CALCULATION OF METABOLIC POWER IN LEVEL SURFACE RUNNING USING THE JOINT POWER METHOD

Manfred M. Vieten, Hartmut Riehle

University of Konstanz, Konstanz, Germany

INTRODUCTION

Running is essential in almost all sports. But it was not till the beginning of the century that running became a subject of academic interest. Pioneered by Fenn's *Work of Sprint Running* (1930), numerous articles have since been published concerning the work, energy, and power in running. In the last six decades, three different methods of calculation, based on kinematics, have been discussed to determine the physiological energy consumption of movements during running. In the first method, energy expenditure is calculated from the mechanical energy changes of the body segments. In the second method, it is calculated as the positive changes of external and internal mechanical energies. In the third method - considered to be the most apt - the calculation is based on joint power. Elftman (1939) and other groups used this method for planar motions study; Aleshinsky (1977, 1978) applied it in three-dimensional cases. Lately, results of full three-dimensional calculations using this method were presented by Vieten in the ISBS'95 Proceedings.

In this study we used the full three-dimensional approach to calculate the metabolic power for level surface running, to identify the joints whose muscles exert the most power, and to give a functional description of the power produced per mass, according to the running speed.

METHOD

Eleven sport students (10 male, 1 female - see general characteristics in the following table) participated in this study.

Running	Subjects	Mass [kg]	Height [m]	Age [y]
outdoor	7 male	74±6	1.81±0.05	25±2
indoor	3 male	82±6	1.83±0.01	26±3
	1 female	54.5	1.66	23

Their anthropometry (38 measurements) were recorded in order to establish a data reference (Hanavan model) for each person for use with our animation and simulation system (SDS). Seven male students in the first group ran using spike running shoes on the outdoors Tartan track. Each of them performed twice: the first run was at a speed of 7.8 - 8.9 m/s. They took off 40 m before reaching the filming area in order to attain maximum speed before the actual filming began. The second run was performed at a speed of 4 - 5 m/s. Here, they started 100 m before reaching the sector where the filming began in order to stabilize the running speed.

A second group of four students (3 male and one female) ran indoors using normal indoor running shoes. They ran twice at their personal best speeds (7.7 m/s - 8.8 m/s). The third run was done at a speed of approximately 6 m/s and the fourth run at approximately 4 m/s. For these trials they had a distance of 20 m to accelerate before the filming took place. The outdoor and indoor activities were filmed using three high-8 video cameras (PAL 50 Hz) synchronously. For the outdoor filming the cameras were mounted on tripods and rotated around the longitudinal axis in order to obtain the best focus possible. The indoor filming was done with fixed camera orientations. We did the digitizing of the videos manually using a Peak Performance system. For the outdoor group we digitized 18 points: the ears, shoulders, elbows, wrists, fingers, hips, knees, ankles, toes. For the indoor group we digitized only 16 points (excluding the fingers). We filtered the digitized raw data using a Butterworth filter with a cutoff frequency of 6 Hz. The calculation of the 3D-coordinates (Calculation method: DLT - Direct Linear Transformation) was done using a calibration cube of 2m by 2m by 1m. The average volume % error was 0.262% for outdoor running, and 0.267% for indoor running. The resultant coordinates were the input for our program **TP16V** which calculates and converts all necessary parameters (coordinates, angles, velocity, and acceleration) for use with the SDS animation and simulation program. The underlying algorithm of the SDS program, found in Walker et al. (1982), uses inverse dynamics to calculate all resulting parameters. The following additional steps were taken during the airborne phases to reduce the noisiness of the resulting parameters. During these phases the angular momentum is set at zero, the acceleration in the vertical direction is set at minus 9.81 m/s² and the two horizontal components at zero.

RESULTS

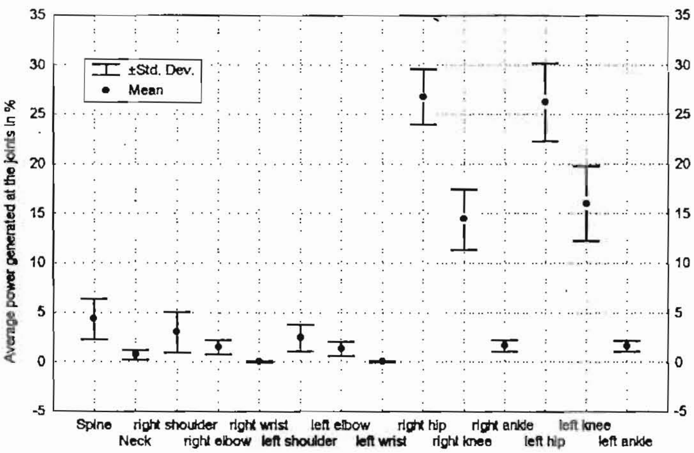

Figure 1 shows the average joint power for 14 joints as a percentage of the total power. The calculation was done for each joint by adding the percentage values of all 26 runs of the participants and dividing it by the number of runs. The average power generated in the hip and knee joints constitutes 81.5% of the total power. Since these 4 joints contribute the major power we found it worthwhile to examine their contributions as functions of time as shown in figure 2 (slow running) and figure 3 (fast running). In both cases distinguished peaks in the power curves can be seen at the last milliseconds of the support phases. However, while the slow running curves show only these support-phase peaks, the fast running curves indicate other peaks too - during the support as well as the airborne phases. Moreover, with increasing velocity, the hip power contribution of the supporting leg is tremendously increased at the touch down while during the airborne phases the four main contributing joints (hips and knees) increase their power output with almost equal weight. Figure 4 shows the net average power of

surface running. We calculated this parameter as the average power of a complete (two steps) cycle divided by the body mass. The results are classified into three categories: Male running outdoors, male running

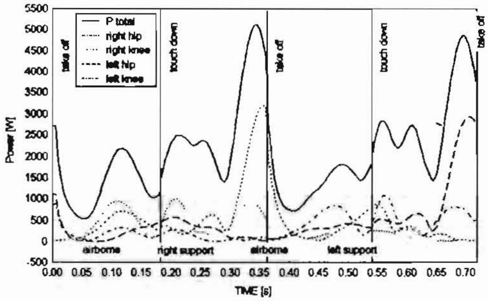

Figure 2: Slow running (male, m=68kg, <v>=4.0m/s, <P>=17.5W/kg)

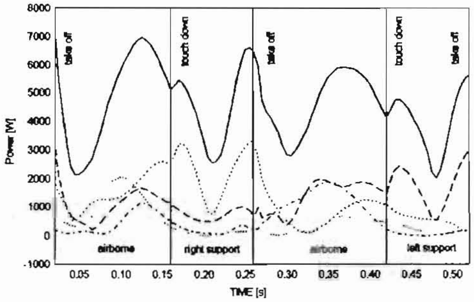

Figure 3: Fast running (male, m=68kg, <v>=8.8m/s, <P>=60.2W/kg)

indoors, and female running indoors. For all categories, in slow running - aerobic movements with velocities up to v = 5.5 m/s - we compared our results with measurements of the *Oxygen Intake Method* (Howley et al. 1974). While this method calculates the total power our method calculates the net power. In order to make the two sets of parameters comparable we subtracted a base-line value (power needed at rest) from the data of the *Oxygen Intake Method*. The numeric value is P_{rest}/m = 1.884 W/kg.

CONCLUSION

From the results it is clear that during running, the muscles of the hip and the knee joints contribute the most energy - at least 75% of the total energy needed. In slow running high energy generation occurs during the support phase, whereas in fast running high energy generation occurs during the airborne as well as the support phases.

The net energy expenditure during running shows two defined areas: aerobic running with a velocity up to 5.5 m/s and anaerobic running above 5.5 m/s. Power per mass as a function of time in aerobic running can be approximated by a linear function. Anaerobic running seems to exhibit an exponential-like behavior. In view of this, we suggest the approximating function as follows:

$$\frac{P}{m} = \begin{cases} = c_0 + c_1 \cdot v & \text{for} \quad v < v_a = 5.5\frac{m}{s} \\ = c_0 + c_1 \cdot v_a \cdot e^{a(v-v_a)} & \text{for} \quad v \geq v_a = 5.5\frac{m}{s} \end{cases}$$

The three constants (c_0 = 6.78 W/kg, c_1 = 2.72 m/s², a = 0.488 s/m) were calculated using the least square method. The value v_a = 5.5 m/s denotes the border between aerobic and anaerobic running which can vary slightly according to the (trained) individuals.

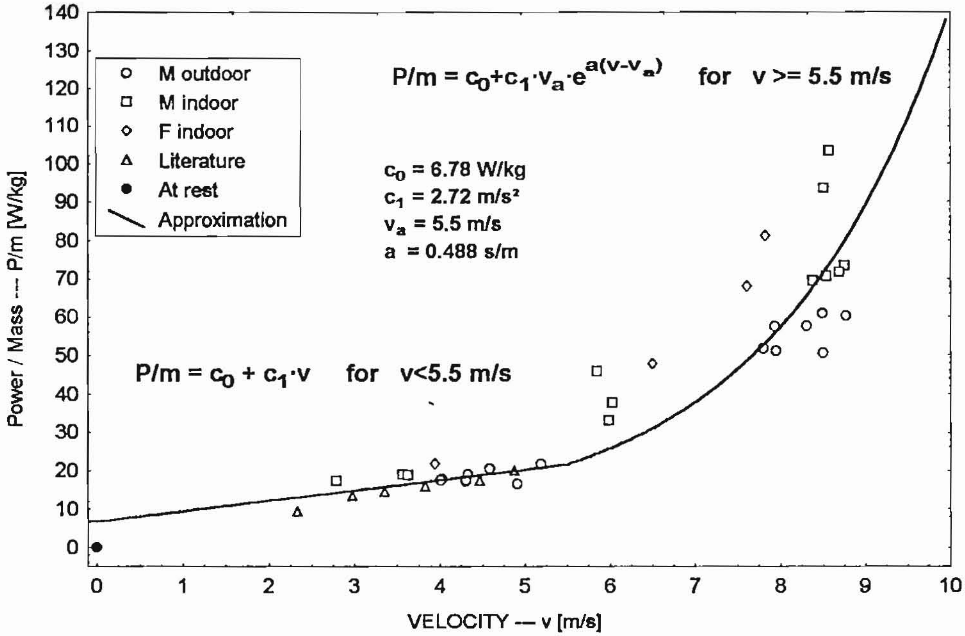

Figure 4: Net energy expenditure of distance running

Finally, it may indeed be worthwhile to investigate the reason for the extremely different functional behavior of aerobic and anaerobic running. We assume that in aerobic running, subjects running at a speed below v_a behave like resonance systems storing big fractions of the mechanical energy throughout. But anaerobic running does not seem to conform to such a mechanism. To explain this will require further studies which we plan to undertake in future projects.

REFERENCES

Aleshinsky, S. Y. (1977, 1978). see Aleshinsky, S. Y. (1986).

Aleshinsky, S. Y. (1986). An energy 'sources' and 'fractions' approach to the mechanical energy expenditure problem - I. Basic concepts, description of the model analysis of a one-link system movement. J. Biomechanics 19, 287-293

Elftman, H. (1940). The work done by muscles in running. Am. J. Physiol. 40, 149-154

Fenn, W. O. (1930). Work against gravity and work due to velocity changes in running. Am. J. Physiol. 93, 433-462

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

Vieten, M. M., Riehle, H. (1996). Energy expenditure during running calculated from cinematographic data. ISBS'95 Proceedings

Walker, M. W., Orin, D. E. (1982). Efficient dynamic computer simulation of robotic mechanisms. J. Dynamic Systems, Measurement, and Control 104, 205-211