

MECHANICAL EFFICIENCY AS AN INDEX OF SKILL IN SPORTS

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Kinesiologists as well as physiologists have been aware of the existence of optimal energy cost during various sports activity, daily behavior, basic movement patterns and so on. Although research has explored this issue from a biomechanical approach, no published research has involved a quantitative approach of mechanical efficiency, that is, skill to optimization problem. On the other hand, in order to facilitate the understanding of movement of humans and other living things, a number of equipments and techniques have been devised to record and measure movement with respect to efficiency involved in various movement patterns. Most researches in many sports include informations concerning the analysis of the effectiveness (degree of success or level of skill) and safety aspects of movement of human being. But little is written concerning efficiency, that is, mechanical efficiency, as it relates to sports. The purpose of this study was to present mechanical efficiency research of skill in sports pertaining to methods by which mechanical efficiency can be determine. Mechanical efficiency may be considered as one of the effective and significant parameters in quantitative analysis of skill in sports. And also generally a skilled athlete will normally have a high mechanical efficiency. Data concerning mechanical efficiency of persons performing various ways in which the knowledge of training and conditioning and exercise physiology are integrated into the coaching of sports through mechanical efficiency concept. The application of this concept to the quantitative analysis of movement patterns will be shown. Mechanical efficiency analysis of skilled and unskilled performance techniques in various sports activities will be summarized to facilitate the understanding of how the concept of mechanical efficiency as an index of skill can be applied to improving athletic skills.

The human body has been studied as a "Living Machinery" analogous to the internal combustion engine. Work, power and efficiency are of paramount consideration. A.V. Hill introduced the concept of mechanical efficiency in 1927, a concept of interest to several fields of study such as physics, chemistry, anatomy, physiology and biomechanics. Animal and human movement, self powered and otherwise, are also a matter of great interest. For example, a man on a bicycle uses energy most efficiency as shown in Fig.1.

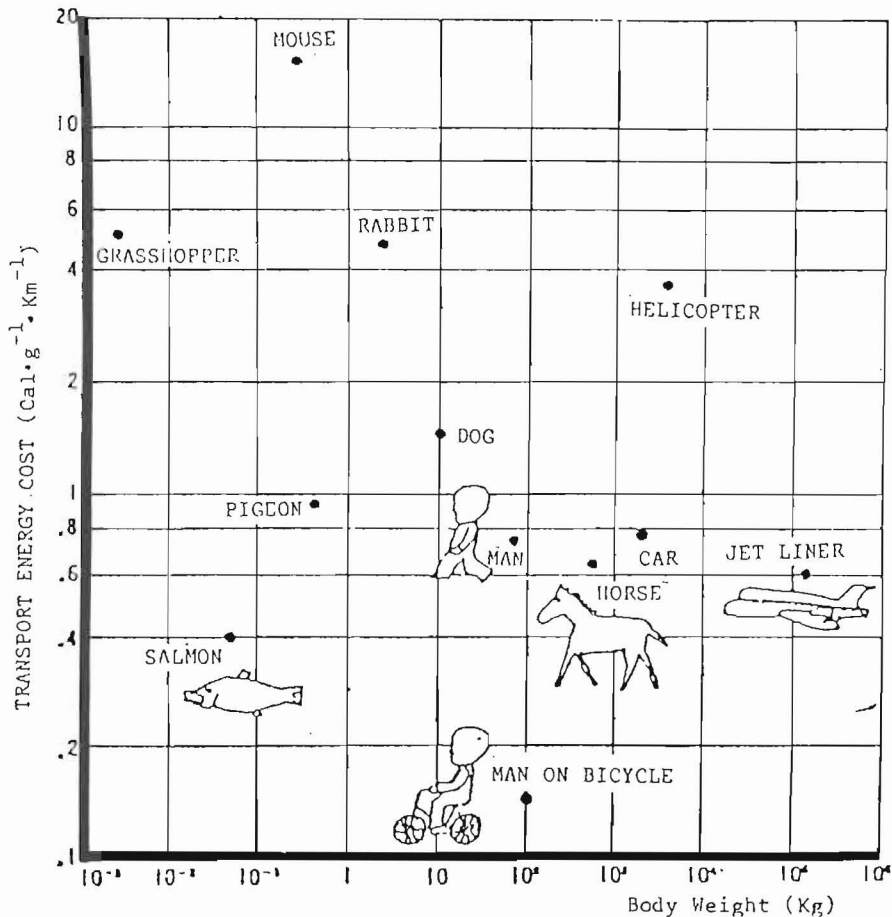


Fig.1 Man on bicycle uses the energy most efficiently in all transport patterns.(Cited from the data of Duke Univ.)

Hill states in his book "Living Machinery", "The efficiency of a muscle, measured by the ratio of the mechanical work which it can do to the energy of the fuel (foodstuffs) with which it is provided, may be 25 per cent or more, if it be properly loaded and allowed to work at a suitable speed, which compares quite well with the best machines of human manufactures." With respect to the mechanical efficiency of the internal combustion engine, a steam engine, for example, may work at 9 to 19 per cent, a gasoline engine 14 to 28 per cent and a diesel engine 29 to 35 per cent. The electric locomotives may run at about 70 to 90 per cent efficiency but steam locomotives 3 to 6 per cent or less. In comparison with the mechanical efficiency of machines, the mechanical efficiency of human beings varies as follows: walking (23 to 34 per cent), running (23 to 45 per cent), cycling (16 to 25 per cent)

and swimming (1 to 7 per cent). Mechanical efficiency of movement is a topic to be in Sports Biomechanics for 2 reasons: 1) integrate biomechanical and physiological concepts of work and energy and 2) investigate effects of prolonged movement performance from a biomechanical perspective. Theory and application of mechanical efficiency should be included as the two subtopics for Sports Biomechanics.

I. THEORY OF MECHANICAL EFFICIENCY

Generally speaking, efficiency is a ratio of work done to amount of energy used.

2. Calculation

All efficiency calculations involved some measure of mechanical output divided by a measure of metabolic input (Winter, 1979). Mechanical efficiency is calculated from the following formula by Gaesser and Brooks (1975) and Lloyd and Zacks (1972).

$$a). \text{ Gross efficiency} = \frac{\text{work accomplished}}{\text{energy expended}} = \frac{W}{E} \times 100 (\%)$$

$$b). \text{ Net efficiency} = \frac{\text{work accomplished}}{\text{energy expended above that at rest}} = \frac{W}{E-e} \times 100 (\%)$$

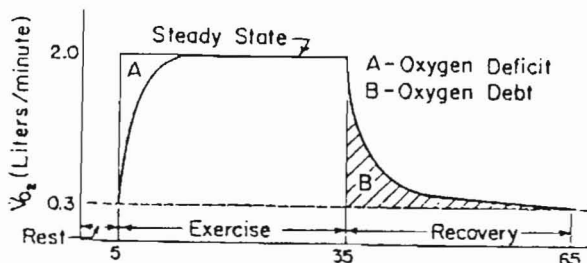


Figure 2. Determination of Net Energy cost of exercise based on oxygen consumption Mathews & Fox, 1971).

II. APPLICATION OF MECHANICAL EFFICIENCY

The basic concept of mechanical efficiency, as defined above, combined data from persons performing various exercise and sports activities will provide application to training and conditioning, motor learning and teaching. Samples of lecture/lab. material on the application to training and skill will be given.

The subject participated in 5-minutes of constant-load exercise performed on a Monark bicycle ergometer (900 kgm/min) five days a week for nine consecutive weeks. During this period, there was about 5 percent increase in mechanical efficiency (Fig.3) . Furthermore there was no decrease in mechanical efficiency after a detraining period of 79 days. On the other hand, the electromyograms of the upper limb decreased remarkably in voltage as a result of training (Fig.4) . Considering this improvement in mechanical efficiency as evidenced by the electromyograms, it is concluded that repetition of a given exercise, namely training, creates more concentrated activity within the prime muscles employed in the performance of the exercise and inhibits the activities of the muscles of lesser importance. In other words, the subject had to use the muscles of the upper limb as well as the lower limb in the pedaling motion at the beginning of the training but gradually the lower limb had the exclusive role in pedaling without the use of the upper limb as a result of training. It is suggested that the decrease in the energy used to perform the standard ergometer exercise was the function of improved technique.

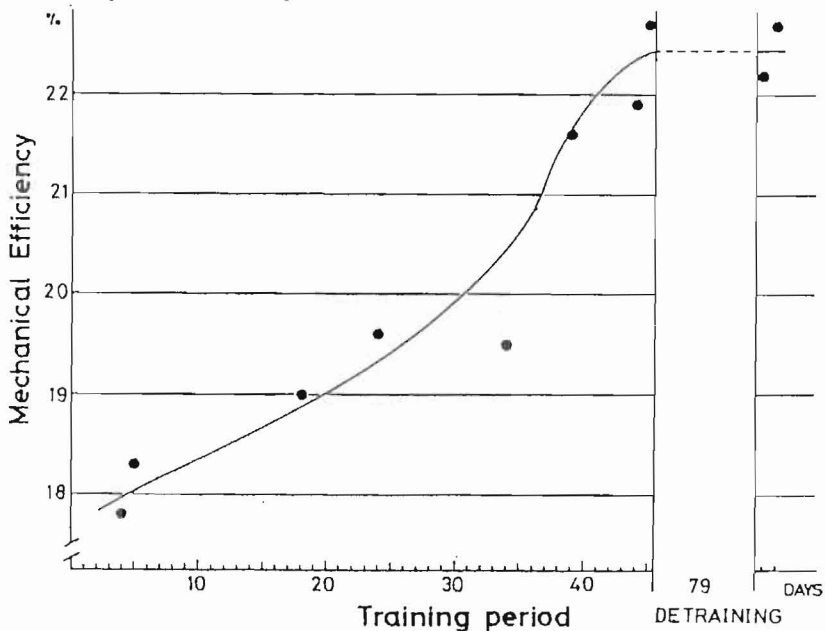


Fig. 3. Changes in mechanical efficiency during training and after detraining

— Laboratory Experiment —

- i). Repeat this experiment using heart rate in lieu of oxygen data.
- ii). Monitor EMG, heart rate and work load before and after training.
- iii). Plot mechanical efficiency using heart rate on ordinate work on abscissa.
- iv). Draw conclusions concerning mechanical efficiency from plotted curve and EMG patterns.

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2. Mechanical Efficiency in Sports Skill ; Mechanical Efficiency versus Skill

Mechanical efficiency may be considered as one of the effective and significant parameters in quantitative analysis of skill according to Åstrand (1970). Winter (1979) pointed out theoretically, in say that a skilled athlete will normally have a high mechanical efficiency.

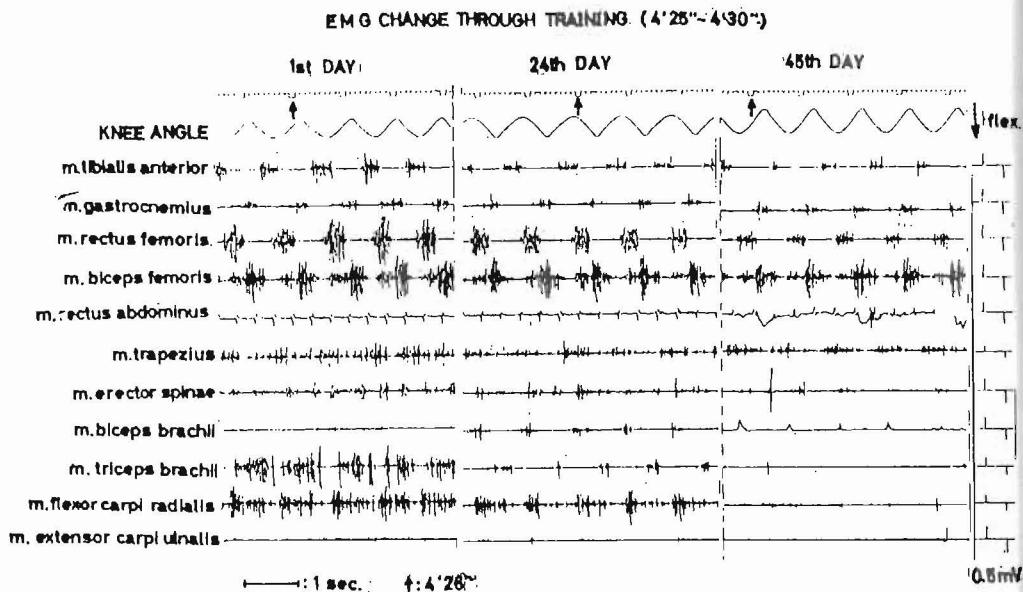


Fig. 4. EMG changes just before the end of work through training

a). The Mechanical Efficiency of Shomen Suburi in Kendo.

Mechanical efficiency of shomensuburi (swing the Kendo stick e.g. SHINAI in A-P plane) performed by 3 male Kendo athletes was determined with a 16-min suburi ergometer exercise test. The subjects performed shomen suburi 30 swings per min according to a metronome. External work-loads were incremented every four minutes (average increments were 11.6 N, 18.1 N and 24.5 N). These increments represented mild, moderate and heavy energy

expenditures. Expired gas was collected using the Douglas bag method and gas samples were analyzed using the Scholander technique during the last minute of each work-load level increment. The external work rate and corresponding steady state energy cost were determined for each subject of shomen suburi exercise. For each subject, the $\dot{V}O_2$ for each work-load was determined and power was calculated. The energy cost with respect to power was plotted. Mechanical efficiency was calculated as the inverse of the power-energy slope. Changes in gross efficiency and work efficiency at different work rates (power) were calculated with the formula of Gaesser et al.(1975). The results indicated that efficiencies of the suburi ergometer exercise performances were 9.3-13.7%. These values are higher than those of swimming, lower than those of simple joint exercise such as knee-bending, cranking and rowing exercise previously obtained by others. As for mechanical efficiency of swimming exercise, this study represents the first investigation of its kind. Furthermore it presents a unique ergometer useful for determining efficiency of other swinging type movements. Moreover, the excellent Kendo athlete, subject M.F., had the highest mechanical efficiency of 13.7%.

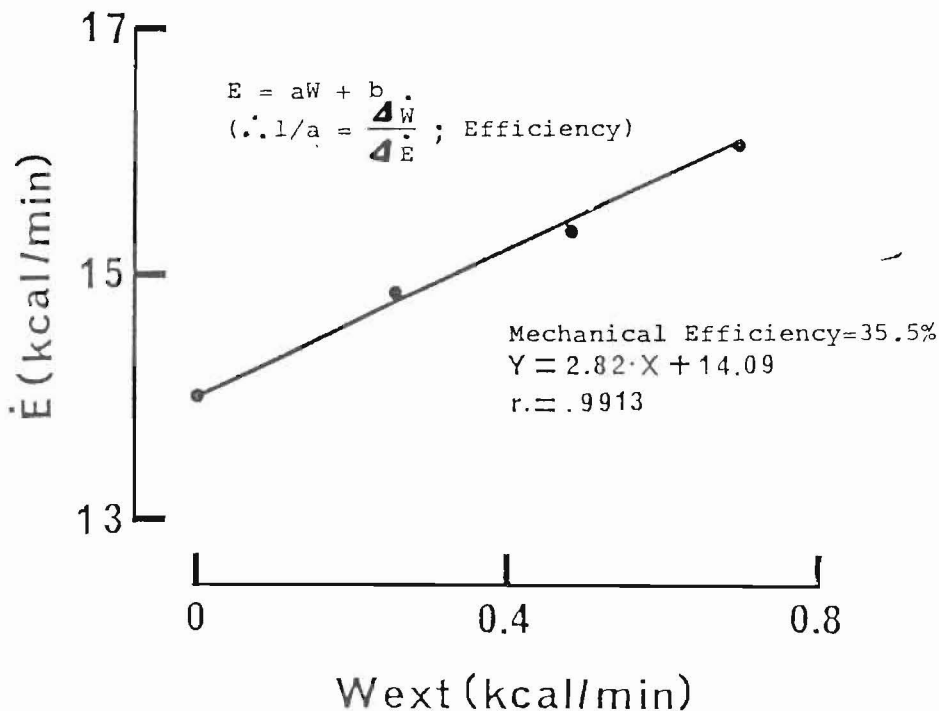


Figure 5. The relationship between metabolic rate and external work rate.

— Laboratory Experiment —

- i). Repeat the protocol collecting heart rate data in lieu of oxygen data with chopping wood, pulley weight or latissimus dorsi pulls on universal gym.

- ii). Calculate work done on these activities.
- iii). Video tape or observe movement during each load level.
- iv). Plot efficiency using heart rate in lieu of energy cost.
- v). Interpret data using the movement patterns and anatomical characteristics.

b). The Mechanical Efficiency of Overarm Throw in Handball.

In order to investigate the mechanical efficiency of the overarm throw in handball, eight male students performed 15 European handball throws per min on a 6-min test. Tests were performed at ball velocities of 40, 50, 60, 70, 80 and/or 100 percent of maximal ball velocity of each subject. Ball velocity was measured using CdS photocell system and the external work was calculated. Expired gas was collected using the Douglas bag method and gas samples were analyzed using the Scholander technique. The mechanical efficiency was calculated with the formula of Gaesser et al. (1975). The mechanical efficiency of all subjects showed a convex quadratic curve (Fig.6). The highest mean values of mechanical efficiency were 3.9% for the skilled subjects and 3.3% for the unskilled subjects. The difference between these two groups was found to be significant at 0.05 level. Furthermore, The highest skilled subject S.S. showed the highest mechanical efficiency. This occurred at 73 percent of his maximal ball velocity and was 4.2%.

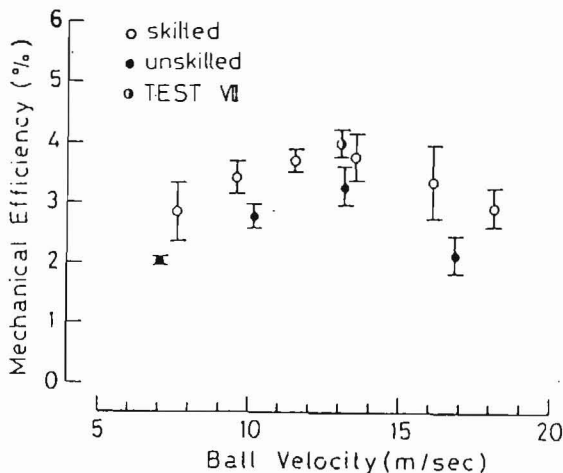
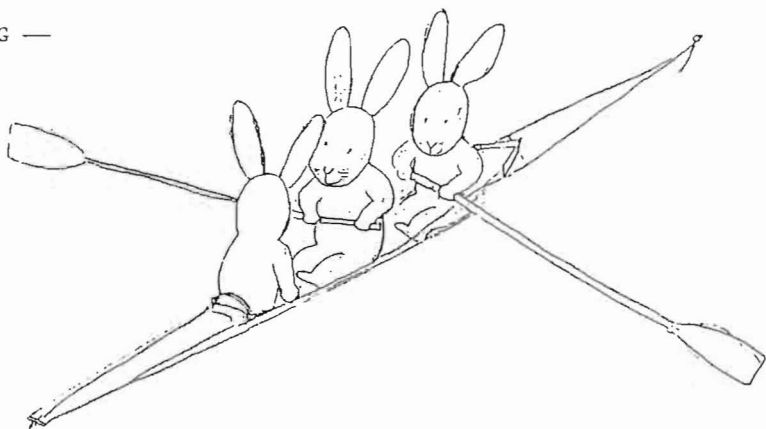


Figure 6. Relationship between ball velocity and mechanical efficiency for skilled and unskilled subjects in European Handball throwing movement

— Laboratory Experiment —

- i). Ask athletes to throw balls of their choice using the protocol of the research described above.
- ii). Observe (use videotape) movement patterns and measure ball velocities.
- iii). Calculate work done ($\text{work} = \frac{1}{2} mv^2$ of ball) and use heart rate in lieu of oxygen consumption.
- iv). Plot mechanical efficiency and interpret data with respect to changes in movement patterns and anatomical characteristics.

— ROWING —



Mechanical Efficiency for

UNSKILLED (N=24)	10%
SKILLED (N=4)	12%

(* P < 0.05)

— BASKETBALL —



Mechanical Efficiency for

UNSKILLED (N=4)	10%
SKILLED (N=5)	15%

(* P < 0.05)

CONCLUSION

When trained or practiced individuals are engaged in physical exercise, they naturally accomplish more work with less apparent exertion and less subjective distress. Therefore, in this paper, it is suggested that the concepts of mechanical efficiency might be presented as one unit in quantitative analysis of skill, i.e., an index of skill in Sports, with respect to training and learning. Experimental studies of mechanical efficiency were described and laboratory experiments presented to allow coaches and athletes an understanding of the economical relationship between input and output energy and movement of the human body in Sports.

REFERENCES

- Åstrand, P.-O., and Rodahl, K., Textbook of work physiology, McGraw-Hill Book Company : New York, 1970.
- Gaesser, G.A., and Brooks, G.A., "Muscular efficiency during steady state exercise : effects of speed and work rate", J.Appl.Physiol., 38 : 1132-1139, 1975.
- Hill, A.V., Living machinery, Harcourt, Brace and Company : New York, 1927.
- Karpovich, P.V., and Sinning, W.E., Physiology of muscular activity, W.B. Saunders Company : Philadelphia, 1971.
- Lloyd, B.B., and R.M. Zacks, 1972. The mechanical efficiency of treadmill running against a horizontal impeding force. Journal of Physiology 223, 353-363.
- Mathews, D.K., and Fox, E.L., The physiological basis of physical education and athletics, W.B. Saunders Company : Philadelphia, 1971.
- Yamamoto, H., "Effects of training on the mechanical efficiency in bicycle ergometer exercise," Master's Thesis, University of Tokyo, 1975.
- Winter, D.A., Biomechanics of human movement, John Wiley and Sons Inc. : New York, 1979.

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