et al, 2005)

Jumping

Primary muscles
- Hip (40%), knee (24.2%) and ankle (35.8%) musculature (Hedrick & Anderson, 1996)
- Activation increases stiffness - utilization of elastic energy (optimal level? Non linear relationship)

Arm Swing - increase GRF, increase muscle loading
Countermovement Jump

Four Common Theories to explain increased jump height:

• Storage and re-utilization of elastic energy (Komi, 1992)
• Increased time for force generation (Chapman & Anderson, 1990)
• Potentiation of contractile elements (through stretch)
• Spinal reflexes

Jump Performance

Common tests:
- Jump and reach
- Assumptions: ...

- Jump belt test:
  Assumptions: ...

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Determining Jump Height

- Determine flight time:
  (contact mats or foot switches, video??)

Assumptions: ...
- Error of 0.5 – 2 cm
  (Linthorne, 2001)

Countermovement jump force trace

Analysis of standing vertical jumps using a force platform
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Am J Phys 131, November 2011
Impulse-Momentum Relationship

Momentum (of a moving object):

\[ \text{Mom} = m \times v(t) \]

at any point in time \( t \)

Impulse:

\[ I = F \times t; \]

actually:

\[ I = \int F \times dt \]

Resulting vertical impulse (GRI):

\[ M \times V = v - u - w; \]

\( M = \) body mass
\( V = \) TO velocity
\( v, u, w = \) areas under force curve
In other terms

\[ BW_{\text{impulse}}: \quad BWI = t_{\text{contact}} \cdot BW \]

Total Impulse: \[ TI = \int F(t) \, dt = \sum F_i \cdot \Delta t \]

Resulting momentum:

\[ \text{Mom} = TI - BWI \]

Realisation in excel

To calculate from measured force signal:
- Acceleration of CoM
- Velocity of CoM
- Displacement of CoM

(all in vertical (z) direction; however applies for horizontal forces as well)
Viscoelasticity of tendon material

Stiffness from cadaver experiments:

\( \varepsilon_{\text{Tendon}} = 0.08 - 0.2 \) GPa

Oscillating systems
Achilles tendon anatomy

Stiffness testing

Experiment by Shorten & Kerwin (1986)

Setup:

Damped oscillation at 3 - 6 Hz
Results

EMG is constant during oscillations → activation is const.

Stiffness increases curvilinearly with increasing load

Exp. on isolated muscle show a linear increase with number of cross bridges (Λ ≈ k_s P)

→ change of the model

Mechanical muscle model

\[ K = \frac{k_T}{k_p + k_s P} \; \text{overall stiffness} \]

- \( k_t = 1091 \text{ Nm rad}^{-1} \)
- \( k_p = 14.7 \text{ Nm rad}^{-1} \)
- \( k_s = 13.5 \text{ rad}^{-1} \)

Ankle extension moment [Nm]
Angular equivalent stiffness [Nm/rad]
Summary

Sports biomechanics covers more than the mere description of movement

Energy approaches can be used to explain effects of equipment

Total body (i.e., center of mass) information is a useful performance indicator and relatively easy to access

Energy or basic mechanical principles allow to estimate internal characteristics from external measurements