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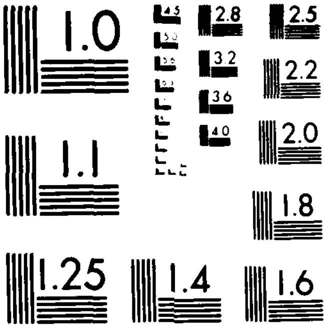

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Predicting metabolic cost of running with and without backpack loads

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Running head: Metabolic cost of running

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In the past, a mathematical equation to predict the metabolic cost of standing or walking (M_w) was developed. However, this equation was limited to speeds $<2.2\ m \cdot s^{-1}$ and overestimated the metabolic cost of walking or running at higher speeds. The purpose of this study was, therefore, to develop a mathematical model for the metabolic cost of running (M_r), in order to be able to predict the metabolic cost under a wide range of speeds, external loads and grades. Twelve male subjects were tested on a level treadmill under different combinations of speed and external load. Speed varied between 2.2 to 3.2 $m \cdot s^{-1}$ using 0.2 $m \cdot s^{-1}$ intervals and external loads between 0-30 kg with 10 kg intervals. Four of the subjects were also tested at 2 and 4% incline while speed and load remained constant (2.4 $m \cdot s^{-1}$, 20 kg). The model developed is based on M_w and proportionately linear with external load (L) carried as follows:

$$M_r = M_w - 0.5\ (1-0.01L)\ (M_w-15L-850), \qquad \text{(watt)}$$

The correlation coefficient between predicted and observed values was 0.99 ($P<0.01$) with

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SER of 7.7%. The accuracy of the model was validated by its ability to predict the metabolic cost of running under different conditions extracted from the literature. A highly significant correlation (r=0.95, P<0.02, SER=6.5%) was found between our predicted and the reported values. In conclusion, the new equation permits accurate calculation of energy cost of running under a large range of speeds, external loads and inclines.

SUMMARY

In the past, a mathematical equation to predict the metabolic cost of standing or walking (M_w^n) (has been developed. It is, however,) ~~was developed. However, this equation was~~ limited to speeds < 2.2 $m \cdot s^{-1}$ and overestimated the metabolic cost of walking or running at higher speeds. This study's purpose was ~~The purpose of this study was, therefore,~~ to develop a mathematical model for the metabolic cost of running (M_r^n) in order ~~to be~~ able to predict the metabolic cost under a wide range of speeds, external loads and grades. Twelve male subjects were tested on a level treadmill under different combinations of speed and external load. Speed varied between 2.2 to 3.2 $m \cdot s^{-1}$ using 0.2 $m \cdot s^{-1}$ intervals and external loads between 0-30 kg with 10 kg intervals. Four of the subjects were also tested at 2 and 4% incline while speed and load remained constant (2.4 $m \cdot s^{-1}$, 20 kg). The model developed is based on M_w^n and is proportionately linear with external load (L) carried as follows:

$$M_r^n = M_w^n - 0.5\,(1-0.01L)\,(M_w^n-15L-850) \qquad \text{(watt)}$$

(in watts).

The correlation coefficient between predicted and observed values was 0.99 ($P<0.01$) with SER of 7.7%. The accuracy of the model was validated by its ability to predict the metabolic cost of running under different conditions extracted from the literature. A highly significant correlation ($r = 0.95$, $P<0.02$, SER = 6.5%) was found between our predicted and the reported values. In conclusion, the new equation permits accurate calculation of energy cost of running under a large range of speeds, external loads and inclines.

Key Words: metabolic cost, running, work efficiency, load carriage, backpack load, prediction model

Over the last two decades, the Military Ergonomics Division of the U.S. Army Research Institute of Environmental Medicine has been establishing the data base and developing a series of predictive equations for physiological responses of clothed soldiers performing physical work in various environmental extremes (Pandolf et al. 1986). Individual predictive equations for rectal temperature, heart rate and sweat loss as a function of the physical work intensity, environmental conditions and particular clothing ensemble have been published (Givoni and Goldman 1972; Givoni and Goldman 1973; Shapiro et al. 1982). These prediction equations incorporated a metabolic component which in itself can be predicted by the following equation as originally published by Pandolf et al. (1977):

$$M_w = 1.5W + 2.0\,(W+L)\,(L/W)^2 + \eta(W+L)\,(1.5V^2 + 0.35\,GV), \qquad \text{(watt)}$$

where M_w = metabolic rate (watt), W = nude body weight (kg), L = clothing and equipment weight (kg), η = terrain factor, V = walking velocity ($m \cdot s^{-1}$), G = grade (%). This prediction model of metabolic cost is limited, however, to standing or walking with and without loads, on level or graded terrains, but is not applicable for walking speeds above ~2.2 $m \cdot s^{-1}$ or running. At higher speeds, the efficiency of running becomes higher than that of walking, which means that the prediction model of walking overestimates the actual energy cost of running (Ogasawara 1934; Margaria et al. 1963; Keren et al. 1981).

In the past, Givoni and Goldman (1971) suggested that the metabolic cost of running (M_r) could be expressed as a linear function of the predicted metabolic cost of walking (M_w) as follows (units were given, originally, in $Kcal \cdot h^{-1}$):

$$M_r = [M_w + 0.47\,(900 - M_w)]\,(1 + G/100), \qquad (kcal \cdot h^{-1})$$

According to this model, the crossover point for efficiency between walking and running is constant (900 $Kcal \cdot h^{-1}$; 1050W). This prediction model was challenged by some investigators as overestimating the actual values, probably due to the use of too high a crossover point for efficiency (Falls and Humphrey 1976). Furthermore, the correlation coefficient between observed and predicted values of energy cost reported by Givoni and Goldman themselves was only 0.86. This value, while indicating a good linear relation between the predicted and actual values, leaves 26% of the variance unexplained by this equation. This high level of unaccountable variance is too great to be acceptable when a mathematical model is adopted to describe this type of relationship.

The purpose of this study was, therefore, to develop a mathematical prediction equation for the metabolic cost of running. The intended use of this equation is to extend the existing prediction equation used for walking, in order to be able to predict the metabolic cost under a wide range of running speeds, loads and grades.

MATERIALS AND METHODS

Subjects. Twelve young fit males gave their informed consent to participate in the study. The subjects had an average (mean ± SEM) age of 20.6 ± 0.6 yr; weight, 68.7 ± 1.6 kg; height, 172.4 ± 2.1 cm; and body fat, 13.1 ± 1.5%, determined by underwater weighing according to Goldman and Buskirk (1961). Their mean maximal oxygen uptake ($\dot{V}O_2$ max) determined for an uphill treadmill running, measured according to the method of Taylor et al. (1955) was 3.88 ± 0.09 $\ell \cdot min^{-1}$ (56.8 ± 1.6 and $ml \cdot kg^{-1} \cdot min^{-1}$).

Protocol. Eighteen combinations of load and speed (Table 1) were presented to each subject in a randomized order. Before experiments all subjects were familiarized with treadmill running with and without loads. While running without loads, the subjects wore shorts and running shoes which weighed ~0.5 kg. Loads consisted of the subjects' clothing and boots (3.2 ± 0.1 kg) and a backpack adjusted to give a total load of 10, 20, and 30 kg. Lead bars were used for the external load. They were secured to an army aluminum backpack frame, which was well fitted to the subjects. Running speed ranged from 2.2-3.2 $m \cdot s^{-1}$ employing increments of 0.2 $m \cdot s^{-1}$. Each experiment was 10 min in duration at 0% grade on a treadmill in an ambient climate of 22-25°C and 30-40% relative humidity. Each subject completed four tests per day with 60-90 min of rest between tests to allow for proper lactate clearance (Diamant et al. 1968). To determine the effect of incline on the metabolic cost of running, four of the subjects were tested at inclines of 2 and 4%, while running at constant conditions of speed (2.4 $m \cdot s^{-1}$) and load (20 kg).

Oxygen uptake ($\dot{V}O_2$) was measured by open circuit spirometry. The expiratory gases were analyzed by an automated metabolic measurement system (MMC Horizon, Sensormedic). Measurements were taken for the last 5 min of each run at 15-sec intervals. During this period, the subjects were at a steady state and $\dot{V}O_2$ did not vary by more than ± 2.5%. Energetic equivalent of O_2 was presented in watts (W) based on the appropriate respiratory quotient (RQ) during exercise (Consolazio et al. 1963). ECG electrodes were affixed to the subjects' chest (CM5 placement) and heart rate was determined at the same time as oxygen uptake measurements.

Statistics. All mathematical manipulations assumed the linear relation between the metabolic cost of walking (M_w) and that of running (M_r). Thus the developing of the prediction equation was based on the transformation:

$$Y = ax + b$$

Multiple linear regression analysis was used to compare the predicted values $M_{r(p)}$ to the observations $M_{r(o)}$. A prediction equation was adopted if the variance of error $(1-r^2)$ was less than 2% at a significance level of $p<0.05$.

RESULTS

Relationship between M_w and M_r

The basic transformation to describe the metabolic cost of running (M_r) in relation to that of walking (M_w) is:

$$M_r = M_w + (ax+b) \qquad (1)$$

for $V \geq 2.2\ \mathrm{m \cdot s^{-1}}$

Analysis of all 216 observations while running on the level treadmill with different loads, resulted in a linear relationship between the observed metabolic rates and the predicted values for walking ($r = 0.87$, $p<0.05$) as is presented in Fig. 1. Equation 1 can be transformed to be a function of M_w:

$$M_r = M_w + (aM_w + b) \qquad (2)$$

In this equation, b is the crossover point of efficiency between walking and running and a is the slope of the line. The best fit regression line describing this transformation is:

$$M_r = M_w + (-0.45\ M_w + 450) \qquad (3)$$

or

$$M_r = M_w - 0.45\ (M_w - 1000) \qquad (3a)$$

for $V \geq 2.2\ \mathrm{m \cdot s^{-1}}$.

The Effect of Load Carriage

Based on previous observations which showed that load carriage affects the crossover point between walking and running, the value given in eq. 3 is presumably a value which should not be constant. Both the y intercept (crossover point between walking and running) and the slope of the regression line were found to be a function of the weight of the load carried. This results in the following transformation of eq. 3:

$$M_r = M_w + 0.5\ (1-.0.01L)(850 + 15L - M_w) \qquad (4)$$

for $V \geq 2.2\ m \cdot s^{-1}$.

The term (850 + 15L) in eq. 4 indicates that the crossover point (i.e., y intercept) between walking and running is a function of the external load. The term [0.5 (1-0.01L)] indicates that the change in slope of the regression line is also a function of the load. This equation can be transformed to show that M_w at a given speed ($\geq 2.2\ m \cdot s^{-1}$) overestimates the actual metabolic rate as follows:

$$M_r = M_w - 0.5\ (1-0.01L)\ (M_w - 15L-850) \qquad (4a)$$

The correlation coefficient between observed and predicted values calculated according to eq. 4 is very high ($r = 0.998$, $P<0.01$), and is presented by the regression lines in Figs. 2a and 2b. Fig. 2 presents the individual regression lines for each subject and Fig. 2b the regression line based on the mean value for each speed and load combination.

The effect of grade on M_r

Equation 4 fits very well with data collected while running on the level. Using this equation to predict the energy cost of running on a graded treadmill (Fig. 3), the mathematical expression was also highly accurate ($r = 0.983$, $P<0.02$) without the need of a correction factor. Thus, no attempt was made to correct eq. 4 and adjust it for grade.

Comparison of predicted values with results of other investigators

Figure 4 presents the comparison between the predicted energy cost calculated according to the present equation (eq. 4) with the reported data from various other studies. These reported data, which were extracted from five different reports (Margaria et al. 1963; Pugh 1970; Falls and Humphrey 1976; Keren et al. 1981; Francis and Hoobler 1986) represent experiments over a wide range of running speeds (2.2-3.6 $m \cdot s^{-1}$), grades (0 or 5%) and loads (0 or 20 kg). A highly significant correlation exists between the predicted and reported values ($r = 0.952$, $P<0.02$). Furthermore, all observations, except two, fall within the range of ±10% from the line of identity and all of them are within the range of ± 15%.

DISCUSSION

Energy expenditure of walking and running may vary within wide limits due to a number of factors, such as total weight (body weight plus external load), speed, grade, and type of surface (Givoni and Goldman 1971; Pandolf et al. 1977; Keren et al. 1981). In the past, a mathematical equation was established to predict the metabolic rate of walking with and without loads (Pandolf et al. 1977). This prediction model incorporated these variables and was found to be valid for speeds slower than 2.4 $m \cdot s^{-1}$. The present study extends this prediction model over a wider range of speeds (up to 3.2 $m \cdot s^{-1}$) with and without external loads.

The equation developed is similar in nature to that suggested by Givoni and Goldman (1971) based on a linear relation between the metabolic cost of running to that of walking. However, Givoni and Goldman based their prediction model for the energy cost of running on a constant mean value of 1050 W as the crossover for efficiency between walking and running. This value was questioned by Falls and Humphrey (1976) and did not match with the observations made in the present study. Thereafter, Keren et al. (1981) suggested that the crossover point of efficiency may change with load carriage. In addition, it was observed, in the present study, that the slope of the line is also dependent on the load carried. Thus, in the present study, both the crossover for efficiency and the rate of change in energy cost, were transformed from constants into varying factors which were dependent on the weight of the load carried (L).

An important factor in determining the energy cost of walking and running is the placement of external load over the body (Soule and Goldman 1969; Pandolf et al. 1977). Manual transport of an external load may cause a forward shift in the body's center of gravity, which may alter efficiency and in turn may force an increase in energy expenditure. This is particularly the case when external loads are carried away from the body's center of gravity, such as on the ankles or in the hands (Kamon and Beldning 1971; Robertson 1982; Francis and Hoobler 1986; Legg and Mahanty 1986). For greatest efficiency and stability, however, the load should be kept as close as possible to the trunk and the center of gravity of the body. It is suggested that heavy loads should not be carried using small muscle groups, but rather be carried around the waist or in a backpack (Soule and Goldman 1969; Robertson 1982; Legg and Mahanty 1985). Therefore, Pandolf et al. (1977) developed their prediction model only for backpack load carriage, and the same attitude was taken in the present study. In reality, except perhaps in athletic events, carrying a backpack is associated with wearing heavy footwear (boots). Thus, the external load carried by the subjects was, in the present study, comprised of their clothing, boots, and the backpack. No attempt was made to separate the effect of the backpack and boots on energy cost. Recent studies imply, however, that each 100g increase in total weight of footwear causes a 0.7 - 1.0% increase in energy cost (Jones et al. 1984; Jones et al. 1986; Legg and Mahanty 1986). This increase in energy cost due to footwear might be important for athletes and especially for distance runners under a training program when a higher energy expenditure would be more demanding for the cardiorespiratory system; it will increase work intensity ($\dot{V}O_2/\dot{V}O_2$ max) and ultimately improve $\dot{V}O_2$max. Under competitive running, lower work intensity, while running with lighter shoes, might be less fatigueing. However, for soldiers who carry backpacks, the effect of footwear weight on total energy expenditure will usually be small. The prediction model presented, being valid for backpack carriage, might therefore be somewhat inaccurate when applied for predicting the energy cost of running with loads carried by hand or around the ankle, which recently has become very popular in physical training.

Speed of running and grade of incline are two of the factors which determine energy cost. Margaria et al. (1963) who developed a nomogram de novo to predict the energy cost of running use these two basic factors as determinants. Givoni and Goldman (1971) who suggested an equation to predict the energy cost of running, based on the energy cost of walking, included grade as a factor also in the prediction of M_r. The present prediction equation, however, was found to be dependent on external weight and was accurate for predicting the metabolic cost of running, on the level or uphill, without the need to correct for speed or grade. This probably derives from a sufficient relative weight already given to speed and grade while calculating M_w; whereas external weight might have an additional effect on the biomechanics and energy cost while running.

The validity of the prediction model was tested by its ability to predict the metabolic cost of running under different conditions. The results reported in different publications (Margaria et al. 1963; Pugh 1970; Falls and Humphrey 1976; Keren et al. 1981; Francis and Hobbler 1986) were compared to the calculated values using the basic parameters reported. Bearing in mind the difficulties to extract very accurate data from published reports, the highly significant correlation between the reported and the predicted values ($r = 0.952$, $p<0.02$) and the fact that almost all data points fall in the range of ±10% from the line of identity is very encouraging. However, a very limited data base exists in the literature. The existing data refers mainly to tests on the level or at 5% grade with external loads of 0 or 20 kgs. The most comprehensive report, in this respect, is that of Keren et al. (1981), who tested their subjects while running at different speeds on a 5% graded treadmill, without any load and with a 20 kg loaded backpack. Their results are about 5% higher than generated by our prediction model. These differences, however, could be accounted for differences in technique and non-specific variability between laboratories. Nevertheless, further information for a wide range of loads and grades will be helpful to further establish the prediction model developed over a larger range of grades.

In conclusion, a highly accurate mathematical model was developed to predict the metabolic cost of running. This model together with the model developed by Pandolf et al. (1977) enables the prediction of metabolic cost for walking and running at a wide range of speeds, external loads and grades.

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The views, opinions and/or findings in this report are those of the authors, and should not be construed as an official Department of the Army position, policy or decision, unless so designated by other official documentation. Human subjects participated in this study after giving their free and informed voluntary consent. Investigators adhered to AR 70-25 and USAMRDC Regulation 70-25 on Use of Volunteers in Research.

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Table 1: Combinations of external load, speed, and grade studied.

Velocity ($m \cdot s^{-1}$)	Load (kg)	Grade (%)
2.2	0,10,20,30	0
2.4	0,10,20 30	0
2.6	0,10,20	0
2.8	0,10,20	0
3.0	0,10	0
3.2	0,10	0
2.4	20	2,4

FIGURE LEGENDS

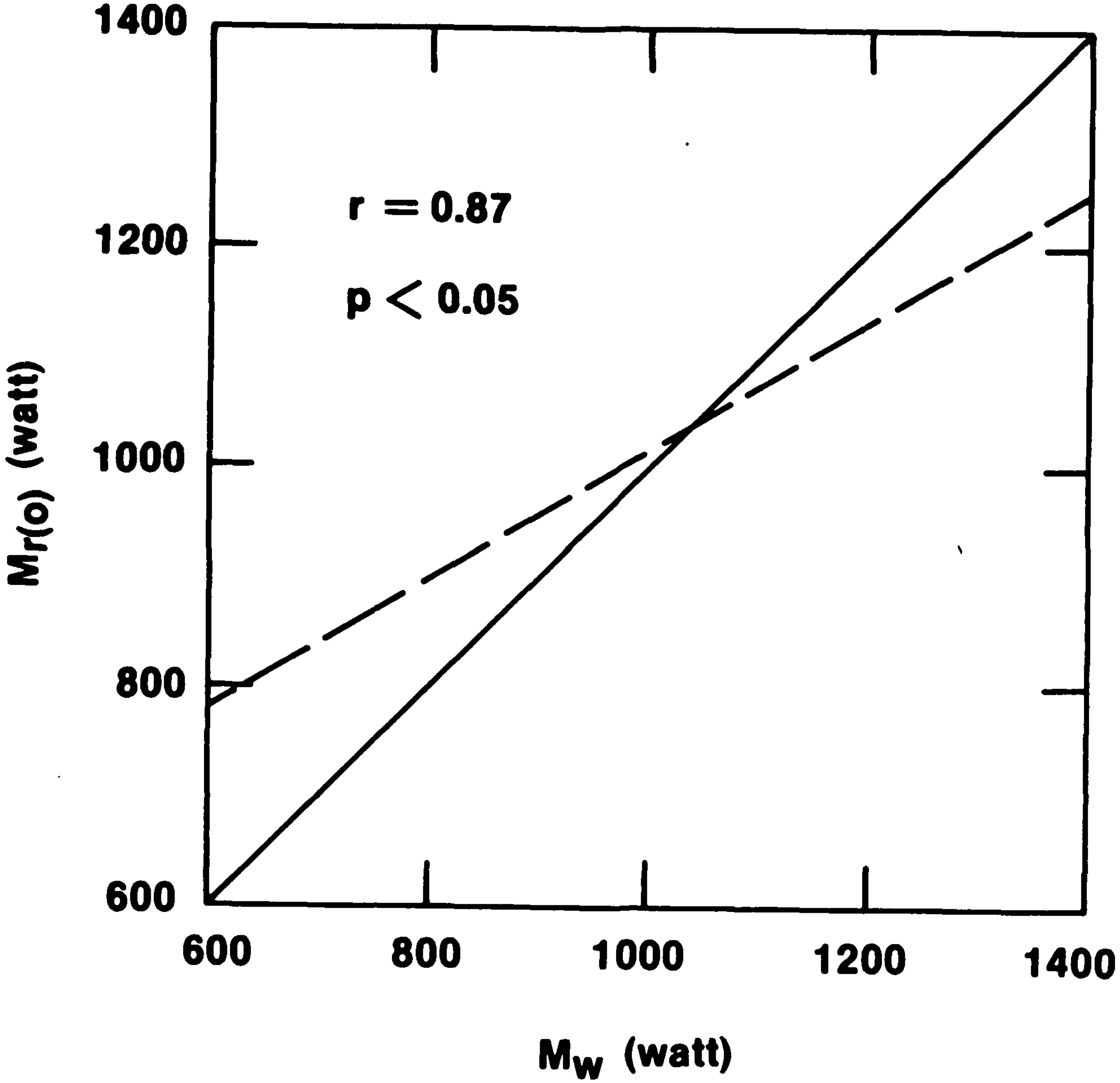
Fig. 1 The relationship between the calculated metabolic rate of walking (M_w) and the observed metabolic rate of running [$M_{r(o)}$]. The dashed line indicates the mean for all subjects; the solid line is the line of identity.

Fig. 2a The relationship between the predicted metabolic cost of running [$M_{r(p)}$] and the observed [$M_{r(o)}$]. The regression line for each subject is presented.

Fig. 2b The correlation coefficient between predicted and observed values of the metabolic cost for running. Each point represents the mean value of each load-speed combination of all subjects.

Fig. 3 . Metabolic cost of running on a 2 and 4% graded treadmill. Comparison between predicted and observed values.

Fig. 4 Comparison between the predicted values of metabolic cost for running and reported values in the literature. The dashed lines represent the range of ± 10% from identify. (closed symbols - running on 5% grade).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M_W (watt)

Fig. 1

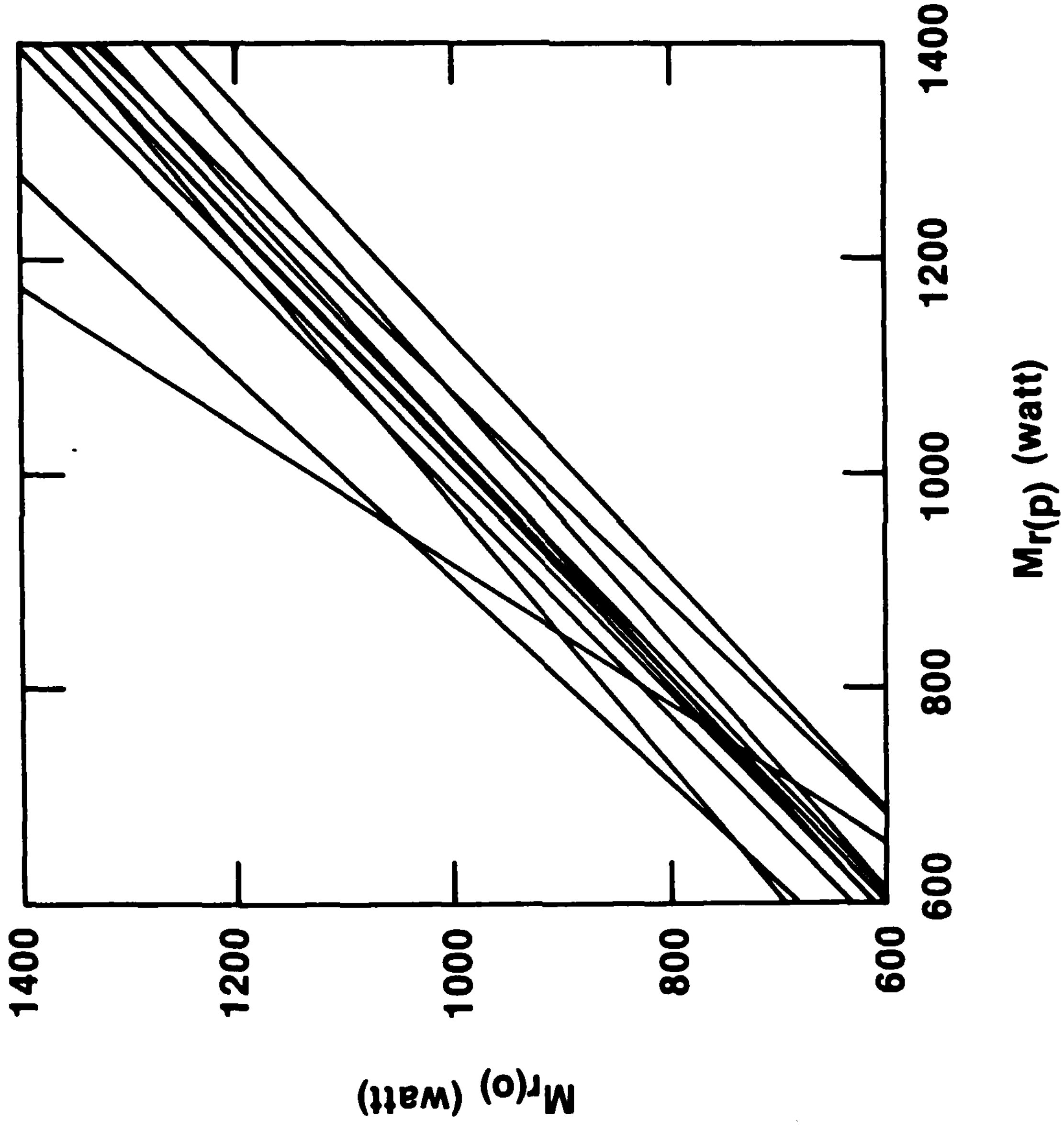
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Fig. 2a

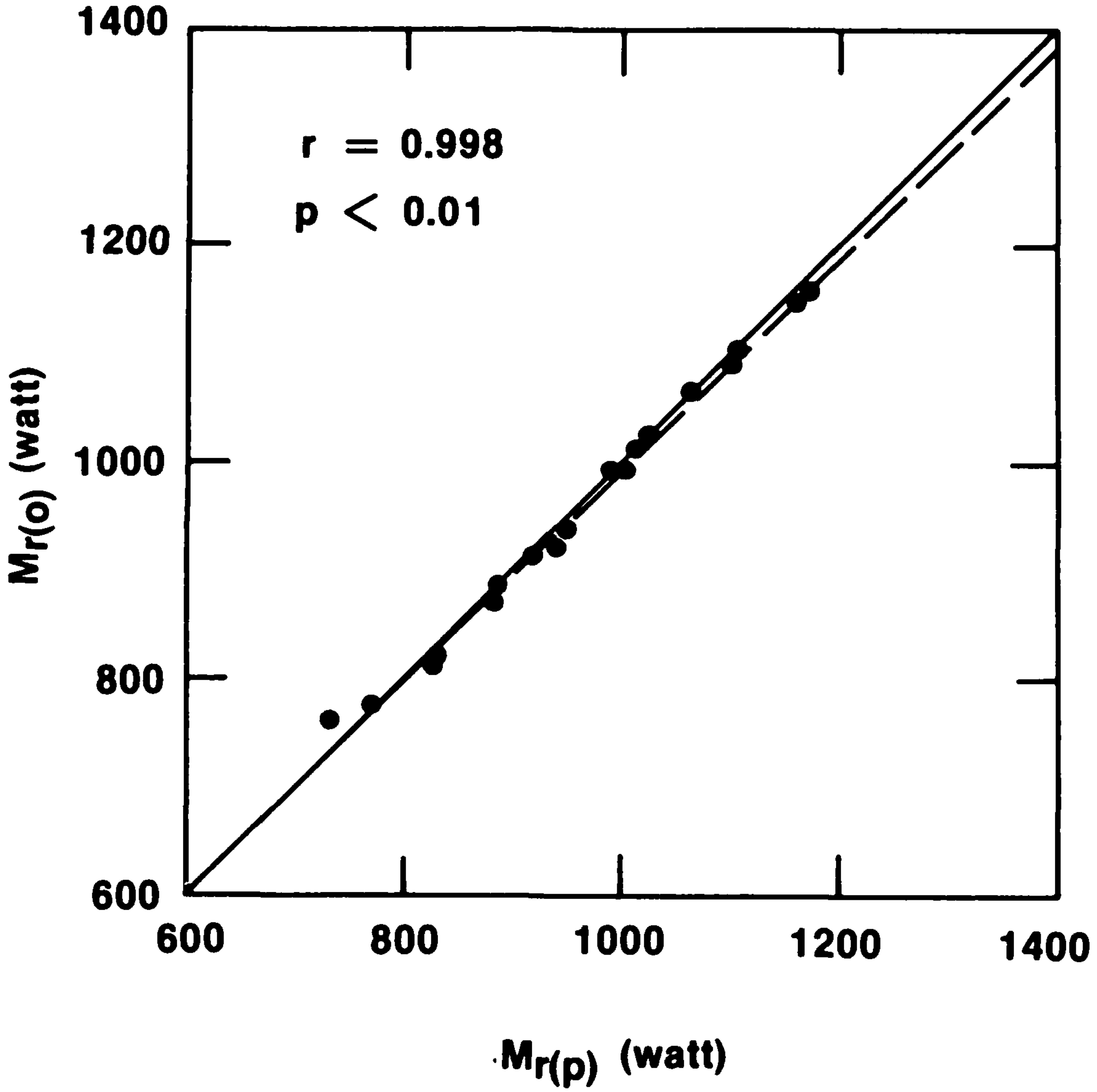
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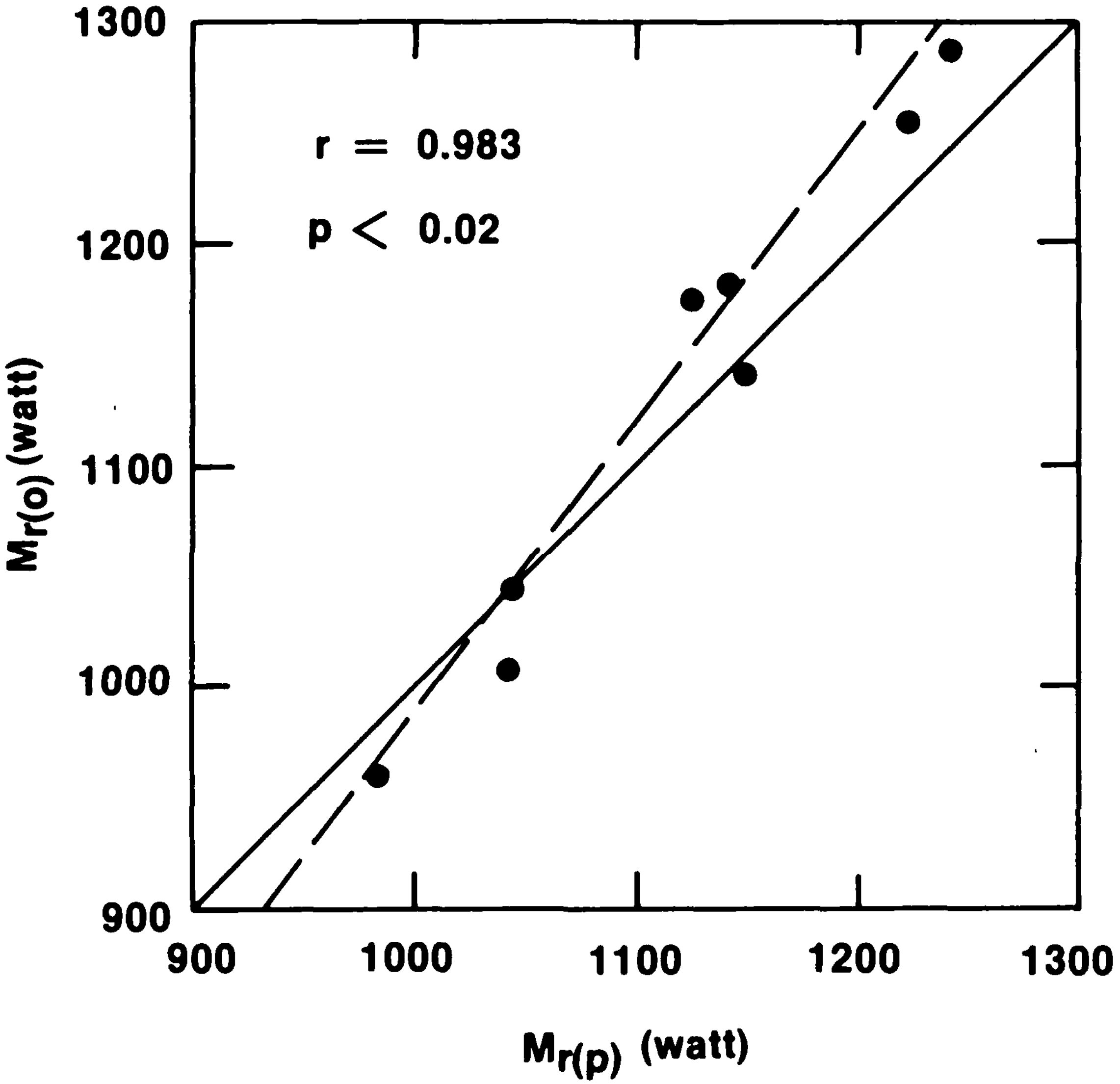
Fig. 2b


r = 0.983
p < 0.02
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M_r(o) (watt)
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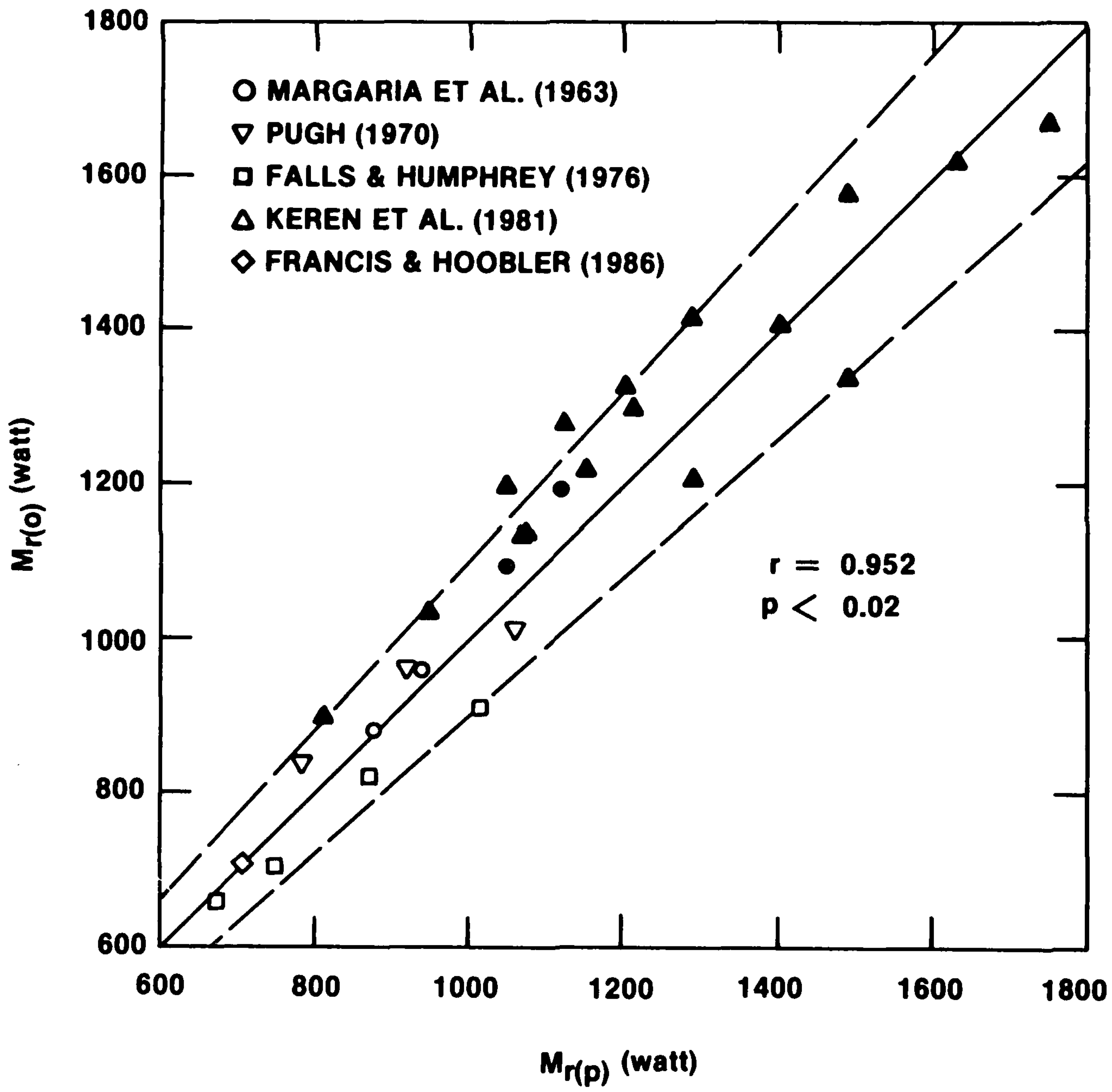
Fig. 3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▽ PUGH (1970)
□ FALLS & HUMPHREY (1976)
△ KEREN ET AL. (1981)
◇ FRANCIS & HOOBLER (1986)
r = 0.952
p < 0.02
$M_{r(o)}$ (watt)
$M_{r(p)}$ (watt)
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Fig.4

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