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MUSCULAR EFFICIENCY DURING STEADY-RATE EXERCISE II:
EFFECTS OF WALKING SPEED AND WORK RATE

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Running Head: Energetics of Walking

Abstract

A comparison of walking against vertical (gradient) and horizontal (trailing weight) forces was made during steady-rate exercise at "0", 250, 500 and 750 kgm/min with speeds of 3.0,4.5 and 6.0 km/hr. In all cases exponential relationships between caloric cost and increasing work rate and speed were observed. These exponential relationships indicated that muscular efficiency during walking is inversely related to speed and work rate. "Work" (level, unloaded walking as the baseline correction), "delta" (measured work rate as the baseline correction) and "instantaneous" (derived from the equation describing the caloric cost of work) efficiencies were computed. All definitions, work (range of 21.0% to 43.9%), delta (19.6% to 43.9%) and instantaneous (18.3% to 44.1%), yielded decreasing efficiencies with increasing work rates. At work rates above 250 kgm/min the curves describing the relationship between caloric cost and work rate were parallel for vertical and horizontal forces, indicating equivalent efficiencies in this range. Only the delta and instantaneous definitions accurately described these relationships for vertical and horizontal work. Of these two, the delta efficiency estimation was judged to be superior as it is based directly on the raw data. The work efficiency definition was found inadequate when the relationship between caloric cost and work rate is non-linear. Determinations of combined work loads (gradient plus trailing weights) were made and the energy costs of both types of work found to be additive.

Key Words: exertion, exercise, efficiency, energetics, work, indirect calorimetry, steady-rate, steady-state, walking.

Introduction

A variety of methods have been developed to quantify the work accomplished in walking and running. Several of these methods have estimated the forces involved by means of cinematography (5,6,13), force plates (6,7), accelerometers (5,6), and sensor transducers (17,21). Other approaches have involved the imposition of added work by means of gradient walking (2,3,12,20, 22,25), wind resistance (22) and trailing weights (17,30). All of these methods have been employed to determine the effects of work rate on energy expenditure and efficiency of bipedal locomotion in man. It has generally been assumed that these methods provide comparable results in their determinations of energy expenditure and efficiency. However, the one study (22) that has compared two methods of applying work suggests that there are differences in energy cost and efficiency that may be the result of the manner in which forces are distributed over the body.

The effects of speed and work rate on the energy expenditure in walking have been the subjects of a number of investigations which, in many cases, have found the relationships between caloric output and work rate or speed to be exponential in nature. Yet, few researchers have considered what effects these two factors of work rate and speed might have on the efficiency of walking. As efficiency represents the ratio of work accomplished to energy expended, the exponential nature of the energy expenditure curve would suggest a decreasing efficiency with increasing work rate or speed.

In a previous study, Gaesser and Brooks (14) demonstrated that the baseline correction factor in efficiency calculations for energy expenditure is critical in providing an accurate description of efficiency and its relationship to work rate. "Net"[1] and "gross" efficiency calculations proved inadequate in this respect, yielding results that were artifacts of the computation. They, therefore, defined "delta" efficiency as the ratio of change in external work rate to associated change in energy expeditures. For cycling, in which the relationship between energy expenditure and work rate is essentially linear, the "work" and delta efficiency calculations provided similar results. It was suggested, however, that given a clearly non-linear relationship between energy expenditure and work rate, as is sometimes found in walking, the work definition would result in erroneous estimates of efficiency while the delta calculations would provide more valid results.

The purposes of this present study were to: 1) compare the energy expenditures and efficiencies of walking against vertical and horizontal forces, 2) determine if these two types of work (vertical and horizontal) are additive with respect to their energy costs, 3) describe the effects of speed and work rate upon the energy expenditure and efficiency of walking, and 4) evaluate the adequacies of various baseline corrections in describing relationships between caloric expenditure, work rate and speed of movement.

Methods

Subjects for this study were nine well conditioned males between the ages of 21 and 30 years. Treatment of subjects was consistent with the principles of the Declaration of Helsinki, and written informed consent was obtained. Each subject was exercised on a Quinton Treadmill (Model 18-60) for a total of 8 times under three different conditions: 1) walking on a level treadmill against a horizontal impeding force, 2) walking up various gradients on the treadmill, and 3) walking on the treadmill at a set gradient against a horizontal impeding force. Under the first condition subjects performed one trial at each of three speeds (3.0, 4.5, and 6.0 km/hr) on separate days. The horizontal impeding force was applied by attaching a weight to a cord which was connected to an 8 inch wide canvas belt around the subject's waist and suspended over a pulley supported on a heavy metal frame to the rear of the treadmill, (see Lloyd and Zacks, 17). The height of the pulley was adjusted before and during each run to insure that the cord was parallel to the walking surface. During each trial the weights were progressively increased to achieve added work rates of "0", 250, 500 and 750 kgm/min. To achieve a "steady-rate" of $\dot{V}O_2$, the exercise bouts were 5,6, 7 and 8 minutes for work rates of 0, 250, 500 and 750 kgm/min., respectively (27). Rest intervals between work bouts were equal in duration to the previous work bout. The experimental design for the second condition was identical to that of the first with the exception that the work rates were altered by adjusting the treadmill gradient. Subjects were weighed before each trial to insure accurate calculation of the work rate. Under this second condition work rate was equal to the product of the subject's body weight, treadmill speed and percent gradient. For the third condition subjects performed one trial at each of two gradients (3% and 6%) at a speed of 4.5 km/hr. During each of these trials "added" work rates of 0,250, 500 and 750 kgm/min. were induced by means of the horizontal impeding force described in condition one. Again, the level of the pulley was adjusted so that the cord was parallel to the walking surface. The duration of the exercise bouts were 6, 7, 8 and 9 minutes for added work rates of 0, 250, 500 and 750 kgm/min., respectively. Rest intervals between work bouts were equal to the duration of the previous work bout. In all cases subjects were allowed at least 48 hours between trials. Subjects were required to have eaten their last meal at least 2 hours before a trial began.

Subjects inspired room air through a Daniel's low resistance valve. Expired air samples were collected in a 120 liter Tissot spirometer during the last one to two minutes of each exercise bout. Gas analyses were performed by pumping expired air from the Tissot over color indicator $CaSO_4$ and through Beckman E2 O_2 and LB-1 CO_2 analyzers. The analyzers were calibrated before, during and after each experiment with samples from tanks of known gases (established by Schollander and Haldane analyses).

Steady-rate $\dot{V}O_2$ and $\dot{V}CO_2$ were calculated (8; 11,p.300-309), and the respiratory exchange ratio (R) was used to estimate caloric output (11, p.628). The data obtained on each subject were used to calculate efficiency using both work and delta definitions as presented previously[1] (14).

The work efficiency definition has been widely used in walking studies as unloaded walking conveniently serves as zero work rate from which one can make the baseline correction for energy expenditure. While the delta efficiency calculation has only recently been developed, it has been shown that the delta efficiency calculation best describes changes in efficiency when there exists a non-linear relationship between work rate and energy expenditure (14). The gross and net efficiency definitions, which have traditionally enjoyed wide use in cycling studies, and the recently described theroretical-thermodynamic approach (28) of calculating efficiency were not considered for reasons discussed previously (14).

Instantaneous efficiency was determined from analysis of the curve describing the relationship between caloric expenditure and work rate. This type of calculation has been previously employed in studies where the relationship between energy expenditure and work rate was linear (17, 28). In those cases efficiency was calculated as the inverse of the slope and yielded values comparable to work or delta efficiencies. In instances where a plot of energy expenditure (y) against work rate (x) is exponential in nature and is described by the equation $y=ae^{bx}$, efficiency can be calculated as the recipricol of the first derivative of that equation describing the curve ($Ef_I=(abe^{bx})^{-1}$). This method provides an instantaneous efficiency value at any given work rate. Equations describing the relationships between caloric expenditure and work rate were obtained by least squares best fit analyses.

For energy expenditure and efficiency data, repeated measures analyses of variance(REANOVA) were conducted to determine if significant differences existed between any of the factors being considered (speed, work rate, efficiency definition, type of force imposed). Where appropriate Duncan's multiple range tests were applied to further determine where differences existed. Individual F tests were carried out separately for both the work and delta efficiency calculations.

Results

Figure 1 presents the relationships of energy expenditure to work rate for both gradient and loaded horizontal walking. This figure demonstrates that in all cases the caloric costs rise exponentially as work rate increases. At any given speed the curves for vertical and horizontal work are essentially parallel between work rates of 250 and 750 kgm/min. The results of REANOVA indicate that the divergence in caloric cost at the 0 to 250 kgm/min. increment, leads to the absolute energy expenditure at a given work rate being slightly, but significantly ($p < .05$) higher for horizontal work. It can also be seen in Figure 1 that at a set work rate the energy expenditure increases exponentially as the speed increases.

Figure 1

Data on the work (W) and delta (Δ) efficiencies as a function of work rate are presented in Figures 2A-2D. In all cases efficiency is seen to decrease as the result of increasing work rate. The work efficiencies (2A vertical, 2B horizontal) are widely different at 250 kgm/min., but show a tendency to converge so that at 750 kgm/min., there are only small, but significant, differences between the efficiencies of the horizontal and vertical work. Individual F-test results indicate that the delta efficiencies for the two forms of work (2C vertical, 2D horizontal) are only significantly different at the 0-250 kgm/min. step.

Figures 2A -
2D

Effects of speed on efficiency for work and delta efficiency definitions are given in Table 1. These data have been calculated as previously described for bicycle ergometer work^2 (14). In every case the calculated efficiency is seen to decrease as the speed increases. This is illustrated in Figure 3 where the data for both horizontal and vertical work at 500 kgm/min. are plotted. Results of REANOVA indicate that within a definition (i.e.; either work or delta) there is no significant difference between efficiencies of vertical and horizontal work at any speed or work rate.

Figure 3

Equations for the curves describing caloric cost as a function of work rate are presented in Table 2. Also presented are the instantaneous efficiencies derived from these equations and the delta efficiencies for similar work rates. In most cases the instantaneous efficiencies, derived from curve analysis, are comparable to the delta efficiencies. REANOVA indicates no significant differences between efficiencies calculated by instantaneous and delta definitions. Both the delta and instantaneous efficiencies demonstrate decreasing values with increasing work rate.

Table 2

In Figure 4 are presented the additive effects of combining both vertical and horizontal work. Results of the combined work rate studies, when plotted as energy expended versus work rate, is seen to be superimposable on the curve for horizontal work alone at the same speed.

Discussion

Figure 5

The results of this study clearly indicate exponential relationships when plotting energy expenditure as a function of speed or work rate during walking (Figure 5). With regard to the relationship between energy expenditure and speed of movement, the present results corroborate previous studies using both level (1,2, 3,4,15,16,21,23,29) and gradient walking (2,3,12,19). With regard to the relationship between energy expenditure and external work rate, our present data support previous results (2,3,20) describing an exponential relationship between energy expenditure and work. The present results are, therefore, at variance with those suggesting either a linear or complex, partly linear and partly exponential, relationship between energy expenditure and work during walking (9,15,22,25).

The above described relationships indicate exponentially rising energy costs in walking with increases in speed or work rate. As previously pointed out (14), this dictates decreasing efficiency. In Figures 2A-2D the data demonstrate this decrease in both delta and work efficiencies for increasing work rate under all conditions studied. However, if we consider the energy expenditure data in Figure 1 we find that except for that portion between 0 and 250 kgm/min., the curves describing the relationship between energy expenditure and work rate are parallel. These results indicate equivalent muscular efficiencies for both vertical and horizontal work in the range of 250-750 kgm/min. When comparing delta and work efficiency calculations, only the delta efficiency calculation yields these results. The work efficiency calculation produces significantly different values between vertical and horizontal work because the baseline correction factor for energy expenditure in the work efficiency definition remains constant. Thus the relatively greater changes in energy cost at higher work rates are averaged in with the lesser changes at lower work rates, resulting in inflated efficiency values at higher work rates. The delta definition, therefore, provides results more in agreement with those implicit in the steady-rate VO_2 data.

Under experimental conditions in which the energy expenditure rises exponentially with respect to increases in work rate the efficiency should theoretically be constantly decreasing. For this situation the instantaneous efficiency calculation has the advantage of providing an efficiency estimate for any work rate selected. However, the primary disadvantage of this method is that the efficiency is not derived directly from the raw data (as with delta efficiencies), but rather from a curve of best fit to that data.

Attempting to describe a curve by a least squares fit analysis can result in predicted caloric costs and efficiency estimates at variance with the raw data. Perhaps the most accurate method of assessing muscular efficiency is to employ the delta definition along with numerous observations at not greatly different gradations in work rate.

The decrease in efficiency with increasing speed, as demonstrated in Table 1, reflects the increasing energy cost of walking at any given external work rate with an increase in speed. To describe these phenomena the calculation for efficiency required alteration[2] as the standard work and delta definitions of efficiency do not take into account speed or changes in speed. However, it could be debated that an increase in speed really decreases efficiency. Figure 1 demonstrates that the curves describing the relationship between energy expenditure and work rate for both horizontal and vertical work are very close to parallel at all speeds. When comparing any two speeds of a constant external work rate the absolute caloric costs may differ, but with a change in work rate the change in energy expended is similar. In a sense the increased speed raises the energy of activation of the system, but added external work may be performed with little change in efficiency. The effect of speed may, therefore be to increase internal work. Ralston and co-workers (18,24) employing cables attached to the body from sensor transducers, have established that most of the work in level walking is involved in the changing acceleration of legs and torso along with the vertical lift of the torso. It is probable that at faster speeds disproportionately more work is involved in accelerating the limbs and torso resulting in increased energy expenditure. With increasing work rate, force and speed, a shift from red, slow twitch skeletal muscle fibers to the less efficient white, fast twitch fibers may also affect energy.

It is interesting to note that while exponential relationships between energy expenditure and speed or work rate during walking have been realized for years, the obvious implications these observations have concerning muscular efficiency has received little attention. Though Bobbert(2) observed such exponential relationships he could not find a consistant decrease in absolute (work) efficiency. Bobbert did find an increase in gross efficiency with an increase in work rate. However, recently it has been shown (14) that this apparent increase in gross efficiency is an artifact of the mode of calculation. Perhaps Bobbert would have found a decrease in work efficiency had he kept the work rate constant for each subject instead of the gradient which varies the work rate according to the subject's body weight. Other researchers (12,22,25) have apparently been primarily concerned with determining the overall mean efficiency for walking. Typically these investigations have measured the energy expenditure of a few subjects at numerous work rates and speeds, then compiled the data to determine the mean efficiency along with a range. Illustrative of this point is the study of Smith (25) who reported a mean value for efficiency of 31.3%W[3], with a range of 25.2% to 48.7%W. While we obtained similar results (mean 32.3%W, range 13.3 to 66.6%W) our data demonstrate that this range is not a random one as it is often presented, but ordered in a decreasing fashion as the work rate is increased. As the efficiency of walking is dependent upon the work rate, the determination of an overall mean efficiency is of little value in attempting to understand muscular efficiency during walking.

Both mechanical and muscular factors may play important roles in increasing the energy cost of walking as the work rate or speed rises. Dean (10) has suggested two mechanical considerations that might influence energy expenditure as gradient is increased. For level walking, a given energy expenditure is required by the vertical oscillations of the body; these are diminished as the gradient increases. The diminution is related to the fact that at steeper gradients the vertical lift is used to obtain height. The energy expenditure for walking at level or shallow gradients would then be somewhat inflated, thereby elevating the lower part of the curve for caloric output and work, giving it an exponential shape. In efficiency calculations, where vertical oscillations are not considered in the external work accomplished, and where the caloric cost of level walking serves as the baseline correction for energy expenditure, use of the 'inflated' baseline determined during horizontal walking could result in high calculated values of efficiency at low work rates. Thus, the differences in efficiencies for horizontal (Figures 2A-2C) and vertical work (Figures 2B-2D) at lower work rates may be attributed to this baseline effect which would not affect the calculation of horizontal walking efficiency. In Figure 5 it can be seen that the "0" work points are somewhat off the lines describing the other mean data points.

To explain the exponential nature of the upper half of the curve of caloric output on work, Dean has suggested an increase in energy expended as the result of excessive lean to maintain balance at steeper grades. To support his argument he cites studies on miners indicating greatly reduced efficiency when leaning over while walking. This factor of torso inclination might also be applied in explaining the exponential curve for horizontal work and energy expenditure, as subjects continually leaned forward to compensate for increased masses of trailing weights.

In the present study it was observed that the relationship between energy expenditure and work rate was similar for both vertical (gradient) and horizontal (trailing weight) work. This similarity is reflected in the calculated efficiencies which are essentially identical for both types of work except at the lower work rates (Figures 2A-2D). The present results are not in agreement with those of a previous study by Pugh (22) comparing vertical (gradient) and horizontal (wind resistance) work. In his study it was shown that the relationship between energy expenditure and work rate was linear for horizontal while curvilinear and much steeper for vertical work. Consequently Pugh obtained much higher efficiencies for horizontal (43.7%W) than for vertical work (33.4%W). Pugh suggested that the observed discrepancies were a result of inherent differences in two types of exercise during the distributions of work in the various phases of walking. Our type of horizontal force (trailing weight) was different from his (wind resistance) allowing for the possibility that the anatomical distribution of horizontal work was more like that in vertical work in our comparison than in Pugh's. However, given his high mean efficiencies for walking (43.7%W) and running (69.0%W), it is possible that he overestimated work accomplished against the wind. Not only did Pugh's estimation of work involve numerous calculations based on perhaps imperfect models but he did not account for the subjects leaning into the wind which he admits may have reduced drag and increased lift, thereby reducing work.

The horizontal and vertical characters of work studied in this investigation are apparently not only comparable in their effects on energy expenditure during walking, but the energy costs of the two types of work are also simply additive. In Figure 4 it is demonstrated that the combined work rate data are superimposable on the curve for horizontal work alone at the same speed. Since the changes in work rates were accomplished by increasing the horizontal force, these results were anticipated. Though it was not considered in this study, it would be expected that were the trailing weight set and the gradient varied to change the work rate, the curve of this combined work would superimpose itself upon the curve for vertical work at the same speed.

Studies employing gradient work have typically shown that the efficiency of running is much higher than that for walking. Determinations of efficiency usually produce efficiencies of about 40%W or greater for running (19,22) and only about 30%W for walking (2,12,22,25). Pugh (22) demonstrated a similar difference for work against the wind though there may be some problems with his results (vide supra). To our knowledge, the present investigation is the first study employing the trailing weight method of determining work for walking. The trailing weight method has previously been used by Lloyd and Zacks (17) and Zacks (30) to determine the work efficiency of running, which they found to be about 35%W. In our study the mean efficiency as would be calculated by these other authors was 32.3%W. Obviously the large differences between running and walking noted in vertical work do not appear when the efficiencies are determined by trailing weights. A possible explanation for this could be that the elastic recoil force that has been proposed to cause the difference between running and walking up gradients cannot be utilized as efficiently to overcome a force directed in a horizontal direction as it is for vertical work. Another possibility which must be seriously considered is the question of the validity of indirect, open-circuit calorimetry for running energy estimations. Even with fit individuals and relatively slow running speeds, the caloric output may be so high as to preclude acceptance of the assumption that all ATP is supplied by respiration (14). Recent work utilizing infused ^{14}C lactate (T.P. white and G.A. Brooks, unpublished data)[4] indicates significant lactate turnover not completely accounted for by oxidation at mild work rates which produce only small elevations in blood lactate concentration in running rats. Therefore, there exists the possibility that $\dot{V}O_2$ does not account completely for energy turnover during running. In this way the excessively high efficiencies reported for running based upon $\dot{V}O_2$ determinations may be explained. Total body efficiencies for running in the range of 40 to 60 percent (19,22) are probably much too high to represent a reasonable product of oxidative and mechanical coupling efficiencies (14,28).

The results of the present study are directed towards a conclusion recently drawn by Tucker (26) concerning efficiencies of cycling and walking. He contends that the reason people prefer to bicycle from one point to another instead of walking is due to the greater efficiency of cycling. Tucker points out that in terms of distance covered to energy expended, the bicycle is much more "efficient", and that this is due to the lower muscular efficiency (work accomplished/energy expended) in walking. While we agree fully with his first point that cycling allows more distance per quantity of energy expended, we must contest his assumption that this is the result of a higher muscular efficiency in cycling. In Figures 6A and 6B efficiency data from our study on walking are plotted against those obtained in this laboratory using some of the same subjects while cycling (14). It is obvious when considering Figure 6 that at most work rates the efficiency of walking is either equal to or greater than that for cycling. These results are in agreement with those of

Figures 6A
and 6B

Zacks (30) who determined the efficiencies for cycling (26.1%W) and running (33.0%W) utilizing trailing weights. Tucker (26) apparently erred in the manner in which he obtained his efficiencies for cycling and walking. For cycling he utilized a mean value obtained in previous studies on cycling efficiency. However, instead of doing the same for walking, he attempted to derive the efficiency of walking based upon a formula used to determine the work accomplished by a flying animal. In Tucker's calculation the only work component that appears relevant to the walking or running animal is wind resistance, which is negligible, resulting in the low calculated efficiencies, on the order of 0.02 -0.05%. Were he to have determined the efficiency of cycling in the same manner, Tucker most probably would have again obtained low efficiencies. Those components in walking that account for most of the energy expended are leg swinging, and horizontal and vertical oscillations of the body (10,18,24). Investigators using kinematic techniques have estimated these components and found net efficiencies to approximate 23%N, which compare favorably with cycling (14).

If the muscular efficiency of walking is equal to or greater than cycling, it obviously cannot account for the greater distance covered by a bicycle for the same energy cost. A better explanation for this phenomena would be that for a given amount of work (work = force x distance) the cyclist exerts less force and travels farther than the walker. This is easily seen if we compare comfortable speeds of walking (4.5 km/hr) and cycling (60 rpm). For the walker this amounts to 75 m/min. In cycling, given a standard wheel diameter of 27 inches and front to rear gear ratio of 2.6:1, the distance traveled at 60 rpm would be 335.9 m/min. Therefore, at the same work rate a cyclist would travel about 4.5 times as far as the walker. Though the cyclist and his vehicle weigh more than the walker, less force is exerted by the cyclist because, provided the surface is flat and hard, the major forces encountered are rolling friction and wind resistance. Frictional force in rolling vehicles such as a bicycle is only a small fraction of the force normal. In walking there are a number of forces involved in the accelerations and decelerations of the legs and torso, and also the vertical oscillations of the torso. Although the forces in walking are not as easily quantified as the frictional force for cycling, as a matter of deduction using the Newtonian definition, the greater distance traveled by the cyclist for a given energy expenditure implies that the forces are greater in walking.

In this paper, as in a previous one on the same subject from this laboratory (14), we have used the term "steady-rate" in preference to the more generally used "steady-state". In making this distinction we are neither casual in our terminology, nor different for the sake of being arguementative. Rather, our continuing work on the subject of muscular efficiency has lead to the conclusion that there are important conceptual differences between the terms. As exercise starts, many variables such as $\dot{V}O_2$ heart rate, stroke volume, ventilation, local tissue temperatures, concentrations and pool sizes of adenine nucleotides, substrates, ions, hormones, and other factors change and continue to remain in a dynamic flux for the exercise and recovery periods. Therefore, rather than characterize our experimental condition as a "steady-state" we prefer to define our experimental condition in terms of the work rate. The observed "steady-rate" $\dot{V}O_2$ is then acknowledged to refer to the $\dot{V}O_2$ determined at a constant work rate, and no generalization about the organismal homeostasis is made. Furthermore, the term steady-rate acknowledges that open circuit, indirect calorimetry may not adquately account for energy turnover during exercise.

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Text Footnotes

1. Definitions of Efficiency:

$$\text{delta efficiency} = \frac{\text{delta work accomplished}}{\text{delta energy expended}} = \frac{\Delta W}{\Delta E} \times 100$$

$$\text{work efficiency} = \frac{\text{work accomplished}}{\text{energy expended above unloaded level walking}} = \frac{W}{E_l - E_u} \times 100$$

$$\text{net efficiency} = \frac{\text{work accomplished}}{\text{energy expended above that at rest}} = \frac{W}{E - r} \times 100$$

$$\text{instantaneous efficiency} = (abe^{bx})^{-1} \times 100$$

Where W = caloric equivalent of external work performed; E = gross caloric output, including resting metabolism; r = resting caloric output; E_l = caloric output, loaded horizontal and gradient walking; E_u = caloric output, unloaded, level walking; ΔW = caloric equivalent of increment in work performed above previous work rate; ΔE = increment in caloric output above that at previous work rate.

2. Sample calculations of the effect of speed on efficiency using work and delta efficiency definitions:

Work efficiency at 500 kgm/min, 4.5 km/hr =

$$\frac{\text{Caloric equivalent of 500 kgm/min}}{\text{Caloric output at 500 kgm/min, 4.5 km/hr} - \text{Caloric output at "0" kgm/min, 3.0 km/hr}} \times 100 = 33.2\%$$

Delta efficiency at 500 kgm/min, 4.5 km/hr =

$$\frac{\text{Caloric equivalent of 250 kgm/min}}{\text{Caloric output at 500 kgm/min, 4.5 km/hr} - \text{Caloric output at 250 kgm/min, 3.0 km/hr}} \times 100 = 31.6\%$$

3. Postscripts (Δ, N, and W) are used to denote efficiency estimates arrived at by delta, net and work definitions, respectively.

4. Data presented in the symposium, "Detection Of Anaerobic Metabolism During Exercise", at the twenty-third annual meeting of the American College of Sports Medicine, Anaheim, California, May 6, 1976.

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Table 1: Effects of speed on work and delta efficiency calculations.

Method of Calculation	3.0 Km/hr	4.5 Km/hr	6.0 Km/hr
250 Kg·m/min			
Work (Vertical)	38.84 ± 1.72 *	25.77 ± 1.40	15.10 ± 0.63
Work (Horizontal)	34.09 ± 1.40	24.79 ± 1.83	14.06 ± 0.85
Delta (Vertical)		25.77 ± 1.40	19.97 ± 1.06
Delta (Horizontal)		24.79 ± 1.83	16.10 ± 1.06
500 Kg·m/min			
Work (Vertical)	35.24 ± 0.97	27.22 ± 0.37	19.28 ± 0.65
Work (Horizontal)	33.48 ± 1.76	25.47 ± 1.39	18.53 ± 0.90
Delta (Vertical)		21.47 ± 1.18	15.61 ± 0.64
Delta (Horizontal)		19.44 ± 1.01	14.41 ± 0.76
750 Kg·m/min			
Work (Vertical)	29.86 ± 0.59	26.08 ± 0.86	19.26 ± 0.34
Work (Horizontal)	27.77 ± 0.79	24.46 ± 1.03	18.68 ± 0.84
Delta (Vertical		17.62 ± 0.87	12.24 ± 0.51
Delta (Horizontal)		16.02 ± 0.70	12.79 ± 1.29

* Mean ± 1 standard error

Table 2: Equations of the general form $y=ae^{bx}$ for describing the relationship between caloric cost and work rate.* Instantaneous efficiencies** derived from these exponential functions are presented along with comparable delta efficiency estimates.

Condition	Equation for the Curve $y(\text{kcal/min})^{+}=$	Equation for the Curve $y(\text{kcal/min})^{++}=$	Work Rate (kgm/min)	Instantaneous Efficiency (%)	Work Rate (kgm/min)	Delta Efficiency (%)
Horizontal walking at 3.0 km/hr (H_1)	$3.630e^{.0013x}$	$3.630e^{.580x}$	125	40.1	0-250	34.1
			375	28.5	250-500	31.3
			625	20.3	500-750	21.4
Horizontal walking at 4.5 km/hr (H_2)	$4.199e^{.0013x}$	$4.199e^{.555x}$	125	36.5	0-250	35.2
			375	26.3	250-500	24.9
			625	19.0	500-750	23.1
Horizontal walking at 6.0 km/hr (H_3)	$5.765e^{.0011x}$	$5.765e^{.474x}$	125	31.8	0-250	29.1
			375	24.1	250-500	27.7
			625	18.3	500-750	19.6
Grade (vertical) walking at 3.0 km/hr (V_1)	$3.316e^{.0014x}$	$3.316e^{.590x}$	125	43.0	0-250	38.8
			375	30.4	250-500	31.6
			625	21.5	500-750	23.4
Grade (vertical) walking at 4.5 km/hr (V_2)	$4.180e^{.0012x}$	$4.180e^{.501x}$	125	41.2	0-250	43.0
			375	30.7	250-500	29.8
			625	22.9	500-750	24.6
Grade (vertical) walking at 6.0 km/hr (V_3)	$5.679e^{.0010x}$	$5.679e^{.439x}$	125	35.3	0-250	43.9
			375	27.3	250-500	27.0
			625	21.1	500-750	20.6

* Equations based upon a least squares best fit analysis.

** Instantaneous efficiency = $(abe^{bx})^{-1}$.

\+ The curve produced is a plot of caloric cost (y) in kcal/min against external work (x) in kgm/min.

++ The curve produced is a plot of caloric cost (y) in kcal/min against external work (x) in kcal/min.

Legends

Figure 1: Effects of work rate and speed on energy expenditure (X ± S.E.) of 9 male subjects during steady-rate walking exercise. In all cases there is an exponential increase in caloric output with increasing work rate and speed indicating decreasing efficiencies. Note that above "zero" work rate the absolute caloric cost of horizontal work is slightly (and significantly) greater than that of vertical work. The equations computed for the curves indicate that at any given speed the slopes for vertical and horizontal work are essentially the same.

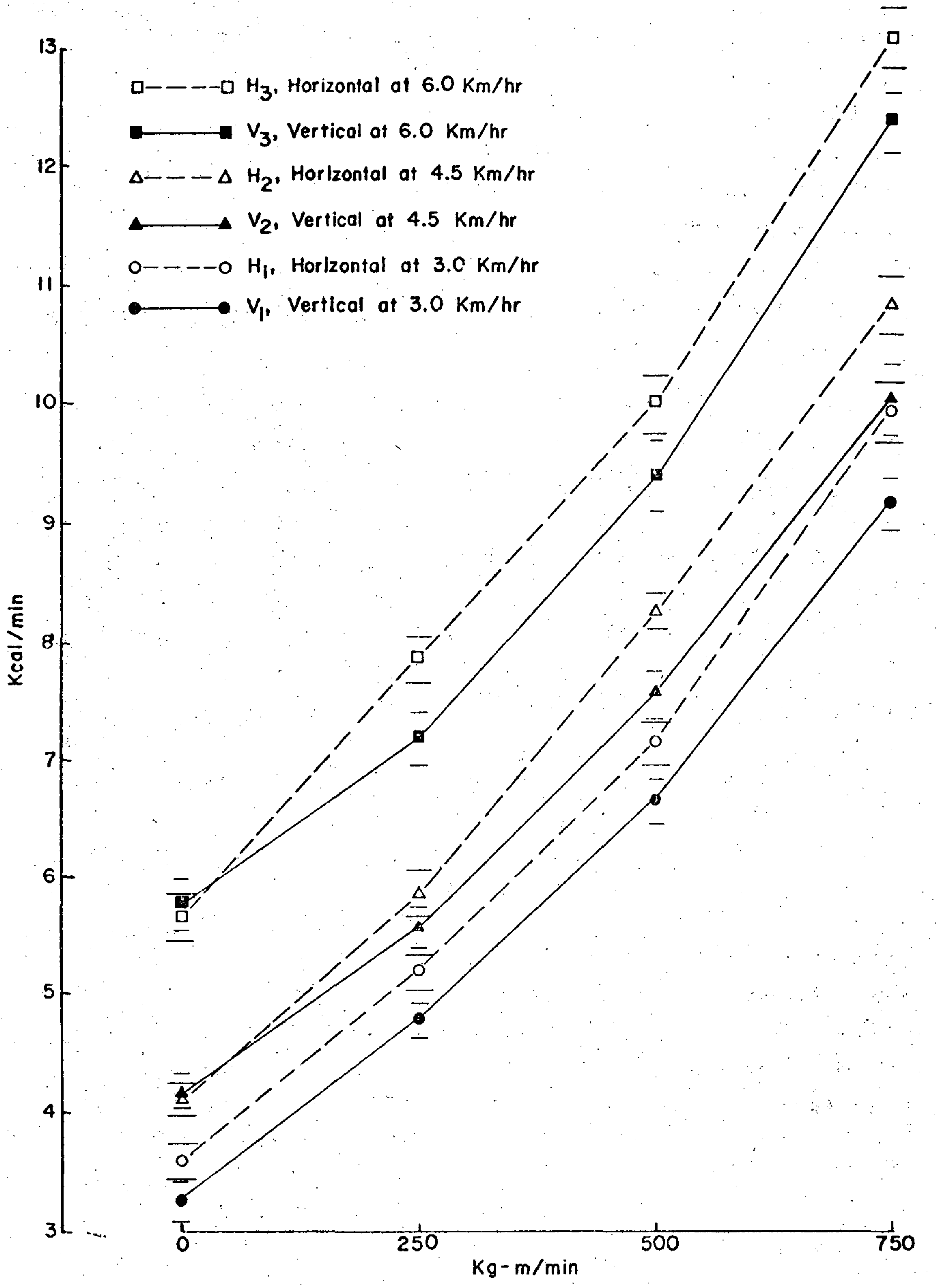
Figure 2: Effects of work rate on 'work' (2A,2B) and 'delta' (2C,2D) efficiencies (X ± S.E.) for 9 male subjects during steady-rate walking exercise at 3.0, 4.5 and 6.0 km/hr. Both efficiency calculations demonstrate decreasing efficiencies with increments in work rate. The curves for horizontal work (2A,2C) appear to be steeper than those of vertical (2B,2D) due to the very high efficiencies found at vertical work up to 250 kgm/min. The work efficiency plots are less negative in slope due to the averaging out effect of the work efficiency calculation.

Figure 3: Effects of speed on delta and work efficiencies (X ± S.E.) for 9 male subjects during steady-rate walking exercise at 500 kgm/min. Both definitions result in decreasing efficiency with increments in speed.

Figure 4: Caloric cost of combined work loads as effected by work rate is plotted against horizontal and vertical work at the same walking speed (4.5 km/hr). Note that the combined work curve superimposes itself on the curve depicting horizontal work alone at the same speed.

Figure 5: Semi-log plot of the effects of work rate and speed on energy expenditure of 9 male subjects during steady rate walking exercise.

Figure 6: Effects of work rate on mean delta (6A) and work (6B) efficiencies for both cycling and walking. Data on cycling from Gaesser and Brooks (14) using some of the same subjects. Note that most of the efficiencies for walking are equal to or greater than those of cycling.



XBL 769-9575

Fig 1

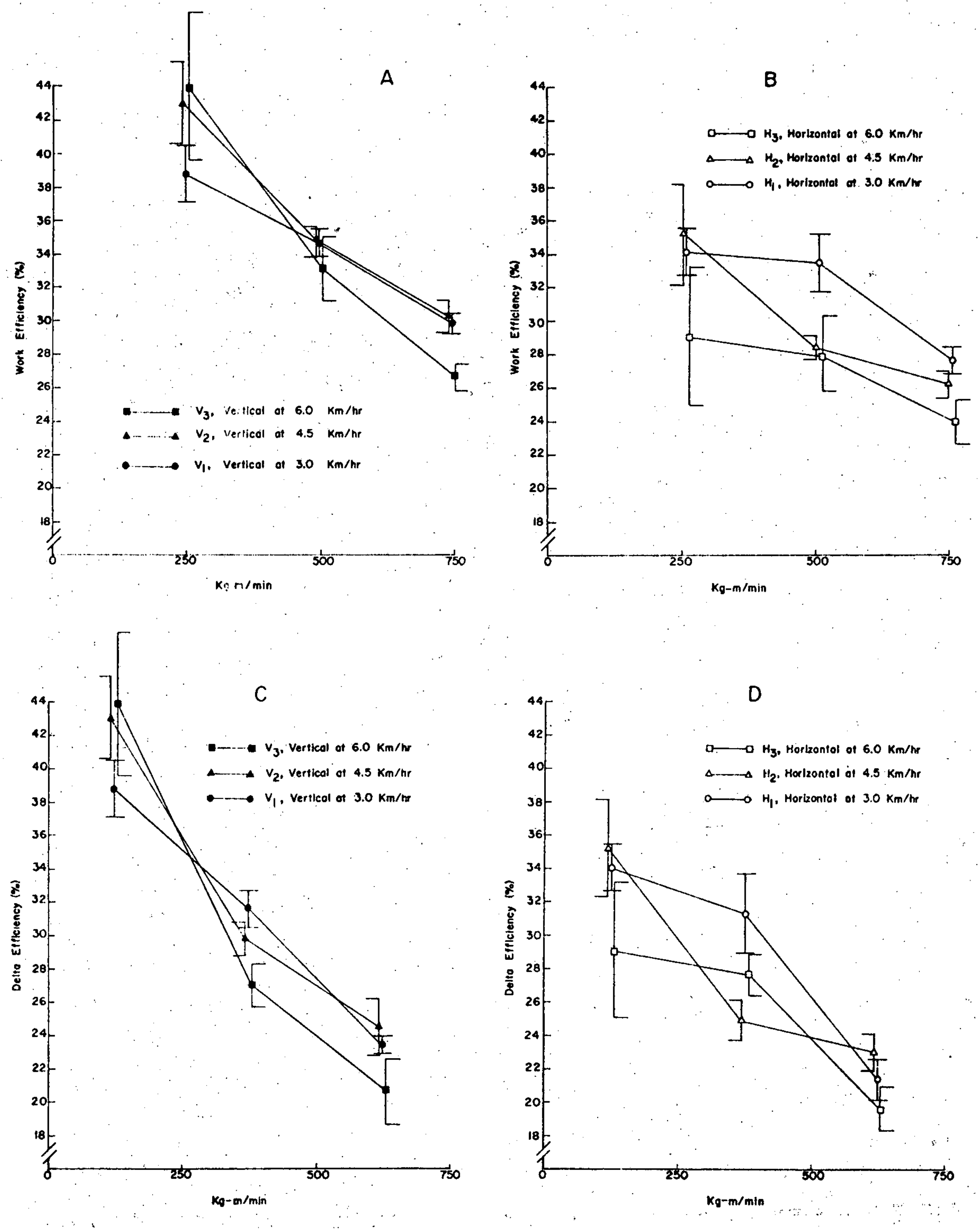


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Fig 2

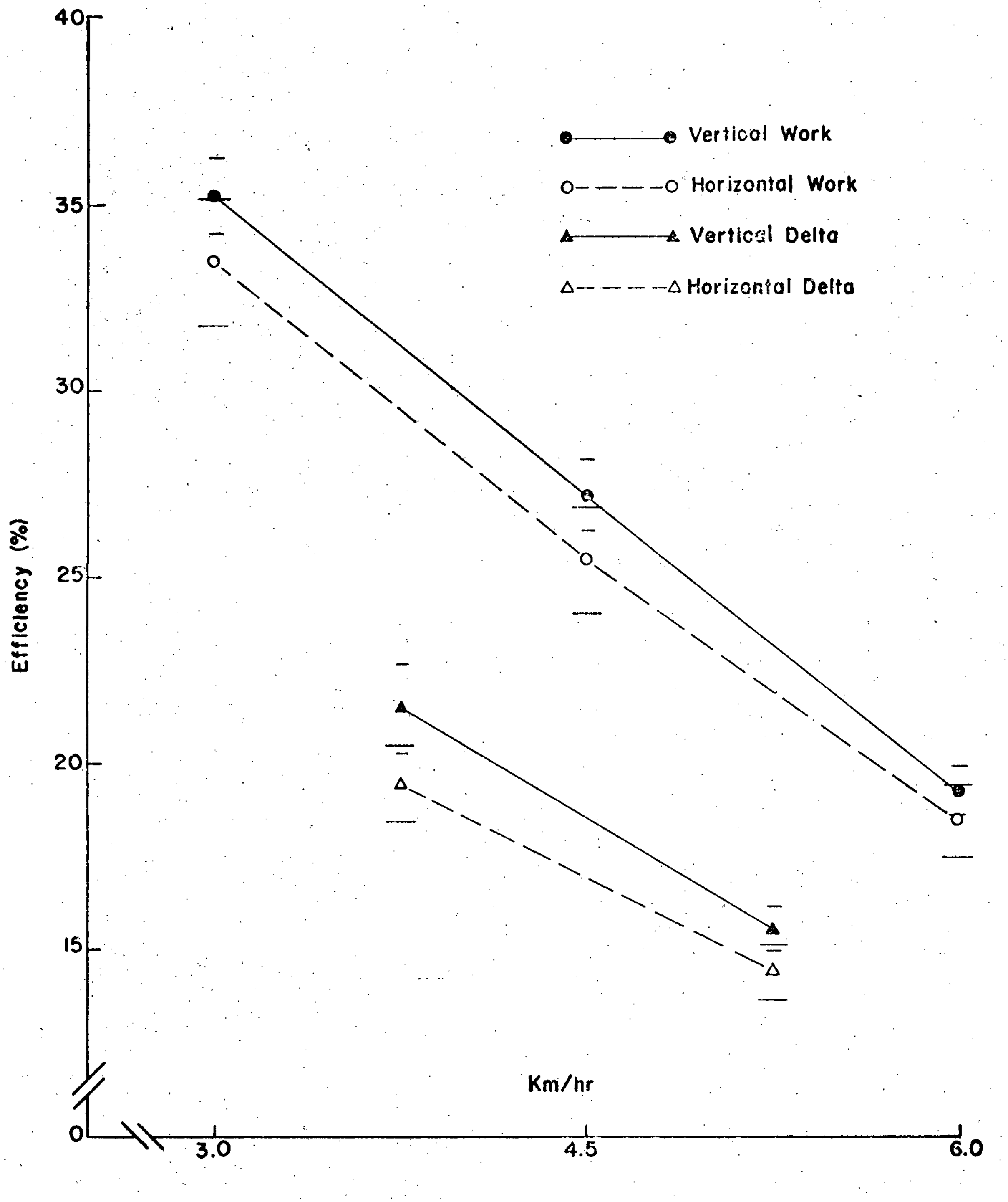

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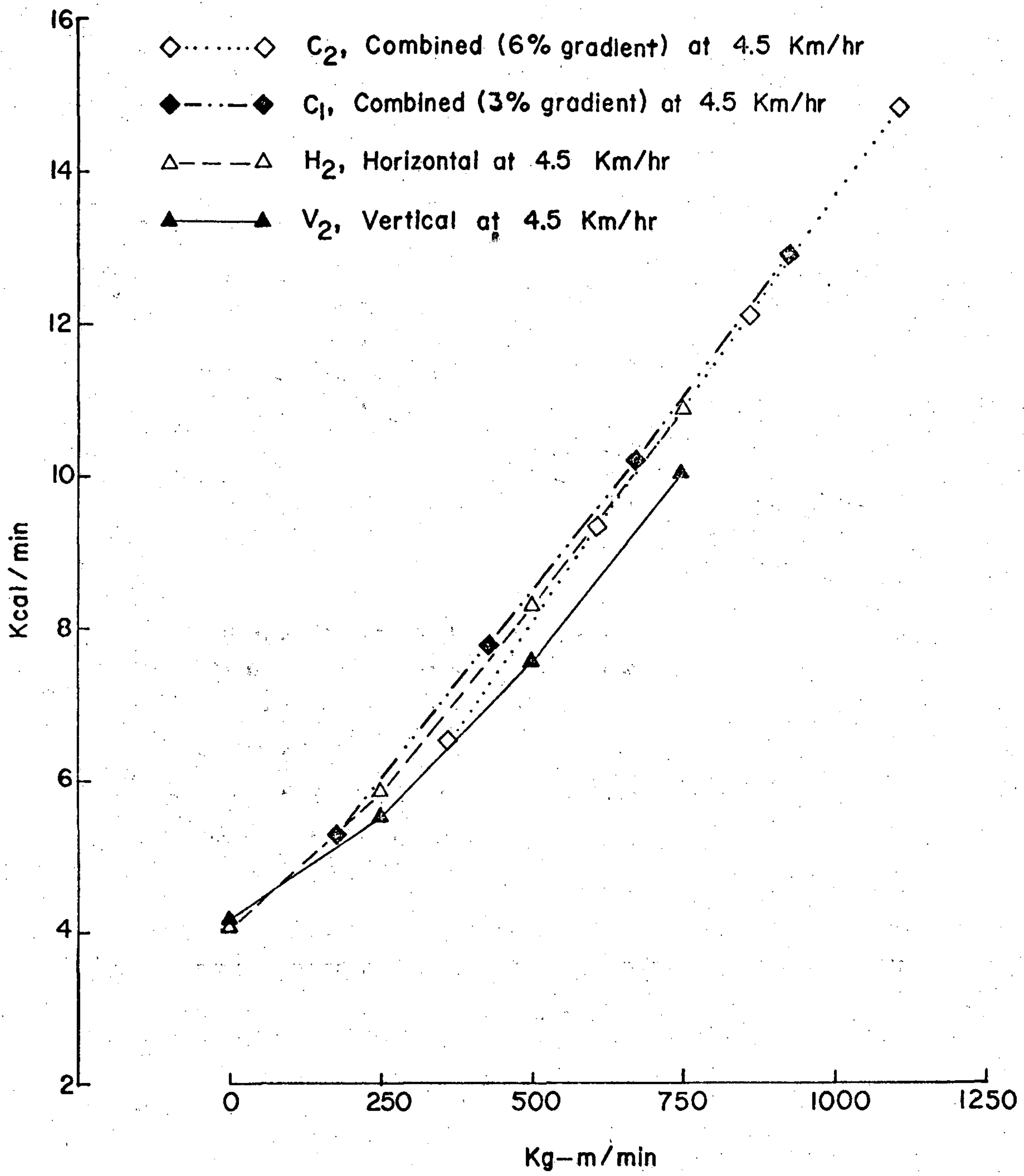
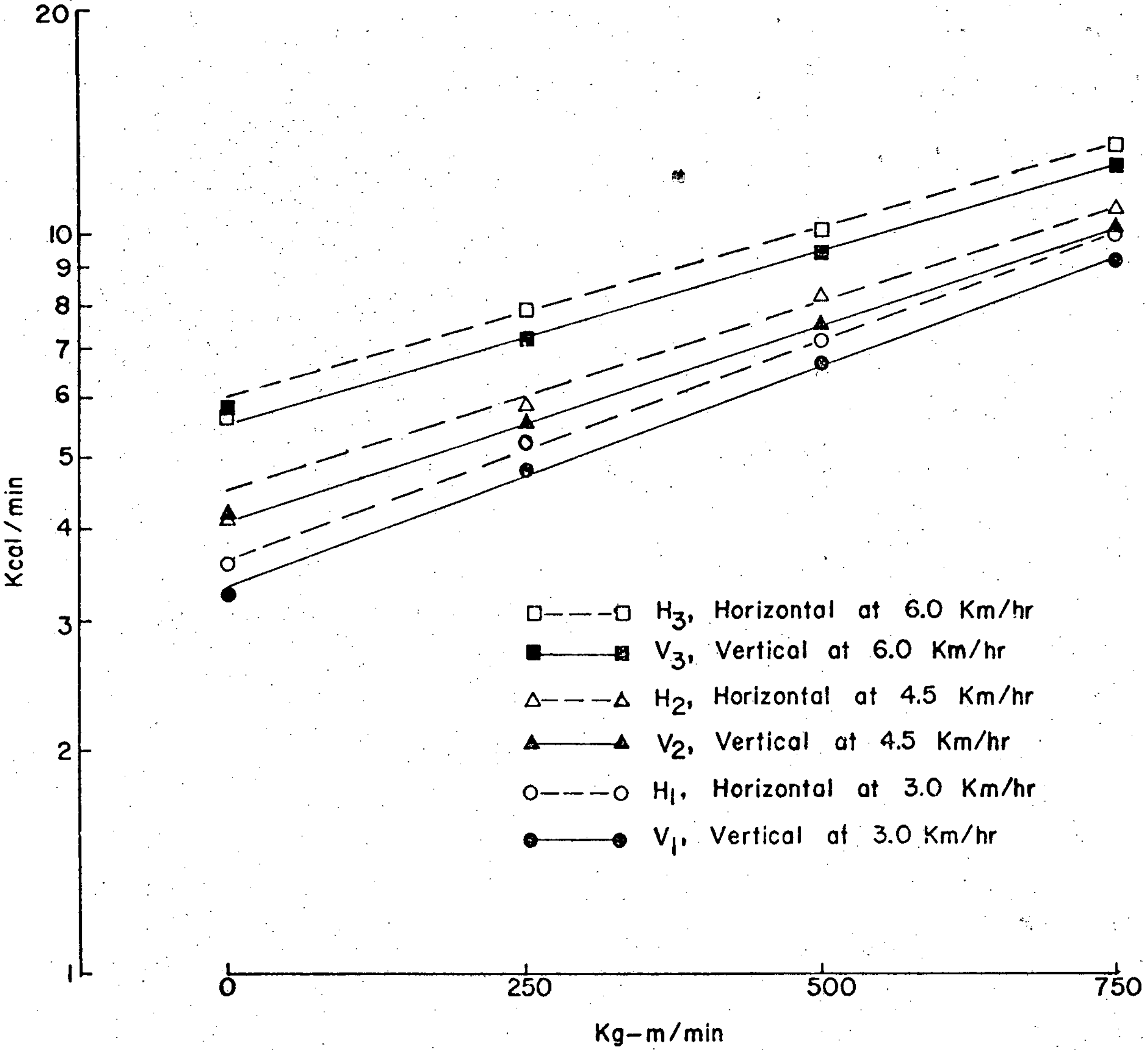
Fig 3



XBL 769-9554

Fig 41



XBL 769-9555

Fig. 5

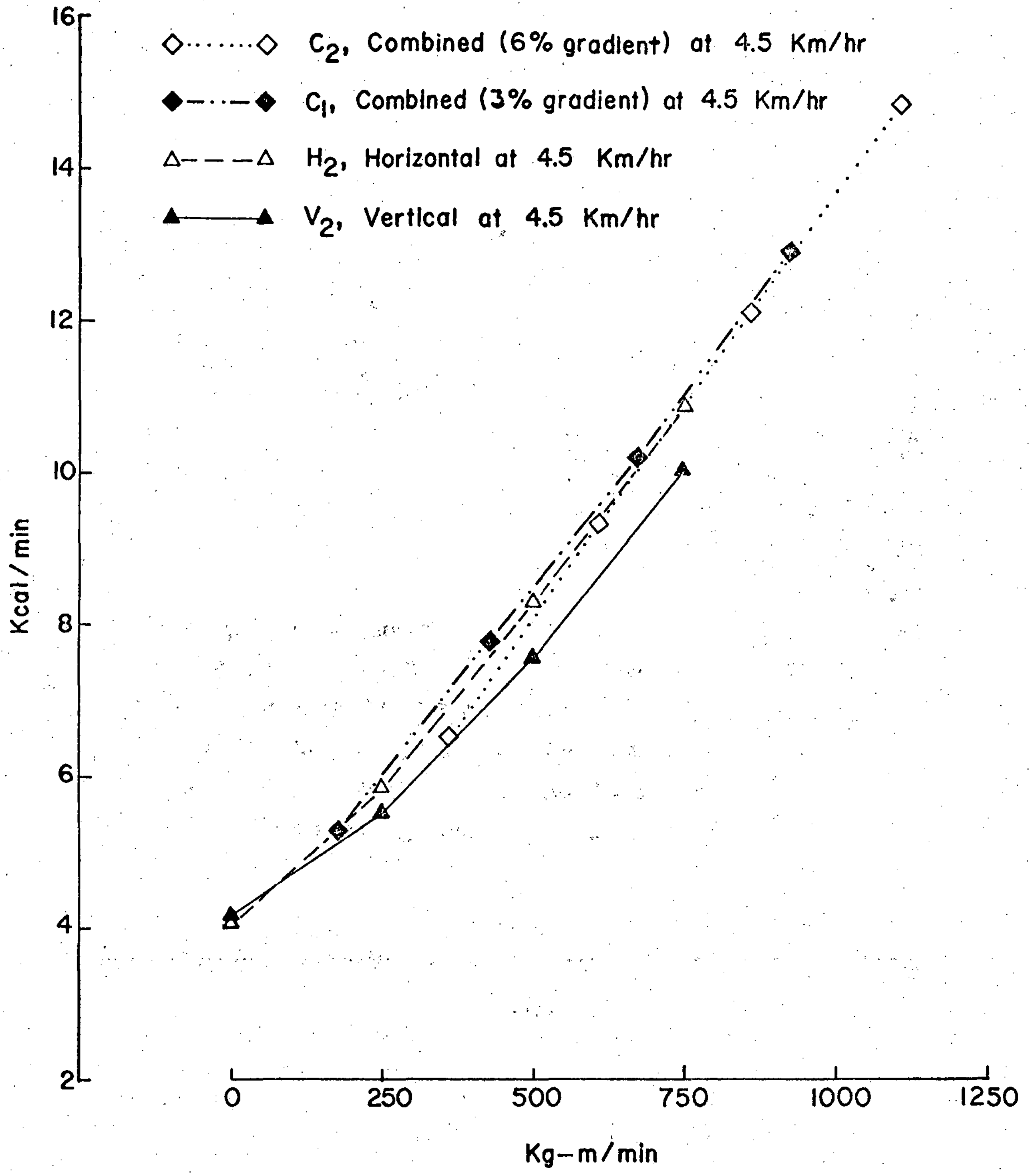


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Fig 41

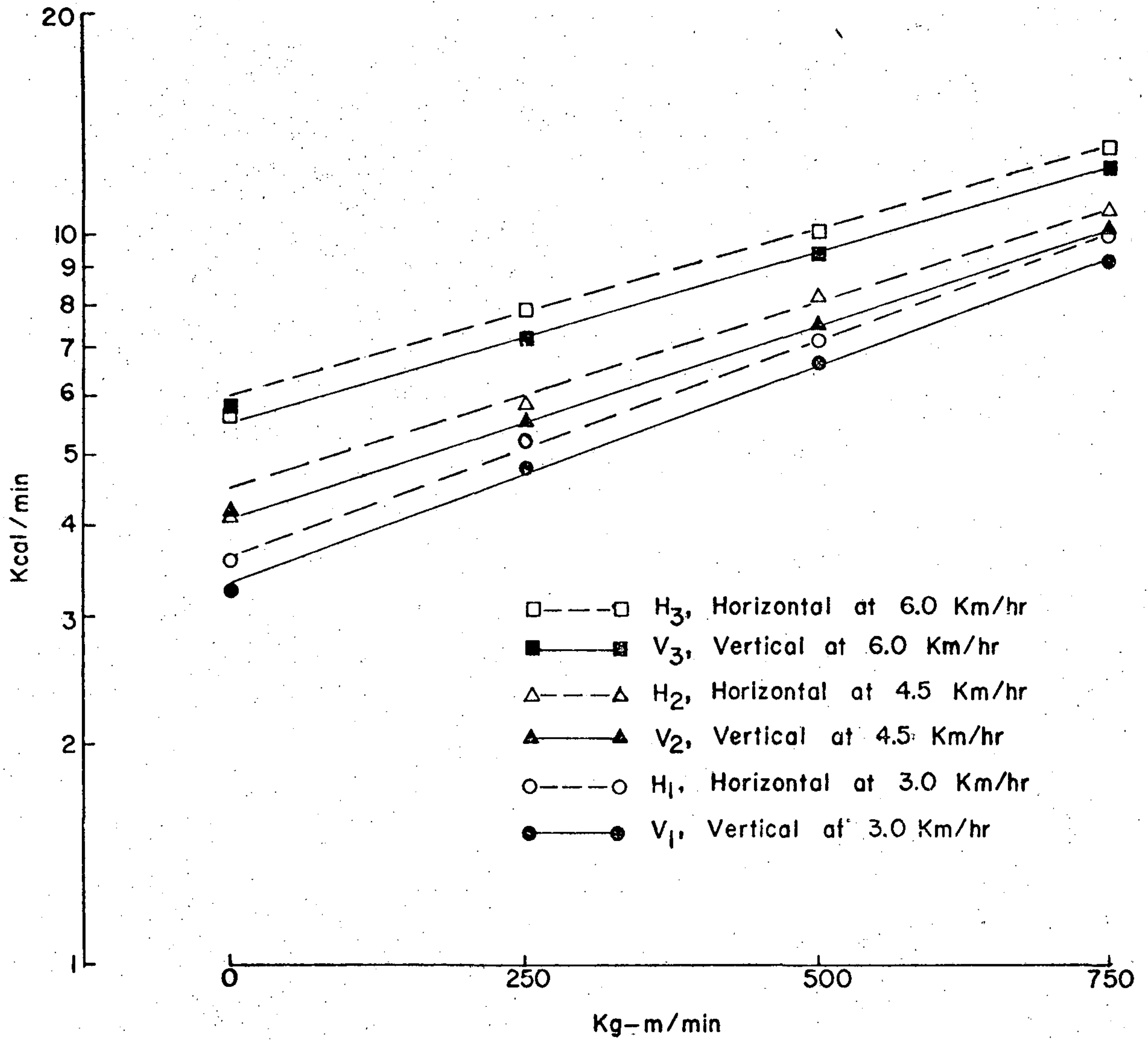

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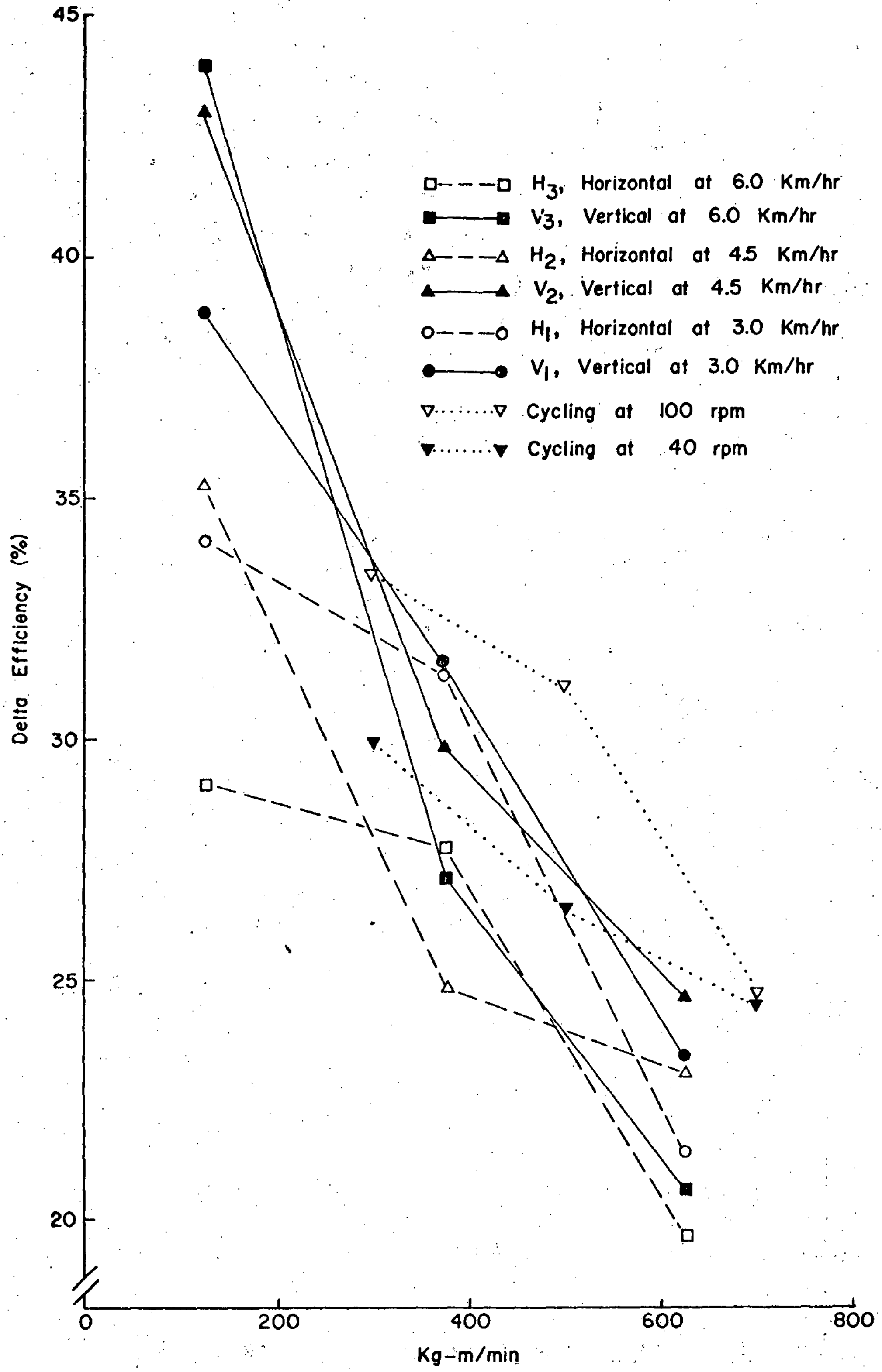
Fig 5



XBL 769-9557

Fig 6A

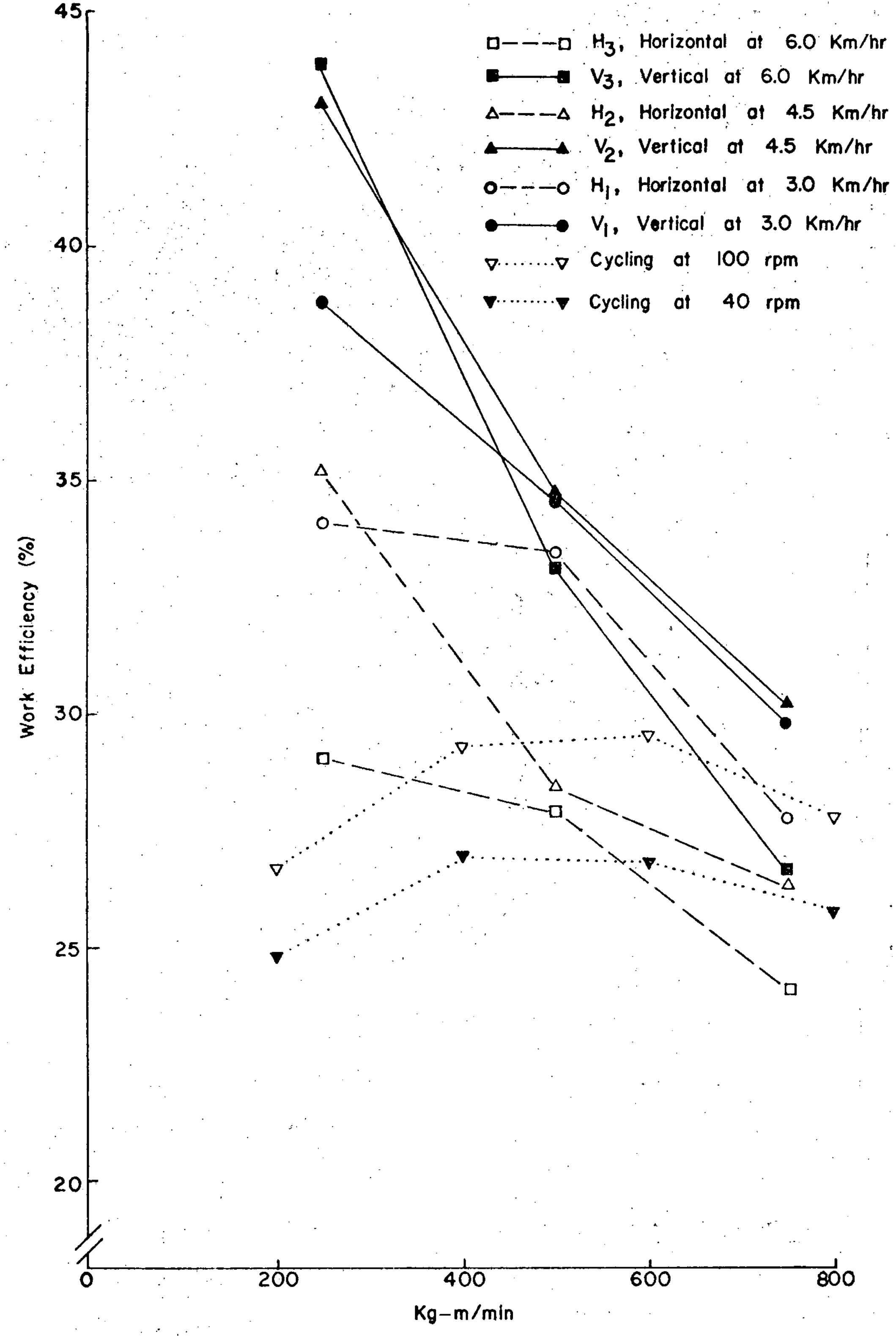


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Fig 6B

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