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Fuel oxidation during human walking☆

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Abstract

Human adults walk at a characteristic speed, but the mechanisms responsible for this ubiquitous and reproducible behavior remain unknown. In this study, preferred walking speed (PWS) was 4.7 ± 0.1 km h^{-1} in 12 overnight-fasted adults, mean age 30.0 ± 2.6 years. Indirect calorimetry was used to measure fuel oxidation during level treadmill walking from 3.2 to 7.2 km h^{-1} progressively increased at increments of 0.8 km h^{-1} and 10.0-min intervals. Corroborating many previous reports, the O_2 cost of transport (mL O_2 kg^{-1} km^{-1}) was numerically lowest at 4.8 km h^{-1}, near PWS, but was not significantly different than 5.6 km h^{-1}. The impact of walking speed on the fuel selection of skeletal muscle was much more dramatic. At speeds less than or equal to PWS, muscle carbohydrate (CHO) oxidation rates were quite low, in the range that could be matched by gluconeogenesis. Above 4.8 km h^{-1}, CHO oxidation rate increased abruptly and tracked the perception of effort (RPE). Stepwise linear regression revealed that CHO oxidation explained 70% of the variance in RPE, and speed provided an additional 4%. In contrast, the other variables included in the analysis, fat oxidation rate, heart rate, and O_2 cost of transport, contributed no additional explained variance in RPE. We conclude that PWS is just below a threshold speed, above which CHO oxidation abruptly increases. The central nervous system may be guided by the perception of effort in selecting a PWS that minimizes dependence on CHO oxidation. We further conclude that skeletal muscle metabolic control is an important factor to be taken into account by the central nervous system motor control of human locomotion.

1. Introduction

Adult able-bodied humans naturally select a walking speed of roughly 4.5 km h^{-1} (2.8 mph) [1-5]. The mechanisms responsible for this unconscious and reproducible behavior remain unknown, but it is generally accepted that the central nervous system (CNS) selects preferred walking speed (PWS) to minimize energy expenditure [6]. According to this "minimal energy hypothesis," the CNS selects the walking speed that minimizes the energy (or O_2) cost to move a unit mass a unit distance (the "energy cost of transport"). Previous studies [2,6] have shown a U-shaped relationship between walking speed and the energy cost of transport, with the nadir indeed occurring at ~4.5 km h^{-1}, the PWS of most adults.

Implicit in the minimal energy hypothesis of PWS is the concept that CNS motor control somehow takes into account the energy metabolism of the activated skeletal muscle. Although the minimal energy model offers no such mechanism, it nevertheless predicts that the CNS selects PWS with great sensitivity [2,6]. The U-shaped energy cost of transport curve vs speed is rather flat, such that a very small, less than 10%, energetic penalty would result from a rather large (33%) error in speed selection. We wondered what mechanism might account for such a link between CNS motor control and metabolic control within myocytes.

Sustained contractile activity by skeletal muscle during walking demands a rate of energy use by ATP-using sites (eg, myosin ATPase) that is matched by an equivalent rate of energy production by mitochondrial oxidative phosphorylation. The minimal energy concept focuses on the energy use side of this energy loop. The energy-producing side of the loop, mitochondrial fuel oxidation, however, has received essentially no attention.

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Carbohydrate (CHO) and fat account for more than 90% of the fuel combusted by skeletal muscle mitochondria during contractile activity [7]. In general, the fractional contribution of CHO to the fuel supply is small at low intensity and rises with the energy turnover rate [8]. The fuel selected by working skeletal muscle profoundly impacts endurance capacity. A lean postprandial 70 kg human body might store about 400 000 kJ as fat (triglyceride), but only about 10 000 kJ as CHO. Thus, the issue of fuel selection predicts over a 30-fold range in walking endurance based on the putative relation between speed and CHO dependence. In marked contrast, the minimal energy hypothesis predicts that a large error in speed selection would result in a very small percentage decrement in energetic economy and endurance.

This evolutionary argument advances the concept that it would be important for the human CNS to naturally select a walking speed that required little or no net CHO depletion. We propose that the CNS senses, subjectively perceived as "effort" [9], the intracellular energetic milieu associated with fuel switching in activated skeletal muscle. Thus, the purpose of the present study was to measure fuel selection in fasted subjects during level treadmill walking and, further, to assess the relationship between CHO oxidation and the perception of effort.

2. Materials and methods

2.1. Subjects

Twelve healthy adults with mean body mass of 68.9 ± 3.3 kg and aged 30.0 ± 2.6 years participated in these studies. The subjects were weight stable and free from any metabolic, cardiovascular, orthopedic, or neurological disorders. Subjects described their habitual diets as "not unusual in any way"; no subject was consciously modifying the intake of any macronutrient for several months before the study. They reported to the laboratory between 7:00 and 9:00 AM in an overnight fasted state. On the first visit, subjects were familiarized with the experimental protocols by walking on the treadmill over the speed range of 3.2 to 7.2 km h^{-1} (2.0 to 4.5 mph). On subsequent laboratory visits, indirect calorimetry was used to assess energy expenditure and fuel oxidation rates [10] during treadmill walking. All procedures were approved by the Institutional Review Board at Arizona State University.

2.2. Protocol

Subjects abstained from strenuous exercise and caffeine for the 24 hours preceding data collection and reported to the laboratory after an overnight fast. Preferred walking speed was measured by timing subjects walking overground on a 53.0-m loop. Subjects were timed as they walked four 53.0-m lengths at their natural rate, and the mean walking speed was calculated. The coefficient of variation for this measurement was 1.6% ± 0.3%. Subjects were then weighed, fitted with a heart rate (HR) monitor (Polar, Lake Success, NY), and instrumented for the collection of expired air. Resting HR and gas exchange were measured while subjects sat quietly for 15 min. Subjects then walked on a level treadmill at 3.2 km h^{-1} for 10.0 minutes. Speed was increased every 10.0 minutes by 0.8 km h^{-1} increments up to 7.2 km h^{-1}, for a total of 60 minutes of treadmill walking. Expired air and HR data were collected during the last 2.0 minutes at each speed. Borg's 6 to 20 rating of perceived exertion (RPE) scale [11] was also assessed at each speed by having subjects point to the appropriate value. These values were then transformed to a 0-to-10 scale [12]. Blood was collected from a fingertip for the assay of blood lactate during the last minute at each speed.

2.3. Measurement of fuel oxidation

Indirect calorimetry was used to estimate CHO and fat oxidation at rest and during walking [10]. Protein oxidation was assumed to be negligible [7]. O_2 consumption and CO_2 production were measured continuously with a TrueMax 2000 metabolic cart (Parvo, Salt Lake City, Utah). The O_2 cost of transport (mL O_2 kg^{-1} km^{-1}) was calculated as mass specific O_2 consumption rate divided by walking speed.

At least 2 important experimental conditions are necessary for the accurate evaluation of skeletal muscle fuel selection during the mild exercise of walking. First of all, the net gas exchange above rest should be calculated to subtract out the relatively large contributions of other tissues (eg, the splanchnic bed and the CNS) to whole-body energy metabolism at these mild intensities. This approach is justified by studies showing that activated muscle almost fully accounts for the increase in oxidative metabolism above rest elicited by exercise [13-16]. Secondly, gas exchange kinetics associated with CHO combustion is very slow in overnight-fasted individuals during mild exercise [17]. Thus, because the half-time of the CHO response is about 2.0 minutes, 10 minutes duration at each speed was an essential feature of the experimental design.

2.4. Statistical analysis

After screening the data for normality and homogeneity of variance, 1-way repeated-measures analyses of variance were used to determine whether O_2 cost of transport, net CHO oxidation, and/or the rate of rise of CHO oxidation differed across speeds. In the presence of a significant main effect, post hoc tests were performed using paired t tests at the points of interest. Bonferroni corrections for multiple comparisons were made to reduce the risk of a type I error. Specifically, the O_2 cost of transport and net CHO oxidation values at the speed (4.8 km h^{-1}) nearest the experimentally determined PWS were compared to values at each of the other speeds. To determine the approximate speed threshold at which net CHO oxidation began to rapidly rise, the slopes representing the rates of rise in net CHO oxidation were compared to the "baseline" slope, or that slope associated with a speed increase of 3.2 to 4.0 km h^{-1}.

Table 1
Metabolic response to walking

Speed (km h^{-1})	$\dot{V}O_2$ (mL min^{-1} kg^{-1})	$\dot{V}CO_2$ (mL min^{-1} kg^{-1})	RER	J_{cho} (cal min^{-1} kg^{-1})	J_{fat} (cal min^{-1} kg^{-1})	RPE	HR
0.0	4.5 ± .4	3.7 ± .3	0.832 ± .015	9.2 ± 1.1	12.3 ± 1.9	0.0 ± .0	67.3 ± 4.7
3.2	10.0 ± .3	8.0 ± .2	0.804 ± .012	16.6 ± 1.7	31.1 ± 2.8	0.6 ± .2	83.9 ± 4.6
4.0	11.3 ± .4	9.1 ± .2	0.805 ± .012	18.9 ± 2.0	34.9 ± 3.3	1.0 ± .2	88.6 ± 4.4
4.8	13.2 ± .5	10.6 ± .3	0.802 ± .011	21.3 ± 2.1	41.3 ± 3.7	1.4 ± .2	95.2 ± 4.8
5.6	15.7 ± .5	12.7 ± .3	0.811 ± .009	28.1 ± 2.1	46.6 ± 3.3	2.1 ± .3	105.3 ± 5.5
6.4	18.7 ± .6	15.5 ± .4	0.830 ± .010	39.9 ± 3.0	49.8 ± 3.9	3.3 ± .3	117.2 ± 6.6
7.2	23.6 ± .8	20.4 ± .7	0.870 ± .014	66.2 ± 5.3	48.3 ± 5.7	4.9 ± .5	139.5 ± 7.9

Metabolic response to walking on a level motor-driven treadmill. Mass-specific whole-body O_2 consumption rate ($\dot{V}O_2$) and CO_2 production rate ($\dot{V}CO_2$) are reported as mL min^{-1} kg^{-1}. RER indicates respiratory exchange ratio ($\dot{V}CO_2/\dot{V}O_2$). Whole-body CHO (J_{cho}) and fat (J_{fat}) oxidation rates are reported as cal min^{-1} kg^{-1}. Rating of perceived exertion is reported as RPE units converted to a 0 to 10 scale (see Materials and methods). All data represent stable values observed from minute 8.0 to 10.0 at each speed. Values are mean ± SE, n = 12.

For all comparisons, a $P < .05$ was used to determine statistical significance. Linear regression was used to characterize the relation between O_2 consumption rate and walking speed. Stepwise regression analysis with RPE as the outcome variable and CHO oxidation rate, fat oxidation rate, speed, HR, and O_2 cost of transport as the predictor variables was also performed to determine which predictor(s) contributed to explained variance in RPE. SPSS statistical software version 12 was used for all analyses (SPSS Inc, Chicago Ill).

3. Results

The PWS in this study was 4.7 ± 0.1 km h^{-1}, which is similar to previously published values [1]. Table 1 reports the gas exchange, HR, and RPE data collected as means ± SE. The estimated whole-body $\dot{V}O_2$max values, based on the heart rate reserve to $\dot{V}O_2$ relation of each subject during treadmill walking, were 33.5 ± 3.0 mL min^{-1} kg^{-1} for female subjects (n = 7) and 46.6 ± 8.3 for males (n = 5), representing roughly the 50th and 75th percentiles for age-specific aerobic fitness, respectively. Subjects rested at metabolic rates and respiratory exchange ratios typical of 12-hour fasted individuals [18,19]. Fig. 1 shows that the familiar quadratic relation between mass specific O_2 consumption rate ($\dot{V}O_2$) and walking speed ($R^2 = 0.99$) was observed.

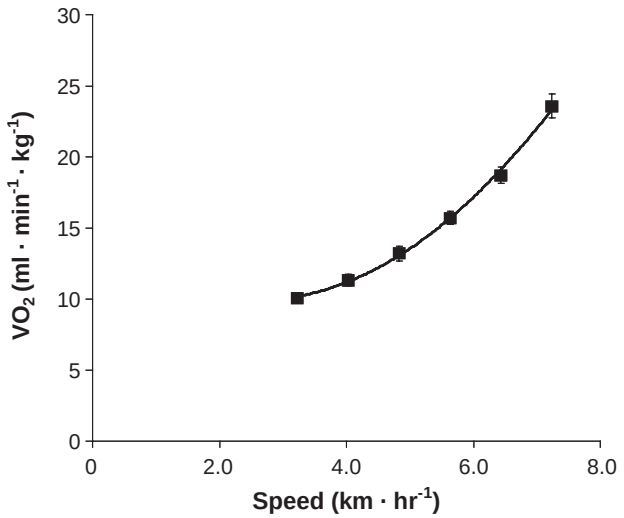

Fig. 1. Mass-specific O_2 consumption rate across walking speeds from 3.2 to 7.2 km h^{-1}. The data corroborate many previous reports showing a quadratic relation between $\dot{V}O_2$ and walking speed. The equation of the line is: $y = 0.62x^2 - 3.17x + 14.00$. $R^2 = 0.99$. All values are means ± SE.

3.1. O_2 cost of transport

The O_2 cost of transport data are plotted in Fig. 2. O_2 cost of transport varied across walking speeds ($F_5 = 31.2$, $P < .001$), with the minimum numerical value corresponding with a walking speed of 4.8 km h^{-1}, the point nearest to the PWS. Relative to the O_2 cost of transport at 4.8 km h^{-1}, values associated with speeds of 3.2, 4.0, 6.4, and 7.2 km h^{-1} each differed ($P < .01$; Fig. 2). Fig. 2 shows clearly that, when the scaling on

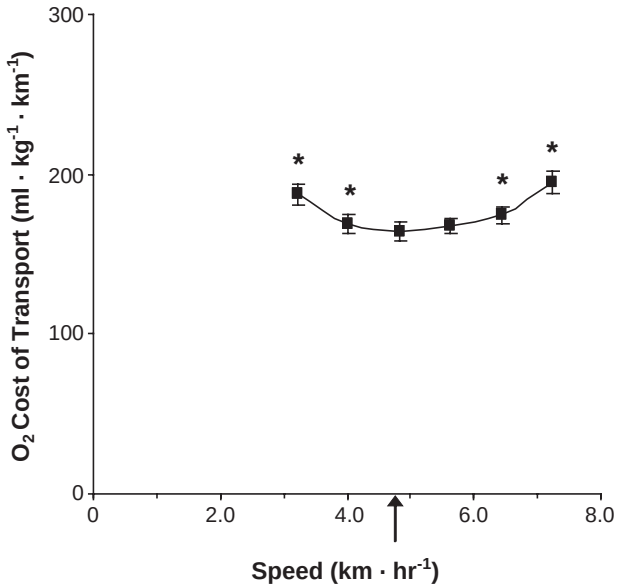

Fig. 2. The O_2 cost of transport, reported as mL O_2 required to move 1 kg body mass 1 km, exhibits the typical U-shaped relation, with PWS (4.7 km h^{-1}) occurring at the nadir. Because the ordinate is not broken in this figure, the U-shaped character is rather flat with small differences in cost of transport across the speed range 4.0 to 6.0 km h^{-1}. The O_2 cost of transport at 5.6 km h^{-1} was not significantly different compared to 4.8 km h^{-1}. The arrow indicates mean PWS in this study. All values are means ± SE. $^*P < .01$ compared to 4.8 km h^{-1}.

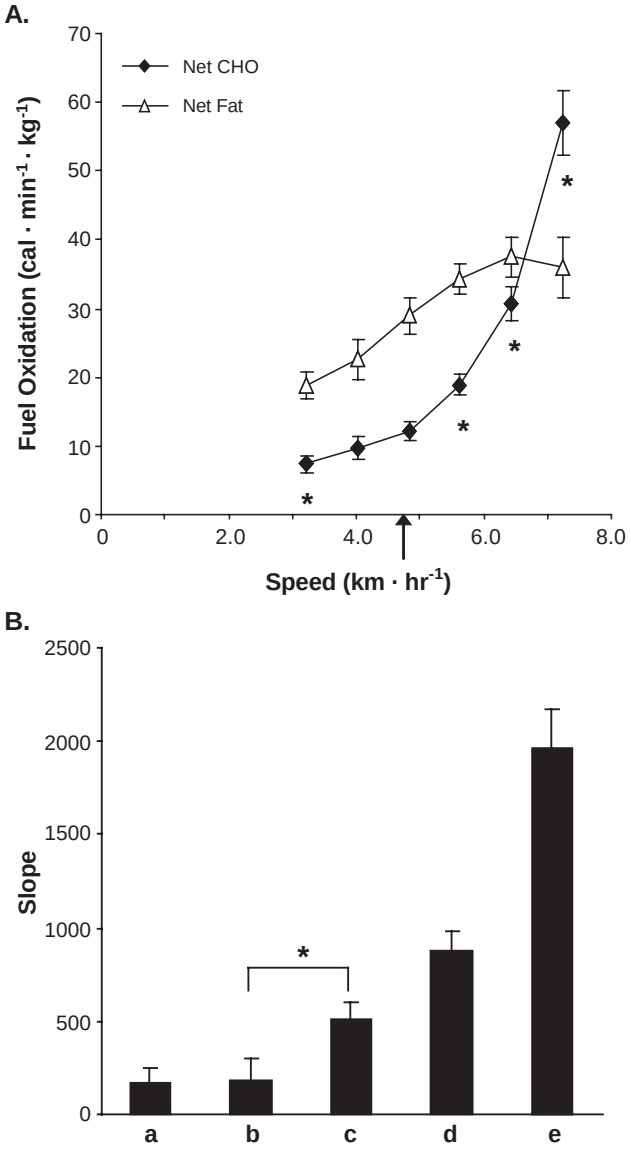

Fig. 3. A, Net fuel oxidation rates were calculated by subtracting resting $\dot{V}O_2$ and $\dot{V}CO_2$ from the corresponding steady-state values measured during walking. These net $\dot{V}O_2$ and $\dot{V}CO_2$ values were then inserted into the equations of Frayn [10] to estimate the CHO and fat oxidation rates of skeletal muscle activated to support walking. Net CHO oxidation rate is low and rises linearly up to 4.8 km h^{-1}. Above this speed, net CHO oxidation rate increases abruptly. The arrow indicates mean PWS in this study. All values are means ± SE. *$P < .01$ compared to 4.8 km h^{-1}. B, Slopes of net CHO oxidation rate reported as cal kg^{-1} km^{-1} are given for each increment in speed in panel (A) above. Thus, *a* is the slope of the CHO oxidation rate from 3.2 to 4.0 km h^{-1}, *b* the slope from 4.0 to 4.8 km h^{-1}, and so on. Carbohydrate oxidation rate abruptly increased at speeds exceeding 4.8 km h^{-1}; the slope across the speed increment from 4.8 to 5.6 km h^{-1} was 3 times greater than that from either 3.2 to 4.0 km h^{-1} or 4.0 to 4.8 km h^{-1} ($P < .01$). *$P < .01$ slope from 4.8 to 5.6 km h^{-1} vs 4.0 to 4.8 km h^{-1}.

the ordinate appropriately avoids a broken axis, the U-shaped curve championed by the minimal energy hypothesis is rather flat. Indeed, O_2 cost of transport values at 4.8 and 5.6 km h^{-1} were not significantly different. Furthermore, walking at either one-third faster (6.4 km h^{-1}) or slower (3.2 km h^{-1}) than the numerical nadir of the curve (4.8 km h^{-1}) demanded O_2 cost of transport values that were only 6% and 14% higher, respectively.

3.2. Fuel oxidation during walking

Fig. 3A illustrates the net rates of CHO and fat oxidation across walking speeds from 3.2 to 7.2 km h^{-1}. Net CHO oxidation rate remains very low at speeds less than 4.8 km h^{-1}. Fat oxidation provides the vast majority of the energy to walk up to this speed. At speeds above 4.8 km h^{-1}, CHO oxidation abruptly increases and becomes the primary source of energy.

Net CHO oxidation differed across walking speeds ($F_5 = 92.9$, $P < .001$). A gradual and linear increase in net CHO oxidation was observed from 3.2 km h^{-1} (7.4 ± 1.3 cal min^{-1} kg^{-1}) to 4.8 km h^{-1} (12.1 ± 1.4 cal min^{-1} kg^{-1}) ($P < .001$). Compared to values at 4.8 km h^{-1}, net CHO oxidation at each of the faster speeds was significantly higher (18.9 ± 1.6, 30.7 ± 2.5, and 57.0 ± 4.7 cal min^{-1} kg^{-1} for speeds of 5.6, 6.4, and 7.2 km h^{-1}, respectively; $P < .001$). This statistical analysis and visual inspection of Fig. 3A suggested that net CHO oxidation rate increased in a threshold fashion at speeds exceeding PWS. Thus, an analysis of the slopes associated with rates of rise in CHO oxidation across speeds was performed. This analysis, shown in Fig. 3B, revealed that slopes differed across speeds ($F_4 = 36.2$, $P < .001$). The slope was constant across the first 3 speeds, from 3.2 to 4.0 to 4.8 km h^{-1} (171.5 ± 78.7 cal kg^{-1} km^{-1}). The first slope to vary from this "baseline" slope was the nearly 3-fold higher slope associated with the speed change from 4.8 to 5.6 km h^{-1} (506.8 ± 94.4 cal kg^{-1} km^{-1}; $P < .01$), agreeing with the visual impression that the

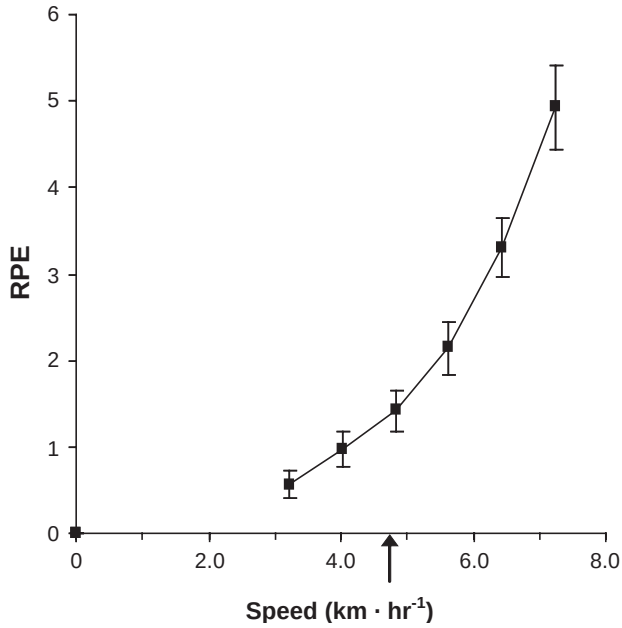

Fig. 4. Borg's converted (0-10) RPE across walking speed. The arrow indicates mean PWS in this study. All values are means ± SE.

Table 2
Contribution of various predictor variables to the explained variance in RPE

Added predictor	Explained variance in RPE
CHO oxidation rate	0.701
Walking speed	0.738
Fat oxidation rate	0.738
O_2 cost of transport	0.738
HR	0.738

Stepwise linear regression analysis of the contributions of the predictor variables net CHO oxidation rate, walking speed, net fat oxidation rate, O_2 cost of transport, and HR to the explained variance in perceived effort during treadmill walking. As can be seen, net CHO oxidation rate accounts for 70% of the variance in RPE, whereas walking speed contributes an additional 4%. In contrast, net fat oxidation rate, O_2 cost of transport, and HR made no contribution to explained variance in RPE. All data represent stable values observed from minute 8.0 to 10.0 at each speed. Data from all subjects (n = 12) across all walking speeds were included in the analysis.

threshold at which net CHO oxidation begins to accelerate is just slightly greater than PWS.

3.3. Perception of effort

The RPE also abruptly rose with increasing walking speed (Fig. 4), in a pattern similar to that of CHO oxidation. In fact, stepwise linear regression with 5 predictor variables revealed that CHO oxidation explained 70% of the variance in RPE (Table 2). Of the other 4 predictors, only walking speed made a small, 4%, additional contribution to explained variance in RPE. Fat oxidation rate, O_2 cost of transport, and, surprisingly, even HR did not account for any additional explained variance in RPE (Table 2).

3.4. Lactate response to walking

Blood lactate concentrations at 3.2, 4.0, 4.8, 5.6, 6.4, and 7.2 km h^{-1} were, respectively, 2.5 ± 0.4, 1.8 ± 0.4, 1.4 ± 0.2, 1.6 ± 0.3, 1.4 ± 0.2, and 3.1 ± 0.4 mmol/L. Thus, with the exception of the highest speed, 7.2 km h^{-1}, blood lactate levels indicated that fuel oxidation measurements based on indirect calorimetry were not confounded by acid-base instability. It should be noted that the net CHO oxidation rate at 6.4 km h^{-1} was 2.5 times that at 4.8 km h^{-1}. At 7.2 km h^{-1}, the slight rise in blood lactate concentration suggests that the estimate of fuel oxidation at this speed must be viewed with caution. Nevertheless, it should also be mentioned that lactate accumulation is itself evidence that the glycolytic pathway is becoming active and that CHO is likely making a greater relative contribution to energy metabolism [20,21]. Moreover, if the stepwise regression analysis described above excludes 7.2 km h^{-1}, then CHO oxidation explains 60% of the variance in RPE, fat oxidation contributes an additional 7%, whereas speed, O_2 cost of transport, and HR cannot account for any additional variance in RPE.

4. Discussion

The major finding of the present study was that able-bodied subjects naturally selected a walking speed just below the speed preceding an abrupt rise in CHO oxidation. We have retrospectively analyzed the data of Martin et al [2] and observed essentially the same relationship of PWS to CHO oxidation rate in their study of 4 groups possessing markedly different physiological profiles: young (21 years) sedentary, young active, older (72 years) sedentary, and older active individuals. Moreover, we report here that the CHO oxidation rate of active muscle can account for 70% of the variance in the perception of effort, whereas the contributions of fat oxidation rate and O_2 cost of transport to the perception of effort are small or nonexistent. Thus, we conclude that the human CNS selects a walking speed that is supported predominantly by fat oxidation, and that the perception of effort may contribute to this selection.

The minimal energy hypothesis proposes that the CNS selects a walking speed to minimize the energy cost of transport [6]. Indeed, the present study PWS of 4.7 km h^{-1} corroborates previously published reports [1,2,6], supporting the concept that human PWS coincides with the most economical speed (Fig. 2). Typically presented in an evolutionary context [22], this model advances the reasonable notion that natural selection would have favored energetically economical behavior. However, a major limitation of the minimal energy hypothesis is that it fails to consider the *source* of the energy (ie, the fuel). Muscle fuel selection is a major determinant of endurance, dwarfing the small differences in economy featured in the minimal energy hypothesis. For example, the CNS could make a rather large error in speed selection (33%) and yet incur a

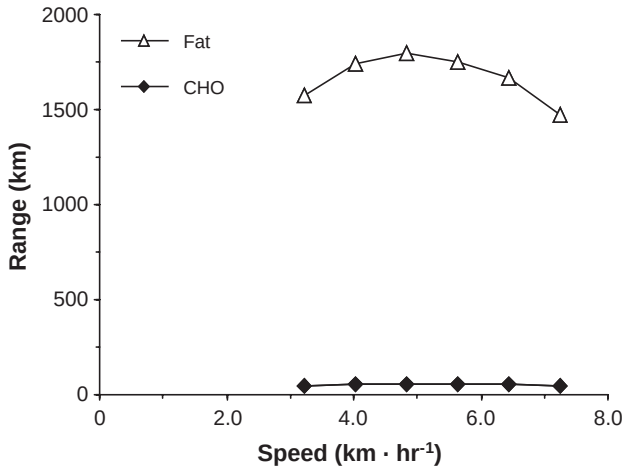

Fig. 5. Hypothetical metabolic range (endurance without refueling) if fat were the exclusive fuel for muscle work (upper curve) or CHO as the exclusive fuel (lower curve). The curves were generated by dividing assumed fuel stores (fat = 1395 kcal [kg body mass]$^{-1}$, CHO = 43 kcal [kg body mass]$^{-1}$) by the experimentally determined energy cost of transport (kcal kg^{-1} km^{-1}) mean values across speed of walking. Both curves are convex upward reflecting the U-shaped curve of the energy cost of transport (Fig. 2). The energy cost of transport, the central concept of the minimal energy hypothesis, predicts very small differences in endurance across speed for a given fuel. In marked contrast, the fuel selected by the metabolic control of skeletal muscle predicts enormous differences in endurance. See Discussion for further explanation.

very small energetic, thus endurance, penalty (<10%), as shown in Fig. 2. In marked contrast, the fuel dependence of walking could alter endurance by over 30-fold, as can be seen in Fig. 5. Minimal energy as a determinant of endurance pales in comparison to the critical importance of fuel selection.

Net CHO depletion occurs when CHO oxidation exceeds gluconeogenesis. In our 12-hour fasted subjects, walking speeds less than or equal to PWS elicited rates of CHO oxidation that were low enough to remain within the gluconeogenic flux of fasted humans [23]. Indeed, prolonged starvation would be expected to further suppress CHO use by active muscle [24], while it further stimulated CHO production via gluconeogenesis [25]. Walking at a speed demanding less than "gluconeogenic income" would avoid depletion of "CHO capital" and provide the expansive metabolic range afforded by the enormous energy stored as whole-body triglyceride (Fig. 5). However, the abrupt increase in CHO oxidation rate that results from walking at a speed only slightly higher than PWS (Fig. 3A) would result in a precipitous transition from the upper (fat) endurance curve to the lower (CHO) curve of Fig. 5.

In an evolutionary context, the challenge of walking away from an expansive region of energy scarcity would more likely be successfully met by an organism able to naturally select the walking speed resulting in the greatest range. Moreover, minimizing net CHO depletion from the very beginning of the trek would defend the ability to engage in burst activity as might be demanded by sudden environmental change or predator/prey activity. Although the enormous energy of fat stores could support very long range locomotion, CHO must be spared from use to support such routine locomotion activity because it is decidedly the fuel of choice for high-intensity activity [26]. Carbohydrate combustion can support an aerobic power over 2-fold that of fat [27], and nonoxidative glycolysis can generate ATP many fold faster than fat-supported oxidative phosphorylation [26].

Successful CNS control of movement for endurance activity critically depends on the fuel mixture supporting the contractile activity, implying the existence of a link between skeletal muscle metabolic control and CNS motor control. By what mechanism might the CNS select a walking speed that minimizes the recruitment of CHO into the fuel supply? We propose a simple model based on the connectivity property of metabolic control analysis [28,29]. Skeletal muscle cells defend cellular ATP free energy because declining energy status inhibits the rate of ATP use, while it stimulates ATP production [30]. Using metabolic control analysis, Jeneson et al [30] have demonstrated in human forearm flexor muscle that low-frequency energy turnover was entirely controlled by sites of ATP breakdown (myosin ATPase and the Ca^{2+} pump of the sarcoplasmic reticulum), but control was redistributed toward mitochondrial ATP production as contractile frequency approached the level of cellular acidification (hence, activated glycolysis). We propose that PWS is the highest muscle energy turnover that can be achieved without redistribution of flux control from cellular ATP use sites to mitochondria. The CNS senses this redistribution of control by comparing efferent motor drive to afferent signals related to contractile performance, with the error perceived as effort [20,31-33]. In contracting myocytes in which the energy state is declining, glycolytic flux rises [34-36], whereas contractile function falls [37-40]. Thus, energy turnover rates high enough to require activation of glycolysis may redistribute flux control away from the ATP-use/CNS axis and toward the mitochondrion.

It is important to emphasize that the model does not propose that it is CHO oxidation per se that the CNS senses, but rather the cellular energetic milieu associated with glycolytic activation in the fasted state. For example, acute ingestion of CHO would elevate CHO oxidation rate of walking muscle by the mass action of a rising extracellular glucose level and insulin, and the kinetic inhibition of fat oxidation [41]. Our preliminary data suggest that such feedforward fuel delivery, which might improve the defense of cellular energy state, decreases RPE and increases PWS.

The model predicts that the perception of effort in fasted walking subjects should track muscle CHO oxidation rate. Indeed, muscle CHO oxidation rate accounted for 70% of the variance in perceived effort. In contrast, walking speed, fat oxidation, O_2 cost of transport, and HR provided very little to no additional explained variance. Although some contribution of HR to RPE variance was anticipated, it is worthwhile to note that Borg et al [42] have previously reported for various exercise modes that the product of HR and blood [La] yields a better fit to RPE than does HR alone. Their findings would appear to be in general agreement with ours because the HR × blood [La] product may be viewed roughly as reflecting a combination of metabolic rate and glycolytic activity.

5. Summary

We propose that, in the fasted state, walking speed is selected simply by increasing the ATP demand of activated muscle (ie, increasing the speed) until it can no longer be matched by fat oxidation. The CNS is made aware of the endpoint of this motor/metabolic titration because the requisite fall in cellular energy state associated with recruitment of the glycolytic pathway is attended by contractile inhibition and raises the sense of effort. The proposed model of the interaction between motor control and metabolic control therefore predicts that, in the fasted state, the perception of effort is linked to muscle CHO oxidation rate. Through this proposed mechanism, the CNS is apprized of the rate at which the body's exhaustible fuel, CHO, is being depleted in the effector organ, skeletal muscle. It may be that preferred rates of walking are most economical under conditions at which muscle CHO oxidation is just restrained and fat oxidation is favored.

This notion suggests that the CNS adopts a PWS that is determined, in part, by the energy state of the muscle and that this motor behavior need not be controlled by least energy cost.

Acknowledgments

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