ENERGY EXPENDITURE DURING RUNNING CALCULATED FROM CINEMATOGRAPHIC DATA

Manfred M. Vieten and Hartmut Riehle
University of Konstanz, Germany

INTRODUCTION

Energy expenditure is of high importance to athletes since energy delivery is one of the limiting factors for performance. Researchers have been working on the energy expenditure problem ever since the second quarter of the twentieth century. Howley and Glover (1974) and Mogan et al. (1989) calculated their results based on **oxygen intake.** The experiments are conducted in laboratories where subjects are directly connected to bulky equipment. Other groups like Cavagna et al., Winter et al., Zatsiorsky et al., (see Aleshinsky, 1986) calculated energy expenditure based on **mechanical movement.** This method of calculation can be divided into:

a) Calculation based on the change of the segments' energy. This method has a major disadvantage, in that it produces equivocal results. Energy transfer from one segment to the other has to be defined for each joint, without a commonly accepted formula.

b) Calculation based on joint power. This method is preferred because it uses one common defining equation as given in (1), and gives definite results. The absolutes of the single terms in the equation represent the joint power as produced by limb movements and muscle force.

$$P = \sum_{j,k\ =\ \text{joining segments}} \left| (\vec{\omega}_j - \vec{\omega}_k) \cdot \vec{M}_j \right| \qquad (1)$$

In this study we calculated energy expenditure based on the joint power method

METHOD

Using 3 video cameras [50 Hz PAL system], we filmed eight male sport students (23 - 29 years old, weighing 68 - 85 kg, and measuring 1.77 - 1.90 m) running at a speed of 4 - 5.2 m/s. Four of them ran also at a speed of 8 - 9 m/s. The kinematics of the movements were produced by using a Peak Performance system which digitized 18 landmarks of the human body (ears, shoulders, elbows, wrists, fingers, hips, knees, ankles, toes) manually. **As** a result we obtained three dimensional coordinates of these landmarks. The calculation of the dynamics is done by SDS, the animation/simulation software of Solid Dynamics. While Peak Performance gives only data of landmark coordinates, SDS requires data of base coordinates (the coordinates of a basic segment), the orientation of the base segment, the Euler angles of all connected segments, the appropriate velocities and accelerations, and the description of the body model. The Peak data, therefore, has to be converted into an SDS readable format so as to meet the SDS requirements. This is done by using the program TP16V. For each parameter a spline of 5th order was calculated to ensure the conformance of the coordinate/angle, velocity, and acceleration. Finally, in order to produce an animation on the screen, **38** anthropometric measurements of each student were projected onto the Hanavan model (using the program ANT). The SDS software uses the Hanavan data together with the converted Peak data to animate the running according to the movements on the video.

To facilitate the calculation of joint power (inverse dynamics) it is necessary to know the external forces acting on the runners, as shown in equation (2). These are the gravitation and the force on the foot during ground contact. The force on the foot acts on the ball of the foot that is close to the ground. While gravity is a constant easily put into SDS, the force on the foot - F_{foot} - is calculated from the kinematic data.

$$\begin{aligned}\vec{F}_{foot} &= \vec{F}_{\parallel} + \vec{F}_{\perp} - \vec{F}_{gravity} \\ &= m \cdot \vec{a}_{CoG} + \frac{\vec{M} \times r}{r^2} - m \cdot g\end{aligned} \quad (2)$$

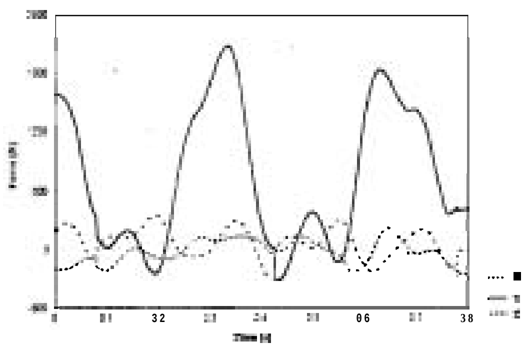

Figure 1: Force on the foot

A typical curve for this force is given in Figure 1. In addition, we note that the force on the foot is determined by the acceleration of the center of gravity (cog), the torque, and the counter force (gravity). During the flight phase the acceleration of the cog and the gravitational constant cancels each other, while the torque is zero. Therefore, the force on the foot is zero. Though valid in principle, minor errors occur due to digitizing inaccuracy and model imperfections.

RESULTS

The following graphs show the results of a participant (23 years old, weight 70 kg, height 1.77 m). His average speed during one stride cycle is (4.29±0.13) m/s.

In equation **(3)** the total energy is the sum of potential energy, translational energy

$$
\begin{aligned}
E_{tot} &= E_{pot} + E_{tra} + E_{rot} \\
&= m \cdot g \cdot h + \frac{1}{2}\sum_{i=1}^{15} m_i \cdot v_i^2 + \frac{1}{2}\sum_{i=1}^{15} \vec{\omega}_i^T I_i \vec{\omega}_i
\end{aligned}
\tag{3}
$$

of each segment, and rotational energy around each individual segment's cog. The kinetic energy is the translational energy of the cog (Figure 2). The graph in figure **3** shows power which is defined as the first derivative with respect to time, of the potential, translational, rotational, kinetic, and total energy as shown in equation **(4)**.

$$
P = m \cdot g \cdot \frac{dh}{dt} + \sum_{i=1}^{15} m_i \, \vec{v}_i \cdot \vec{a}_i + \sum_{i=1}^{15} \vec{\omega}_i^T I_i \frac{d\vec{\omega}_i}{dt}
\tag{4}
$$

The next graph (Figure 4) shows the results of the calculation of the muscle power (equation 1) compared with the results of the total power. Here, the muscle power shows two maxima, one for each support phase.

We compare the results of muscle power calculation with the "oxygen intake" results as given by Howley and Glover (1974). **An**

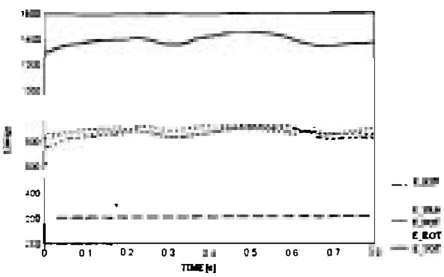

Figure 2: Energy

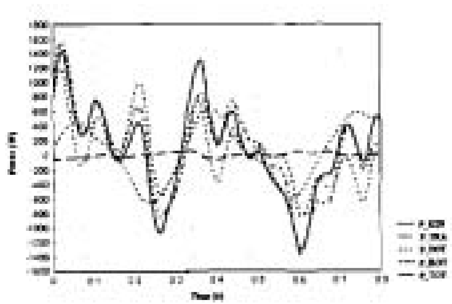

Figure 3: Power calculated from segments' energy

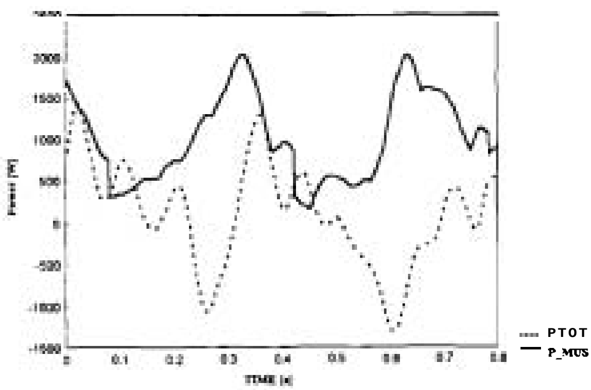

Figure 4: Muscle power versus 'power calculated from segments' energy'

average for the muscle power is calculated for a whole stride cycle and then divided by the body mass of the respective participant. It is noted that our method measures only energy expenditure of movements. However, energy consumption for internal body functions can be accounted for by adding the constant of power at a "stationary standing position". The results in figure 5 are almost identical to those of the "oxygen intake" method. Furthermore, the increase in power output for increasing running velocities is identical in both methods.

However, for high running velocities (8 - 9 m/s), measurements made by the "oxygen intake" method are invalid because the movement is anaerobic and the energy measured is **not** the energy of the movements. On the other hand, our method can measure high running velocities and as shown in figure 5, there is an exponential-like increase of muscle power.

CONCLUSION

The method of calculating energy expenditure based on joint power presents the following advantages:

1. On-the-spot measurement. Possibility of data capture without intensive preparation.
2. Subjects need not be connected to bulky equipment.
3. There is no restriction to aerobic movements.
4. Power can be given as a function of time.

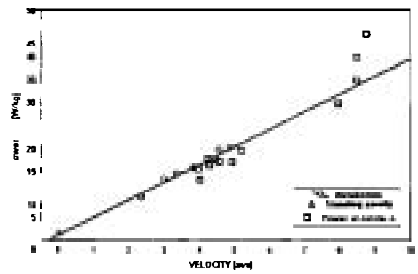

Figure 5: Power at the joints corrected to include internal energy consumption

For running, it is obvious that the drastic increase of power with increasing speed is the limiting factor for velocity. In further studies, this method can be combined with measurements of the external forces, to obtain even more accurate results. This opens the scope for research and experiments to create an optimal running style for individual athletes.

NOMENCLATURE: m = body mass, m_i = mass of a segment, g = gravitational constant, h = height of the center of gravity (cog) over the ground, v_i = segments' linear velocity, a_i = segments' linear acceleration, I_i = segments' inertia tensor, ω_i = segments' angular velocity, M = body's torque around cog

REFERENCES

Howley, E. T., and Glover, M. E. (1974): The caloric cost of running and walking one mile for men and women. ***Med Sci. Sports Exerc.**, 6:235*

Morgan, ***D. W.***, et al. (1989): Ten kilometer performance and predicted velocity at VO, max among well-trained male runners. ***Med Sci. Sports Exerc.**, 21:78*

Aleshinsky, S. ***Y.*** (1986): An energy 'sources' and 'fractions' approach to the mechanical energy expenditure problem (part 1). *J.* **Biomechanics** *19:287-293*