THE INFLUENCE OF TIMING IN MOVEMENT EFFICIENCY

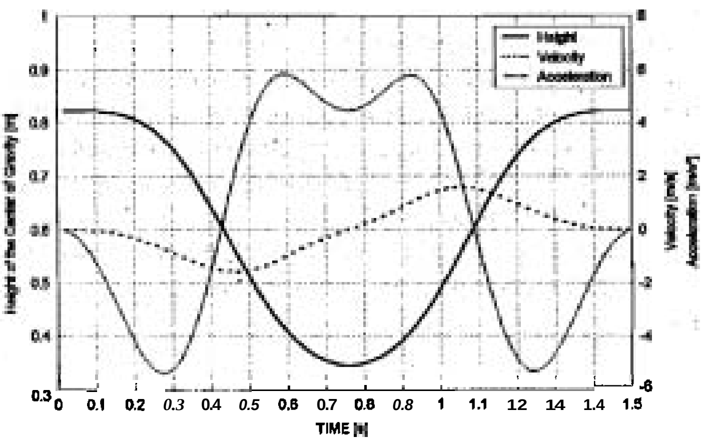
Manfred M. Vieten and Hartmut Riehle
University of Konstanz, Konstanz, Germany

INTRODUCTION

In this study we analyze the efficiency of vertical motion components and discuss timing as one of the factors influencing the energy consumption of movements. The vertical movement of the human body is visible in almost all sports. Even in the case of sports like running, cycling, and long jumping where the aim is to achieve horizontal distance, vertical motion is not only obvious but highly essential in performing the horizontal movement. The vertical component contribute to the total energy needed for the complete movement. Here efficiency is defined as the quotient of the work output divided by the energy needed to perform and is given as $\eta = \frac{W_{out}}{E_{in}}$ where W_{out} is work performed on a mass. In both of the ascending and descending motions, E_{in} is energy produced by the muscles. In classical mechanics efficiency is calculated as positive for ascent and negative for descent.

METHODS

Figure 1. Coordinate, velocity, and acceleration of the center of gravity.



A computer simulation of human motion beginning in a standing position, moving down to a squatting position and vice versa was performed. The motion was constructed symmetrically for upward and downward movements, so that a downward movement can be described as an upward movement with time reversed ($t \rightarrow -t$). The hip angle changed as $a=\delta(1-\cos(\lambda t))$. a being the hip angle; $\delta :=$ maximal hip angle in the full squatting position; $\lambda=2\pi/$(time for a full squatting movement). Therefore, the angular velocity is $\omega=\delta\sin(\lambda t)\lambda$ and the angular acceleration

$$\omega = \frac{d\omega}{\partial t} = \delta\cdot\cos(\lambda t)\lambda^2.$$

The knee angle varies accordingly to the requirement that the contact between the balls of the two feet and the floor is kept in a fixed position. Consequently, the vertical position of the center of gravity the velocity, and the acceleration (in this case, a female weighting 47kg and 1.62m tall) fluctuate as shown in the graph on the right.

In the first stage of the study we used the commercial software SDS Version 3.5 of Solid Dynamics. The human body is always approximate according to the Hanavan model. We used anthropometric data of four males and four females. Their masses vary from m=47kg (height=1.62m) to m=96kg (heigth=1.88m). We set the output energy equal to the potential energy ($W_{out} = E_{pot}$). The input energy is identical to the energy produced by the muscles ($E_{in} = E_{mus}$). Because of the symmetry of the movement, the muscular energy of the downward movement is identical to the muscular energy of the upward movement: $E_{mus}^{-} = E_{mus}^{+} = E_{mus}$

Similar simulations are also done for the following movements:

a) raising the body off the ground with one foot on a bench.

b) alternate stepping with one foot then the other, having the respective foot returning to the same position when landing.

c) lifting weights (2 kg per hand) with the arms flexed.

In the second stage of the study we obtained real movement data (for all the above movements) using 3 cameras and a 3D Peak Performance digitizing system. This data and the anthropometry of our subjects were used in an inverse dynamics analysis, using also SDS to calculate the efficiency. This data provided us with the information needed to decide which of our movements are right for optimization.

RESULTS

The following figures (2, 3, 4) show the efficiency of three different movements simulated by using 8 different anthropometric models. The simulation in figure 2 gives the efficiency for a change of the position from squatting to standing for different timings. The time scale indicates the duration needed for a whole cycle: stand - squat - stand.

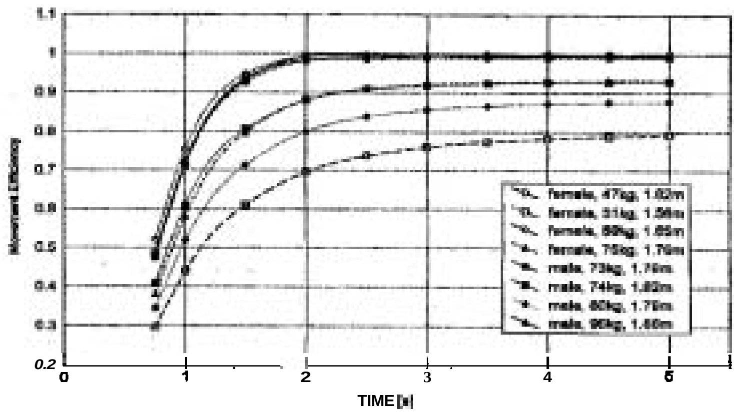


Figure 2. Movement efficiency of squatting to standing motion.

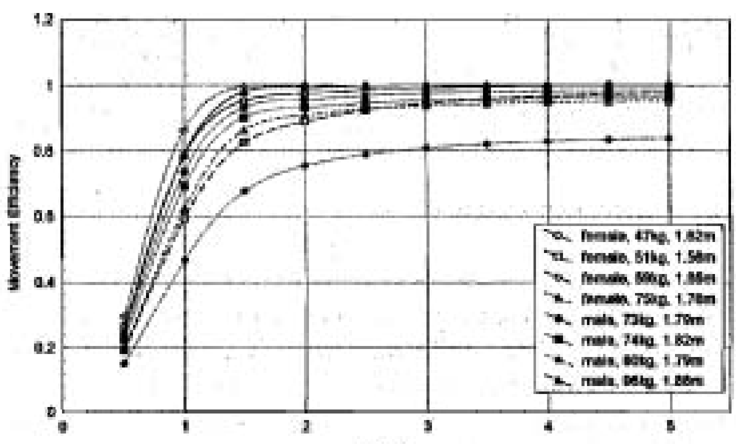


Figure 3. Efficiency of a stepping motion.

Different curve heights result because of different torques applied to the body to stabilize the movement. In some cases the lowering of the efficiency is also caused by the counter-productive work of two joints. This study does not explain the effects of the curve heights. For the purpose of this study, the significance lies in the functional behavior of the curves as well as the mechanism that causes it. For the squatting motion we find significant efficiency changes for the duration of the cycle when it is below 2 sec. The peak velocity of the center of gravity of those movements is greater than 1.5m/s, the peak acceleration is greater than $3.5 m/s^2$. For the stepping motion (figure 3) as well as for the alternate stepping (curves similar to the graph in figure 3) significant efficiency changes are found for cycles of less than 2 sec. For the weight lifting movement (figure 4) efficiency changes appear for a duration that is less than 1.2 sec.

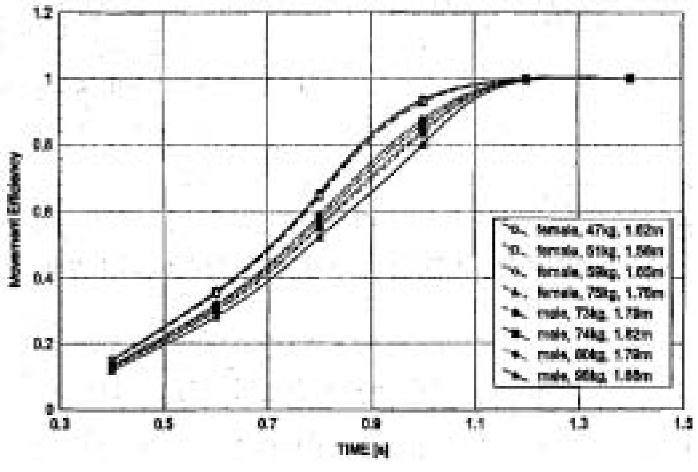


Figure 4. Efficiency of weight lifting.

The detailed analysis of the mechanism of the efficiency is most visible in the simplest of all the above movements - the lifting of weights with flexed arms. The following data was calculated for the anthropometty of the female mentioned above. The weights in each of her hands were 2 kg. Each move started in the position with arms hanging, holding the weights. The whole movement involved raising the flexed arms up to 90 degrees and back again to the starting position. In the first attempt it took 1.5 sec. In the second attempt it took 1.0 sec. The efficiency is almost equal to 1 for the first attempt and 0.92 for the second attempt. The faster the movement the lower the efficiency as indicated by $\Delta t = 0.5 \rightarrow \eta$ **= 0.24.**

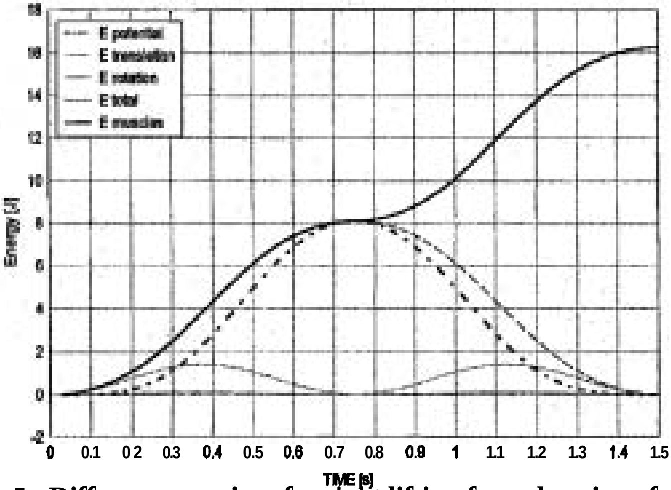


Figure 5. Different energies of weight lifting for a duration of 1.5 sec

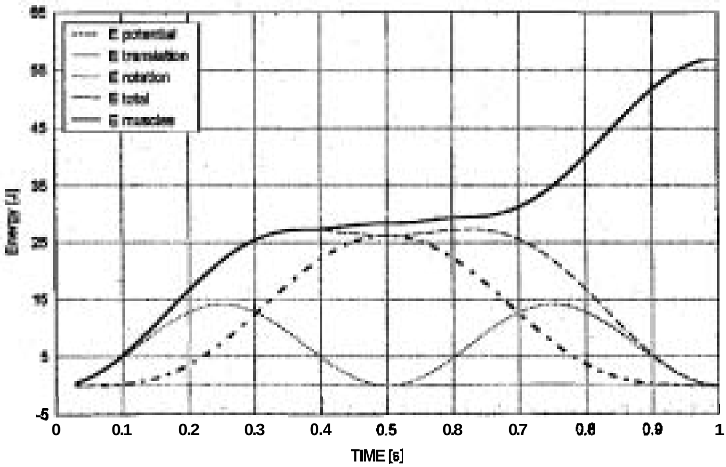


Figure 6. Different powers of weight lifting for a duration of 1.0 sec.

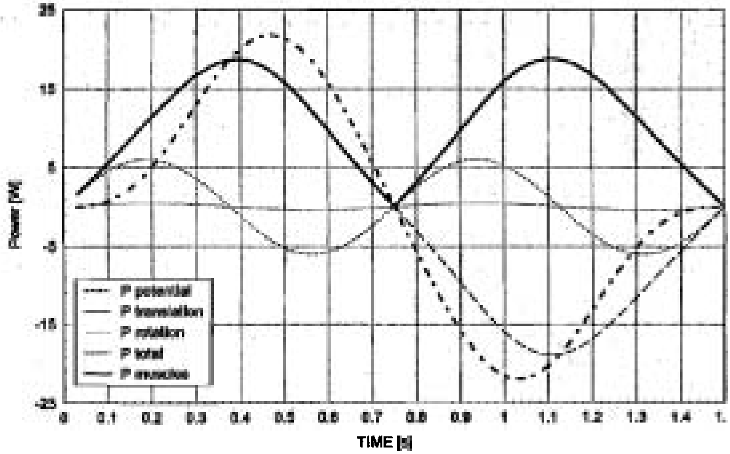


Figure 7. Different powers of weight lifting for a duration of 1.5 sec.

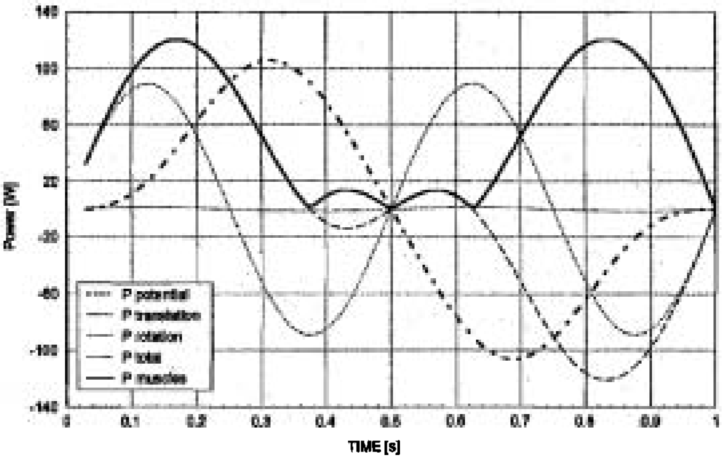


Figure 8. Different powers of weight lifting for a duration of 1.0 sec.

In figure 5 the potential energy and the muscle energy are almost identical at t=0.75 seconds. This can be explained by the following mechanism: when muscle energy is transferred to the arms, it causes the arms to move upwards. This is the translational energy in figure 5. Simultaneously potential energy rises. At t=0.75 seconds all translational energy is transferred into potential energy. Subsequently, gravitation stops the movement. This can also be explained in terms of power (see figure 7). Here muscle power and total power of the body are identical during the first half of the motion. During the second half, total power is of the same magnitude, but negative. Translational power and muscle power causes the transfer of the energies into potential power (For the equations see the NOMENCLATURE at the end of this paper).

For the faster movement the mechanism of generating potential energy is identical at the beginning. Before reaching the halfway point of the cycle, de-acceleration sets in due to gravity, but this is not sufficient to stop. the motion. Therefore, there has to be an additional muscle contraction acting in the downward direction to stop the movement. This stopping action causes the additional muscle energy as seen in figure ***6,*** and which is also visible in the power balance of figure 8.

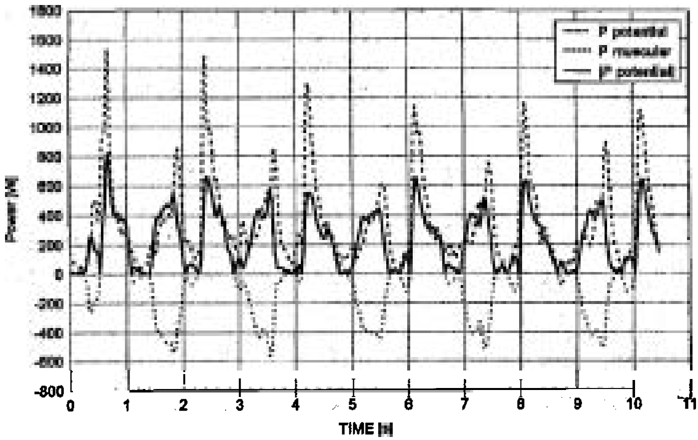


Figure 9. Power of a repeated bench stepping

Out of the four movements of our experimental analysis, bench stepping is the only motion dynamic enough for such anoptimization through changes in the timing. Figure 9 shows the power of a stepping series of 5 repetitions in a little less than 10 sec. The higher peaks of the muscle power occur for upward movements. The lower peaks indicate the downward movements. The decrease of power in the peaks in connection with the stepping down motion is basically due to the non-elastic absorption of energy by the floor (thick gymnastic mats) and the shoes. The high peaks of the stepping up motion is caused by the overshooting of the motion, which results in low efficiency (figure 10). Different timings of the motion can lead to a substantial decrease in the energy consumption equivalent to the increase of the efficiency (figure 10).

CONCLUSIONS

The above described mechanism causes the change of efficiency based on the timing. Unlike our simulated movements, real motion can be non-symmetrically arranged. This helps to make movements more efficient. Out of the four movements, bench stepping is most suitable for this particular case of optimization. For a more accurate analysis it will be necessary to get more data per time interval. This could be established by using a high speed video system. Another suitable movement application is running - a dynamic movement with numerous repetitions. The optimization of efficiency helps to reduce energy consumption of the vertical motion. This subsequently provides more energy needed for the horizontal motion and thus improving theperformance. Such effects seem unimportant for a single movement, but with thousands of repetitions in a cyclic motion, the minute energy conservation adds up to a substantial amount and consequently influences the performance.

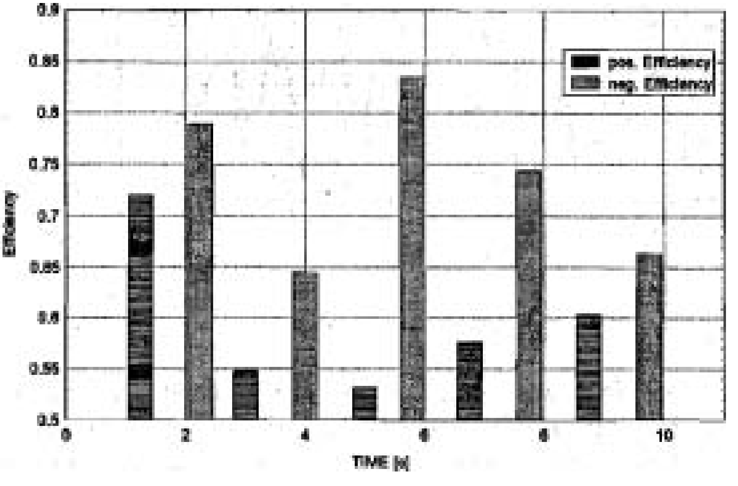


Figure 10. Efficiency of a repeated bench stepping

NOMENCLATURE

We used the 15 segment Hanavan model to do our simulations. In this model the energies and powers are defined as follows:

Form of	Energy	Power
Potential	$E_{pot} = mgh$	$P_{pot} = mg\frac{\partial h}{\partial t}$
Translational	$E_{tra} = \frac{1}{2}\sum_{i=1}^{15} m_i v_i^2$	$P_{tra} = \sum_{i=1}^{15} m_i \vec{v}_i \cdot \vec{a}_i$
Rotational	$E_{rot} = \frac{1}{2}\sum_{i=1}^{15} \vec{\omega}_i^T I_i \vec{\omega}_i$	$P_{rot} = \sum_{i=1}^{15} \vec{\omega}_i^T I_i \frac{\partial \vec{\omega}_i}{\partial t}$
Total	$E_{tot} = E_{pot} + E_{tra} + E_{rot}$	$P_{tot} = P_{pot} + P_{tra} + P_{rot}$
Muscular	$E_{mus} = \int_0^T dt \cdot P_{mus} = \int_0^T dt \sum_{j=1}^{14} \lvert \Delta\vec{\omega}_j \cdot \vec{T}_j \rvert$	$P_{mus} = \sum_{j=1}^{14} \lvert \Delta\vec{\omega}_j \cdot \vec{T}_j \rvert$

m: mass of the whole model; $g = 9.81 \frac{m}{s^2}$: gravitational acceleration; h: relative height of the center of gravity; m_i: mass of the segment i; v_i: linear velocity of the segment i; a_i: linear acceleration of the segment i; ω_i: angular velocity of the segment i; $\Delta\omega_j$: relative velocity at joint j; T_j: torque at the joint j.

For details on the equations see Aleshinsky (1986).

REFERENCES

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