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ENERGETICS AND PERCEIVED EXERTION OF LOW SPEED RUNNING AND HIGH SPEED WALKING

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Abstract. *The primary purpose of this study was to determine whether the relationship between energetic consumption and speed during low speed running fit a quadratic or linear model better, and to determine the effect of model choice on the energetically optimal transition speed (EOTS). Subjects walked and ran on a treadmill at speeds ranging from 60% to 120% of their preferred transition speed (PTS) while* $\dot{V}O_2$ *and RPE data were collected. A quadratic model fit the energy data better than a linear model for walking* ($r^2 = 1.00$) *and running* ($r^2 = 0.94$)*. Neither model was superior in fitting RPE data to speed during walking and running. The EOTS occurred at* 110% *of the PTS* (2.20 $m{\cdot}s^{-1}$)*, close to the EOTS found using a linear model. At low running speeds, a quadratic model for energy-speed data is superior to a linear model, although model choice has little effect on the determination of EOTS.*

Key words: *metabolic cost, gait transition, human locomotion*

INTRODUCTION

The metabolic cost ($\dot{V}O_2$) of walking a given distance reaches a minimum value at a speed of approximately 1.25 $m{\cdot}s^{-1}$, increasing with a progressively steeper slope as speed decreases or increases (Carrier, 1984; Cavagna, 1969, 1978; Cavagna et al., 1976; Hreljac, 1993a; Margaria et al., 1963; Minetti et al., 1995). The relationship between $\dot{V}O_2$ and walking speed has been found to fit a quadratic function almost perfectly when $\dot{V}O_2$ is expressed as an energetic cost per distance walked. In contrast, the metabolic cost of running a unit distance is essentially independent of speed in both animals and humans (Ca-

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vagna, 1969; Kram & Taylor, 1990; Roberts et al., 1998; Taylor et al., 1980). As a result, energy-speed curves for running are generally depicted as being linear with a slope of close to zero. When plotted on the same graph, the speed at the intersection of the walking and running curves represents the energetically optimal transition speed (EOTS) during human locomotion (Brisswalter & Mottet, 1996; Hreljac, 1993a; Margaria et al., 1963; Mercier et al., 1994; Minetti et al., 1994).

In one of the first studies related to gait transitions of humans, Margaria (1938) concluded that the walk to run transition occurs at the EOTS in order to minimize the energetic cost of locomotion. This widely accepted hypothesis has since been refuted in several studies (Brisswalter & Mottet, 1996; Hreljac, 1993a; Minetti et al., 1994; Raynor et al., 2002) which determined that the $\dot{V}O_2$ measured while running at the preferred transition speed (PTS) is significantly greater than the $\dot{V}O_2$ measured when walking at the PTS. These studies agreed that the PTS occurs at a speed of approximately 2.0 $m{\cdot}s^{-1}$, which is considerably less than the EOTS of approximately 2.3 $m{\cdot}s^{-1}$, demonstrating that minimizing energetic cost is not the primary reason for changing gaits.

When Hoyt and Taylor (1981) noted that "there is an old controversy concerning whether metabolic rate increases linearly or curvilinearly in running humans," the "controversy" to which they were referring was related to the relationship between energetic cost and speed at high speeds of running (above the lactate threshold). Since subjects are not in a "steady state" when running at these high speeds, there has been some disagreement regarding the calculation of the non-aerobic contributions to the total energy costs. This has lead to uncertainty in the shape of the energy-speed curves during running near maximum speeds. There does not appear to be any dispute regarding the linearity of the relationship between $\dot{V}O_2$ and running speed at low and moderate speeds.

Energetic cost-speed curves for running have usually been determined by having subjects run at speeds that are considerably greater than the PTS while monitoring oxygen consumption, fitting a curve (line) to the data, then extrapolating the curve to lower and higher speeds (Falls et al., 1976; Kram & Taylor, 1990; Margaria et al., 1963). Since the energetic cost per unit distance approaches infinity as running speed approaches zero, it is logical to assume that the energy-speed relationship at low running speeds (below the PTS) would be non-linear. If this were the case, the EOTS may differ from the speed which has been previously calculated using a linear model for running. The primary purpose of this study was to determine whether energy-speed data during running conform better to a curvilinear (quadratic) or a linear model, and to determine the effect of model choice on the calculation of EOTS.

In a previous study (Hreljac, 1993a), it was reported that the rating of perceived exertion (RPE) while running at the PTS was significantly lower than the RPE while walking at the PTS even though $\dot{V}O_2$ was significantly greater during running than walking at this speed. Since RPE data were not collected at speeds other than the PTS during that study, it is not clear how RPE relates to $\dot{V}O_2$ at low speeds of running. RPE has been found to increase linearly with speed at moderate to fast speeds of running, and at slow to fast speeds of walking (Noble et al., 1973). It is possible that the RPE-speed relationship during running becomes non-linear at very low speeds. A secondary purpose of this study was to determine whether the relationship between RPE and speed conforms to a similar model as found between energy and speed during slow running.

METHODS

Preliminary Procedures

Participants in this study were 12 college students (six males, six females) who were free from musculoskeletal injury or disease at the time of the study. Prior to participation, all subjects signed informed consent forms in compliance with guidelines approved by the human subjects committee at California State University, Sacramento. The consent forms reiterated the basic procedures and intent of the study, and warned of potential risks involved as a result of participation. All data were collected while subjects walked or ran on a motor driven treadmill, with speed unknown to subjects, controlled by the experimenter. Subjects who were unfamiliar with treadmill locomotion were habituated prior to this session by walking and running at a variety of speeds on the treadmill for a period of approximately 10 minutes (more if requested). Previous researchers (Charteris & Taves, 1978; Schieb, 1986; Wall & Charteris, 1980) have demonstrated that this amount of treadmill accommodation is sufficient to reduce variability in kinematic and energetic variables.

Determination of PTS

On the first of two testing sessions, the preferred transition speed of each subject was determined. The PTS was determined on a day prior to the collection of metabolic data to minimize the possibility of fatigue becoming a factor. For this session, the treadmill speed was initially set to a speed at which subjects would be able to walk comfortably (approximately 1.3 $m \cdot s^{-1}$). Subjects were instructed to mount the treadmill and utilize the gait which felt most natural. If a subject walked continuously for a period of 30 seconds and indicated that walking was the preferred gait at this speed, the treadmill was stopped and the subject dismounted. The treadmill speed was then increased by approximately 0.1-0.2 $m \cdot s^{-1}$ before the subject remounted. Again, the subjects were instructed to use the gait which felt most natural at the new speed. If the subject walked continuously at the new treadmill speed for a period of 30 seconds and indicated that walking was the most natural gait, the procedure was repeated. The process was continued until a speed was reached at which the subject ran continuously for 30 seconds and felt that running was the most natural gait at the particular speed. This speed was defined as the walk to run transition speed. By starting the treadmill at a high enough speed to ensure that subjects would run (> 3.0 $m \cdot s^{-1}$), then decreasing the treadmill speed incrementally, the run to walk transition speed was determined. The entire process was repeated three times in random order. In order to obtain a single value, the average of the walk-run and run-walk transition speeds was defined as the PTS. A similar procedure has been utilized to determine PTS in several earlier studies (Brisswalter & Mottet, 1996; Hreljac, 1993a, 1993b, 1995a, 1995b; Minetti et al., 1994; Raynor et al., 2002).

Metabolic and RPE Data Collection

During the second session, subjects ran at 60%, 75%, 90%, 100%, and 120% of the PTS, and walked at 70%, 80%, 90%, 100%, and 110% of the PTS while $\dot{V}O_2$ data were collected. For each of the 10 randomly ordered experimental conditions, an indirect calorimetry method was used to quantify $\dot{V}O_2$. A metabolic cart, equipped with a pneumotach, paramagnetic oxygen analyzer and infrared carbon dioxide analyzer were used to quantify the volume of oxygen expired and consumed, and the volume of carbon dioxide produced (TrueMax 2400 Metabolic Measurement System, Parvo Medics, Consentius Technologies, Utah). Prior to testing, the pneumotach was calibrated utilizing a calibrated three liter syringe at various flow rates. Oxygen and carbon dioxide analyzers were calibrated using medically certified oxygen and carbon dioxide gas concentrations. Each subject was outfitted with a two way, low resistance breathing valve connected by large bore tubing to a 4 L mixing chamber for the determination of expired volume and gas concentrations.

A value for "standing" $\dot{V}O_2$ was obtained prior to any of the exercise trials by monitoring oxygen consumption during four minutes of quiet standing. Average "gross" $\dot{V}O_2$ data were acquired in 30 second intervals until one minute after steady state was reached. Steady state was defined as the point at which a plateau of the $\dot{V}O_2$ value occurred, identified by three consecutive 30 second readings within approximately 5% of each other. A single value for $\dot{V}O_2$ was calculated for each condition by averaging the last three readings obtained during a trial. Between trials, subjects were allowed as much rest as desired. The "exercise" $\dot{V}O_2$ for each condition tested was calculated by subtracting the standing $\dot{V}O_2$ from the gross $\dot{V}O_2$ value obtained during a trial. The value utilized for all subsequent analyses was the exercise $\dot{V}O_2$.

An RPE score was determined for each of the 10 conditions, including walking and running at the PTS. A printed 15 point (6 to 20) graded category scale of perceived exertion (Borg, 1973), mounted on a cardboard background, was exhibited to subjects after two minutes of each condition. To determine RPE, subjects were instructed to point to the number on the scale that most accurately corresponded to their overall sense of effort.

Statistical Analysis

Prior to statistical analyses, all $\dot{V}O_2$ data were normalized to body mass and distance to obtain a metabolic cost of transport in units of $ml\cdot kg^{-1}\cdot km^{-1}$. Curves for individual subjects, as well as for all subjects combined, were fit to the five normalized data points for both walking and running with speed (units of % PTS) along the abscissa of the curve and metabolic cost ($\dot{V}O_2$) per kilometer along the ordinate. Although previous researchers (Cavagna & Kaneko, 1977; Falls & Humphrey, 1976; Hoyt & Taylor, 1981; Margaria et al., 1963; Mercier et al., 1994; Minetti et al., 1994) have used curvilinear (quadratic) models to fit walking data and linear models to fit running data, both linear and quadratic models were tested for each gait, using a least squares regression method. The model which fit the data points better was utilized in each case. Similarly, curves were fit to the RPE data for both walking and running. Both RPE and $\dot{V}O_2$ were compared between walking and running at the PTS using paired t-tests ($p = 0.05$).

RESULTS

The average PTS of all subjects combined was 1.99 ± 0.12 $m\cdot s^{-1}$. Since there was no significant difference between the average PTS of male subjects (2.01 ± 0.13 $m\cdot s^{-1}$) and female subjects (1.97 ± 0.12 $m\cdot s^{-1}$), all subsequent analyses were conducted on the combined group.

The energetic cost of running at the PTS ($\dot{V}O_2$ = 155.1 ± 14.0 ml·kg^{-1}·km^{-1}) was significantly greater than the energetic cost of walking at the PTS ($\dot{V}O_2$ = 132.7±18.9 ml·kg^{-1}·km^{-1}). For all individual subjects, this relationship was also found to be true.

For all subjects, individually as well as for the combined group, a quadratic model fit the energy data better than a linear model during walking. With speed (v) expressed as a percentage of PTS, and $\dot{V}O_2$ expressed in units of ml·kg^{-1}·km^{-1}, the derived relationship between $\dot{V}O_2$ and speed during walking ($r^2 = 1.00$) for all subjects combined was:

$$\dot{V}O_2 = 278.7v^2 - 317.6v + 171.3 \tag{1}$$

During running, a quadratic model was a better fit than a linear model for the combined group, as well as 11 of the 12 subjects individually. The derived quadratic equation during running ($r^2 = 0.94$) for all subjects combined was:

$$\dot{V}O_2 = 120.1v^2 - 231.1v + 263.8 \tag{2}$$

These relationships are plotted in Figure 1. The minimum value of Eq. 1 occurred at a speed of 61.6% of the PTS, while the minimum value of Eq. 2 was found at a speed of 96.2% of the PTS. The intersection of these curves, representing the EOTS, occurred at a speed of 110% of the PTS. When using a linear model for running, the calculated EOTS was also at a speed of 110% of the PTS, but the equation that was derived using a linear model (Eq. 3) was not a good fit ($r^2 = 0.29$).

$$\dot{V}O_2 = -15.4v + 172.0 \tag{3}$$

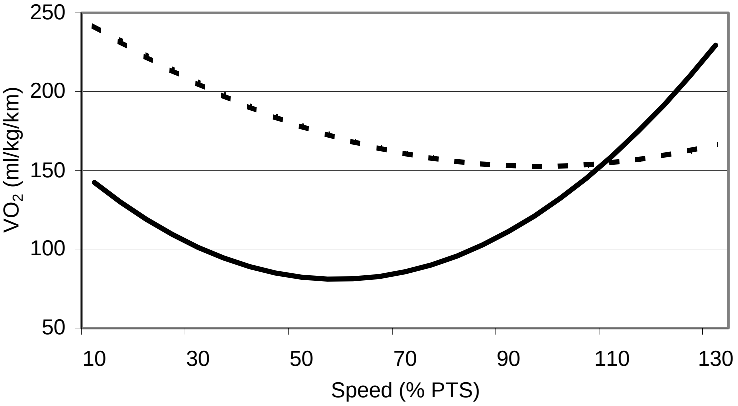

Fig. 1. Relationship between $\dot{V}O_2$ per unit distance and speed (as a % of PTS) for walking (—) and running (- - -). Intersection of the curves represents the EOTS.

The average RPE of subjects walking at the PTS (12.0 ± 2.0) was significantly greater than the average RPE of subjects while running at the PTS (8.7 ± 1.4). At comparable speeds lower than the PTS, RPE values did not differ significantly between walking and running conditions.

Linear and quadratic models fit the RPE-speed data equally well during both walking ($r^2 = 0.95$ and $r^2 = 0.96$, respectively), and running ($r^2 = 0.85$ and $r^2 = 0.90$, respectively).

Actual values of RPE for all conditions, along with the fitted linear and quadratic curves for walking and running are shown in Figure 2.

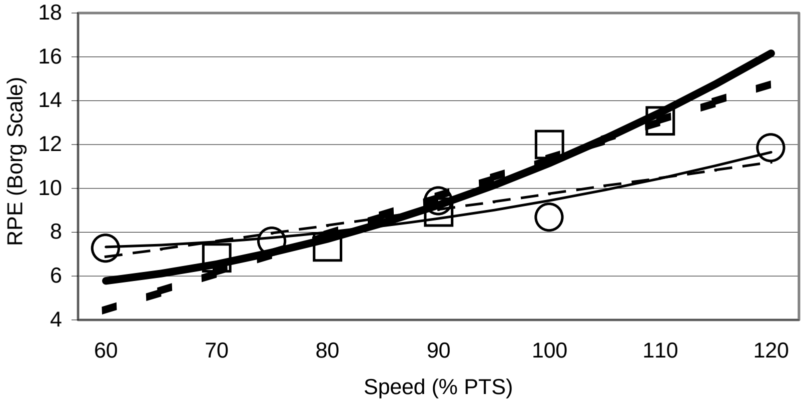

Fig. 2. Linear (- - -) and quadratic (──) models for the RPE-speed relationship during walking (bold printed curves), and running (lighter curves). The actual average RPE values are also shown for walking ( ) and running (o). Note that some values of fitted curves fall below the lowest possible value (6) on the Borg scale.

Discussion

In the present study, the relationship between $\dot{V}O_2$ and walking speed (Figure 1) fit a quadratic model almost perfectly ($r^2 = 1.00$) in agreement with several previous studies (Cavagna et al., 1976; Hreljac, 1993a; Margaria et al., 1963; Minetti et al., 1994) in which a similar relationship was reported. In these studies, the minimum $\dot{V}O_2$ during walking was reported to take place at a speed of approximately 1.25 $m{\cdot}s^{-1}$. This was in agreement with results from the present study in which the minimum $\dot{V}O_2$ during walking was determined to occur at a speed of 1.23 $m{\cdot}s^{-1}$. Thus, during walking, the energy-speed relationship displayed was as expected.

It has been suggested (Alexander, 1984; 1989) that humans avoid walking or running at speeds close to the PTS since terrestrial locomotion at these speeds is not economical. It may be true that humans rarely move at speeds close to the PTS, but in actual fact, running at speeds near the PTS may be the most economical speeds at which to run when measured as a metabolic cost per unit distance. The minimum $\dot{V}O_2$ of the best fitting curve during running occurred at a speed of 1.92 $m{\cdot}s^{-1}$ (96.2% of PTS) which is lower than speeds that have generally been tested by other researchers who have examined the relationship between $\dot{V}O_2$ and running speed. As pointed out in previous studies (Farley & Taylor, 1991; Grillner et al., 1979; Hreljac, 1993a; Hreljac et al., 2001), however, it is not likely that a person could perceive energetic cost per unit distance. The fact that this speed minimizes metabolic energy cost may be a consequence of the running style that is adopted at this low speed. Since this is the lowest speed that subjects choose to run, there may be some biomechanical disadvantage to running at lower speeds. One possibility is that support time increases disproportionately with decreasing running speed, which may subsequently decrease the ability of a runner to recover stored elastic energy with each step (Alexander & Ker, 1990; Morgan et al., 1989; Williams & Cavanagh, 1987). Running at speeds below the PTS may increase the need for eccentric activity of the relatively large muscles of the upper legs, while decreasing the ability of a runner to recover stored elastic energy with each step due to the increase in the time delay between the eccentric and concentric phases of the movement.

Using a modeling approach, Minetti and Alexander (1997) suggested that support time should be three to four time greater than swing time for running to be less economical than walking at the PTS. In actual fact, stance and swing times are nearly equal while running at the PTS (Hreljac, 1995a). The increase in relative support time may increase metabolic demands while lowering the perception of effort when a gait change occurs. In this study, it was found that RPE was significantly lower during running than walking at the PTS, and RPE was approximately equal during walking and running at comparable speeds lower than the PTS. At all speeds equal to or less than the PTS, $\dot{V}O_2$ was significantly lower during walking than running. This may indicate that overall muscular stress was comparable in walking and running, but running involves large muscle groups to a greater extent than walking.

A curvilinear (quadratic) model ($r^2 = 0.94$) was found to fit the energy-speed data for running considerably better than a linear model ($r^2 = 0.29$) at the low speeds tested. This curvilinear energy-speed relationship would likely be found only when very low running speeds are included in the sample. In several previous animal (Alexander & Ker, 1990; Hoyt & Taylor, 1981; Kram & Taylor, 1990; Perry et al., 1988; Taylor et al., 1980) and human studies (Brisswalter & Mottet, 1996; Cavagna, 1969, 1978; Cavagna et al., 1976; Margaria et al., 1963) in which a wide range of running speeds were tested, the relationship between $\dot{V}O_2$ and running speed has been depicted to be linear with a slight positive or zero slope. However, the slope of the $\dot{V}O_2$-speed curve has been reported to be slightly negative when investigators utilized a narrow range of speeds which included relatively low running speeds (Hreljac, 1993a; Minetti et al., 1994). These studies may have examined some speeds that were in the non-linear region of the energy-speed relationship, but when combined with other data collected, the best fitting curve was still linear, albeit with a slight downward trend. Combining evidence from previous studies with the results of the present study, it appears that the true energy-speed relationship for running is linear (and relatively constant) for most mid-range speeds, but increases in a curvilinear fashion when running speeds are at the extreme low and high ranges.

A widespread assumption expressed by several researchers (Alexander, 1989; Cavagna, 1969; Cavagna & Franzetti, 1986; Grillner et al., 1979; Heglund & Taylor, 1988; Hoyt & Taylor, 1981; McMahon, 1985) is that animals, including humans, change gaits at speeds which minimize metabolic energy consumption. By demonstrating that the EOTS occurs at speeds greater than the PTS, this hypothesis has been refuted in the present study as well as in several earlier studies (Brisswalter & Mottet, 1996; Hreljac, 1993a; Minetti et al., 1994).

CONCLUSION

Interestingly, the EOTS found in this study was not affected by the choice of a model (linear vs. quadratic) used to depict the energy-speed relationship during running, and was in agreement with values found in previous studies (2.20 vs. 2.24 $m \cdot s^{-1}$, respectively). In the region of intersection between the running and walking curves (EOTS), the running curve (using a quadratic model) has only a very slight positive slope. It is likely that the running curve has just entered into the region that has generally been depicted as being linear. Thus, the value of the curve in the quadratic model would not differ greatly from the value of the curve using a linear model.

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ENERGETIKA I OPAŽANJE NAPREZANJA KOD SPOROG TRČANJA I BRZOG HODANJA

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Osnovni cilj ove studije bio je da se utvrdi da li odnos izmedju energetske potrošnje i brzine tokom trčanja sporim tempom više odgovara kvadratnom ili linearnom modelu i da se utvrdi efekat izbora modela na energetski optimalnu tranzicionu brzinu (EOTS). Ispitanici su hodali i trčali na tredmilu brzinom koja se kretala od 60% *do* 120% *njihove poželjne tranzicione brzine (PTS), pri čemu su prikupljani početni podaci za* $\dot{V}O_2$ *i RPE. Pronađeno je da kvadratni model više odgovara podacima za utrošenu energiju nego linearni model za hodanje* (r^2=1,00) *i trčanje* (r^2=0,94). *Ni jedan model se nije pokazao superiornijim u odnosu na RPE podatke tokom hodanja i trčanja. EOTS se pojavljuje u* 110% *vrednosti PTS* (2,20$m.s^{-1}$)*, a vrlo blizu EOTS podacima za linearni model. Za male brzine trčanja, kvadratni model za odnos energija-brzina jeste superiorniji u odnosu na linearni model, iako izbor modela ima malo uticaja na određivanje EOTS-a.*

Ključne reči: *metabolički utrošak, tranzicija hodanja, ljudsko pokretanje*