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Metabolic Responses to Exercise

THE EFFECTS OF RUNNING SPEED ON THE METABOLIC AND MECHANICAL ENERGY COSTS OF RUNNING

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ABSTRACT

THE EFFECTS OF RUNNING SPEED ON THE METABOLIC AND MECHANICAL ENERGY COSTS OF RUNNING. **Chad Harris, Mark Debeliso, Kent J. Adams.** *JEPonline*. 2003;6(3):28-37. This study assessed the influence of speed on the metabolic and the mechanical cost to run a given distance. Trained male runners (n=12) performed 2 treadmill run trials of 8 min duration at each of 6 speeds (range 2.33 to 4.0 m/s). Oxygen uptake values were normalized for running speed providing a metabolic task cost variable (MBTC, ml/kg/m). Mechanical work was calculated from digitized video records using three different algorithms. Values were normalized for running speed giving mechanical task cost variables (MTC, J/kg/m). No change in the group mean metabolic task cost was found across speeds (p=0.25). In contrast, mechanical task cost decreased as running speed increased (p<0.001). The three mechanical work algorithms resulted in MTC characteristics that were significantly different from each other (p<0.001). This study suggests that metabolic cost per distance remains relatively constant across running speeds while mechanical cost per distance decreases as speed increases.

Key Words Metabolic task cost, Mechanical work, Mechanical task cost, Economy, Efficiency

INTRODUCTION

It is commonly held that the metabolic cost to run a given distance is not influenced by running speed. Thus, whether one runs at a slow pace or a fast pace, is of no consequence to the total metabolic cost for completing the distance. The acceptance of this association between the metabolic cost per distance and running speed is based on earlier work by Margaria et al. (1), who reported the net caloric cost of level running to be 1 kcal/kg/km (equivalent to 0.20 ml/kg/m) for speeds ranging from 2.5 m/s to 6.1 m/s for 2 highly trained runners. Later work by Pugh (2) and Fellingham et al. (3) supported the results of Margaria's group. However, other researchers have demonstrated both speed-dependent increases (4) and a speed-dependent decreases (5) in the per-distance oxygen cost of running.

While these descriptive accounts identify different responses of per-distance oxygen cost to changes in running speed, they do not explore the mechanisms behind the responses. Intuitively, it would seem that the per-distance metabolic cost would be influenced by the mechanics exhibited by the runner. Gross mechanical cost was shown to increase with running speed (6,7) and was highly correlated with metabolic cost (6). Yet, no studies have examined the response of the per-distance mechanical cost to changes in running speed, or examined both the per-distance metabolic and the per-distance mechanical costs simultaneously. Therefore, the purpose of this investigation was to assess the influence of speed on the metabolic and mechanical cost to run a given distance.

METHODS

Subject Characteristics

Twelve male runners (age 29 ± 5 years; height 179 ± 7 centimeters; mass 72 ± 9 kilograms) served as subjects for the study. All subjects were trained distance runners and exhibited an average $\dot{V}O_{2\max}$ of 62.4 ± 5.0 ml/kg/min and a $\dot{V}O_2$ at ventilatory threshold $\dot{V}O_2(\dot{V}O_{2VT})$ of 52 ± 4.0 ml/kg/min ($82.9 \pm 2.7\%$ of $\dot{V}O_{2\max}$). Current 10-kilometer road race times for the subjects ranged from 29:30 to 36:02 minutes:seconds. Prior to their participation, all subjects were verbally informed of the nature of the study and each signed an informed consent document that was approved by the Institutional Review Board.

Treadmill Accommodation/Maximal Oxygen Uptake/Ventilatory Threshold

On their initial visit to the laboratory, subjects were asked to complete a treadmill accommodation session aimed at reducing stride to stride variability in experienced over-ground runners who were novice to the treadmill (8). The subject's next visit to the laboratory was for the measurement of $\dot{V}O_{2\max}$ and the determination of ventilatory threshold. During this test and subsequent submaximal tests, oxygen consumption was measured via open circuit spirometry using a SensorMedics 2900 metabolic measurement system (SensorMedics Corporation, Yorba Linda, CA). Prior to each test, the gas analyzers of the metabolic cart were calibrated using certified commercial gas preparations and the mass flowmeter was calibrated with a known gas volume.

The $\dot{V}O_{2\max}$ protocol consisted of one-minute stages and began at a speed of 2.67 m/s and 0% grade. Speed was increased 0.22 m/s per stage until a speed of 4.0 m/s was reached. All stages up to and including the first stage at 4.0 m/s were run on a level treadmill. After the first minute at 4.0 m/s, speed was held constant and grade was increased by 1.0% per minute until the subject reached volitional exhaustion. Attainment of $\dot{V}O_{2\max}$ was confirmed through the achievement of two of the following criteria: a) an increase in work rate without a concomitant increase in oxygen consumption, b) a respiratory exchange ratio (RER) exceeding 1.1, and c) heart rate within 10% of age-predicted maximum. Ventilatory threshold was defined as the point at which the ventilatory equivalent for oxygen increased without a concomitant increase in the ventilatory equivalent for carbon dioxide (9).

Submaximal Economy Sessions

Four to seven days following the $\dot{V}O_{2\max}$ test, subjects completed the first of two running economy sessions. Immediately preceding each session, body mass was determined and a quiet 8-minute standing $\dot{V}O_2$ was obtained. During the sessions, steady-state $\dot{V}O_2$ was measured at six running speeds (2.33, 2.67, 3.00, 3.33, 3.67 and 4.00 m/s) completed in ascending order using a non-continuous protocol. Each run was 8-minutes in duration and 10-minute rest periods were provided between successive runs. Oxygen consumption values from the final 5 minutes of running at each speed were assessed for stability via regression analysis. A linear model best fit the data and no subject displayed a significant positive or negative regression slope between the 4th and 8th minute of the run at each speed. Therefore, the average of the final 5-minute $\dot{V}O_2$ values was used as the $\dot{V}O_2$ for each speed. An exercise $\dot{V}O_2$ was then calculated by subtracting the average $\dot{V}O_2$ determined from the final 5 minutes of the standing measurement from the average $\dot{V}O_2$ measured at exercise. The primary metabolic variable of interest in the current study was the $\dot{V}O_2$ of submaximal running normalized for distance

traveled. By dividing steady-state $\dot{V}O_2$ by running speed, a per-unit distance metabolic cost value was achieved. The value was termed the metabolic task cost (MBTC) and was expressed in milliliters of oxygen per kilogram body mass per meter of distance traveled (ml/kg/m). This allowed for running economy comparisons across the tested range of speeds.

Controls were imposed on the factors that have been shown to increase intraindividual variation in running economy during the submaximal runs. The following were the controls employed: a) On a day separate from submaximal economy sessions, subjects ran for 45 minutes on the treadmill for accommodation (8), b) economy runs were performed in duplicate over two testing days, c) subjects performed the tests at the same time of day, and d) the same footwear was worn for each test (8,10, 11).

Experimental Procedures - Mechanical

Video Recording

The mechanical variable of interest in the study was the total body mechanical power normalized for body mass and distance traveled. By normalizing mechanical power in this fashion, comparisons of mechanical cost could be made across speeds, on a per-unit distance traveled basis. The mechanical cost variable was termed the mechanical task cost (MTC) and expressed in joules per kilogram body mass per meter of distance traveled (J/kg/m).

Total body mechanical power was determined from a kinematic-based segmental energy analysis. To track segment displacement and subsequently calculate segmental energies two-dimensional (2D) techniques were used for video analysis. Two video cameras were used to film the subjects from both the right and left sides. The cameras operated at 60 Hertz (Hz), and were synchronized to the nearest frame with an identifying event. Image clarity was improved with use of an electronic shutter with a time of 0.004 seconds. For each economy run, a 15-second video recording was obtained during minute five.

Prior to each economy session, estimated body segment endpoints were marked, thereby creating 7-segment models for each side of the body. Subsequently, the digitized results from right and left view video recordings were merged, resulting in a 12-segment model being used to represent the body. Inertial characteristics of the segments were estimated by employing body segment parameter data from Dempster (12).

Video Analysis

Two strides were digitized per subject at each running speed. Analysis of video records was accomplished using the Peak Performance Video Analysis System (Peak Performance Technologies Inc., Englewood, CO). Coordinate data were smoothed using a 4th order Butterworth recursive, low pass digital filter. Cut-off frequencies for each segment endpoint in both the horizontal and vertical direction were individually determined using the residual analysis method of Wells and Winter (13). Cut-off frequencies in the horizontal direction ranged from a low of approximately 3 Hz in the head and neck to a high of approximately 8 Hz in the foot. In the vertical direction, cut-off frequencies ranged from 5 to 7 Hz for all points.

Energy Calculations

Mechanical cost was determined from total body mechanical energy and work. Mechanical work (W, Joules) and power (P, Watts) were calculated from the sum of potential and kinetic energy level changes of the segments over the time required for a running cycle. Energy transfer between body segments influences mechanical cost. The magnitudes of the potential and kinetic energies of the segments vary depending on the degree to which the component energies are allowed to change form within a segment and/or transfer from one segment to another. If within-segment and between-segment energy transfers are allowed, the total work will be less since there will be less energy level change. Subsequently, total body mechanical work will be lower, as it is calculated from changes in the total body energy curve. Figure 1 shows a typical total body energy curve.

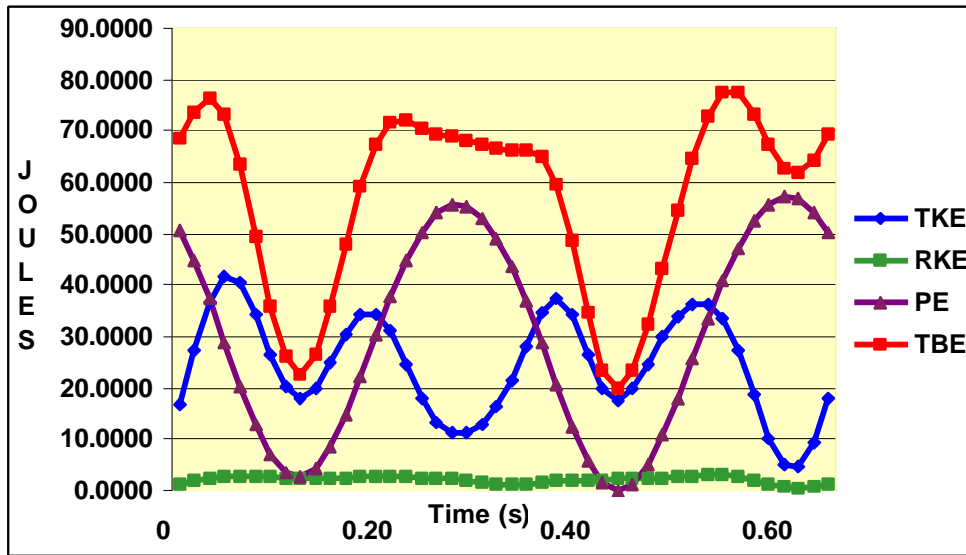


Figure 1: Representative energy curve.

Three separate algorithms were used in this investigation for the calculation of work and power: a) the no-transfer approach of Norman et al. (14), b) the no between-segment transfer approach of Pierrynowski et al. (15), and c) the total transfer approach of Winter (16). For all algorithms, the basic approach involved determination of each segment's instantaneous potential energy (PE), translational kinetic energy (TKE), and rotational kinetic energy (RKE) throughout a running cycle. The component energies were defined as follows:

$$PE = mgh, TKE = \frac{1}{2} mv^2, RKE = \frac{1}{2} I\omega^2$$

where m = segment mass, g = acceleration due to gravity, h = vertical height above an arbitrary datum, v = translational velocity of segmental mass center, I = segment moment of inertia about segment mass center and ω = segment angular velocity. Each algorithm was different in the manner in which energy level changes of the segments are summed, and therefore, unique in the degree of energy transfer allowed.

For the no transfer work algorithm (NTW), the absolute changes of the instantaneous energies of each segment were calculated and summed across all segments (i) and all video pictures (j). Mathematically, the equation used was:

$$Work = \sum_{i=1}^{12} \sum_{j=1}^n \left[\left| \Delta PE_{i,j} \right| + \left| \Delta TKE_{i,j} \right| + \left| \Delta RKE_{i,j} \right| \right]$$

For the no between-transfer work algorithm (NBTW), the total instantaneous energy of each segment was calculated, then the absolute changes of the segmental energy curve were summed over the running cycle. Further summing across the 12 segments in the model resulted in the NBTW value. The mathematical equations employed were:

$$E_i = m_i gh_i + \frac{1}{2} m_i v_i^2 + \frac{1}{2} I_i \omega_i^2$$

$$Work = \sum_{i=1}^{12} \sum_{j=1}^n \left| \Delta E_{i,j} \right|$$

Complete transfer of energy forms within a segment and between all segments was provided for in the total transfer work algorithm (TTW). In the TTW approach, the sum of the instantaneous segmental energies was obtained providing a total body energy curve. The sum of the absolute changes in the curve across the running cycle resulted in the TTW value. Mathematically, the formulae were:

$$E_i = m_i g h_i + \frac{1}{2} m_i v_i^2 + \frac{1}{2} I_i \omega_i^2$$

$$\text{Work} = \sum_{j=1}^n \left| \sum_{i=1}^{12} (\Delta E_{i,j}) \right|$$

To obtain values for P, the mechanical work values were divided by stride time. The MTC variables (J/kg/m) were obtained by normalizing P for body mass and running speed.

Statistical Analyses

For the MBTC variable, differences in means between the first and second submaximal running session were evaluated using separate 2 (session) x 6 (speeds) analysis of variance (ANOVA) procedures with repeated measures. The analyses revealed no differences in running sessions ($p = 0.86$). Therefore, data from the two sessions were averaged and simple regressions were performed to describe the response of the variable across the speed range tested.

For the MTC variables, differences in means between the four analyzed strides (2 strides in each of session one and two) and between the three algorithms were assessed through separate 3 (algorithm) x 4 (strides) x 6 (speeds) ANOVA with repeated measures procedures. Scheffé post-hoc analyses were performed when differences were detected between algorithms and/or strides. The analyses revealed no difference between the four analyzed strides ($p = 0.82$). Therefore, the stride data were averaged and simple regression was performed to describe the response of the variables across the range of speeds tested. Simple regression analyses also were performed to assess the relationship between MBTC and the mechanical task cost variables.

RESULTS

Mean descriptive data from VO_2max testing is provided in Table 1. Mean responses to the submaximal running bouts are provided in Table 2. For the MBTC variable, both simple and polynomial models were fit to the data and simple linear models best described the relationship between MBTC and running speed. The mean response of the MBTC to changes in speed is shown in Figure 2. There was no significant regression slope for MBTC versus running speed ($p=0.25$). Thus, MBTC was independent of speed, averaging 0.164 ± 0.004 ml/kg/m. Data for a single subject that is representative of the response of gross VO_2 and MBTC are displayed in Figure 3.

The response of the MTC variables calculated using the three different algorithms are depicted in Figure 4. MTC values calculated with the three algorithms differed significantly ($p<0.001$). Regardless of the algorithm employed, a significant negative regression slope was observed for MTC versus running speed ($p=0.001$). Using the restricted transfer methods (No Transfer, NTW and No Between Segment Transfer, NBTW), MTC decreased 14% from the slowest to the fastest speed, while a 32% decrease was seen with the complete transfer approach (TTW).

Table 1: Mean descriptive results for VO₂max testing

	VO ₂ max (ml/kg/min)	VO ₂ vt (ml/kg/min)	VT as % VO ₂ max	Time To Max (min)	Speed At Max (m/s)	Grade At Max (%)	RER At Max	HR Max (beats/min)	VE Max (L/min)
Mean	62.43	51.75	82.42	15:28	4.00	8.58	1.14	188.17	158.43
S.D.	5.00	4.20	2.75	1:27	0.00	1.56	0.03	5.32	19.78

Table 2: Physiologic responses to submaximal running

Speed	2.33m/s	2.67 m/s	3.00 m/s	3.33 m/s	3.67 m/s	4.00 m/s
VO₂	28.5±2.54	30.9±2.84	33.6±3.00	37.1±3.28	40.0±3.14	44.0±3.41
%VO₂max	46.41±5.34	50.40±5.98	54.44±6.37	59.72±6.89	64.22±6.11	70.90±7.35
RER	0.90±0.04	0.90±0.03	0.90±0.04	0.91±0.04	0.91±0.04	0.92±0.04
VE	52.20±9.23	56.86±9.35	62.46±10.83	68.08±11.27	75.04±11.79	82.49±12.12
HR	113±10	122±10	128±11	135±12	142±11	152±11

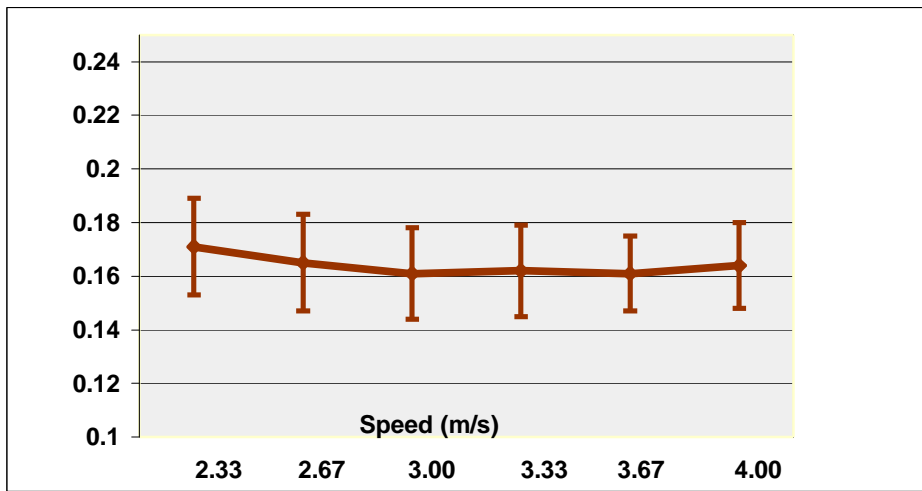


Figure 2: MBTC (ml/kg/m) Versus Running Speed

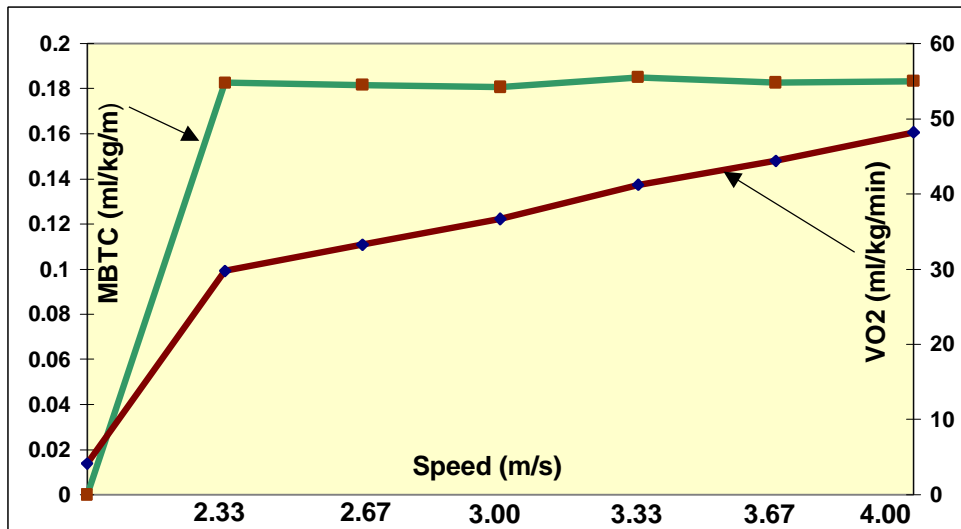


Figure 3: Representative Gross VO₂ and Metabolic Task Cost Response

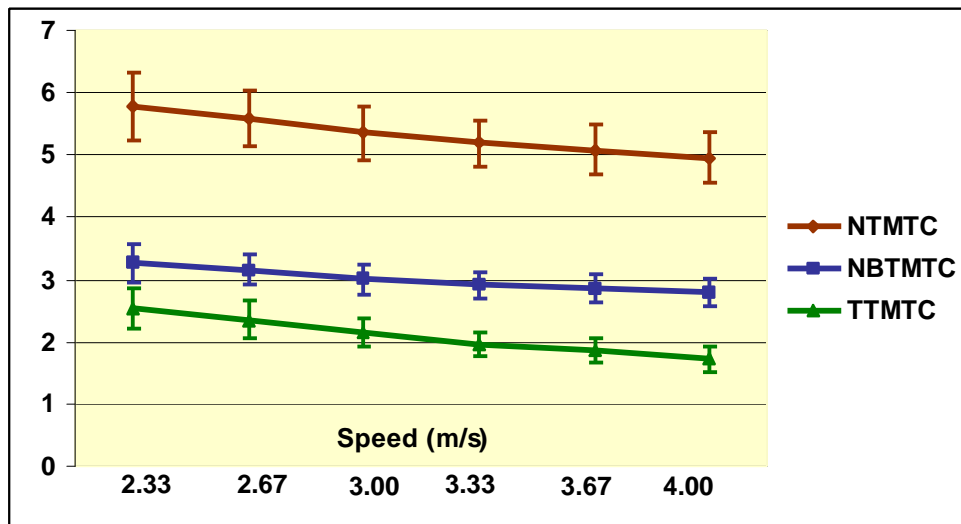


Figure 4: MTC (J/kg/m) Versus Running Speed

DISCUSSION

The purpose of this investigation was to assess the response of the metabolic and mechanical cost to run a given distance to changes in running speed. From a metabolic perspective, the primary finding of this investigation was a constancy of the metabolic cost per distance (MBTC) to changes in running speed, which is in agreement with previous studies (1,2,3). The running speeds used in our study ranged from 2.33 m/s to 4.0 m/s which was within the range of speeds collectively examined in previous research (1,2,3). Margaria et al. (1) found the per-distance caloric cost of 1 kcal/kg/km (equivalent to 0.20 ml/kg/m) for 2 subjects for speeds ranging from 2.5 m/s to 6.1 m/s. Pugh (2) found a constant caloric cost of 0.95 kcal/kg/km for 2 subjects and for a speed range that was approximately the same as that studied by Margaria et al. (1). In a later investigation, a cost of 0.93 kcal/kg/km was reported for 24 subjects of various fitness levels and speeds of 2.23 and 3.13 m/s (3). Based on the current and previous findings, the independence of MBTC and running speed appears to be robust.

Differences do exist, however, in the magnitude of the per-distance metabolic cost between the current study and previous reports. While it was not the intent of this study to examine caloric cost, a caloric equivalent of 4.825 Kcal/L of oxygen (17) was applied to the current data to allow for comparisons with the earlier works. This resulted in an estimated caloric cost of 0.79 Kcal/kg/km that was 17% to 21% lower than prior findings (1,2,3). Differences in the per-distance metabolic cost between the current and previous studies are likely due to differences in the following factors: a) the running economy of the subjects, b) the controls employed on factors influencing running economy, and c) the manner in which resting costs were obtained. It is not surprising that the magnitudes of the MBTC values of this study and previous studies showed variation given that VO_2 has been shown to vary 20% to 30% between subjects running at a particular speed (18) and given that two previous reports each employed only 2 subjects. Furthermore, the factors influencing running economy (i.e. treadmill accommodation, footwear, and circadian variation) have been shown to influence submaximal VO_2 by as much as 11% (19). Subjects in this study were required to accumulate 45 minutes of accommodation time prior to participating in the economy runs. This time was indicated as being sufficient at minimizing stride-to-stride variability in experienced over-ground runners who were novice to the treadmill (8). Also, subjects wore the same footwear, underwent testing at the same time of day, and refrained from exercise within 24 hours of each lab visit. Since the effect these factors have on running economy was not known to the researchers of the previous studies (1,2,3,4), it is unlikely that purposeful attempts were made to control the variables. Additionally, past studies (1,2,3) failed to document the procedures used to assess resting costs. Since a net

oxygen cost value was used to calculate the per-distance metabolic cost, variation in resting cost would lead to differences in the magnitude of the net cost per-distance.

The differences in per-distance metabolic cost may have practical significance in the prediction of metabolic cost from running speed. Currently, the American College of Sports Medicine (20) uses a value of 0.2 as the regression constant for converting running speed in m/min to oxygen cost in ml/kg/min. The current data suggest that the use of 0.2 as the regression constant may overestimate true oxygen cost by as much as 18%.

Based on the findings of the current study and supporting data from previous studies, it appears that when runners are able to freely choose their running speed, reasons other than lowering metabolic cost to cover a given distance determines the selection. Perceived comfort of the running gait and/or mechanical cost may be a stronger influence on speed selection. Through an informal survey of the subjects in this study it was determined that the most comfortable running speeds were 3.67 m/s and 4.00 m/s. The runners indicated that these speeds were most representative of common training speeds. This impression was reflected in the MTC results, where MTC values were the lowest for the various running speeds.

Regardless of the algorithm used, MTC decreased as running speed increased up to 4.0 m/s. The largest decrease in MTC (32%) occurred with the total transfer algorithm (TT-MTC). A 14% decrease across running speeds occurred with both NT-MTC and NBT-MTC algorithms. Therefore, disregarding energy transfers, to run a given distance it was at least 14% more economical mechanically at the highest running speed than at the lowest running speed. For the subjects of this investigation, this suggests a beneficial change in running kinematics as running speed increased. Furthermore, it suggests that between-segment energy exchanges were increasingly more important as running speed increased. This finding is supported by previous studies examining the mechanical cost of running (6,7). Although the changes in stride kinematics and energy exchanges were not of sufficient magnitude to generate a reduction in the per-distance metabolic cost, they may have contributed to its consistency across the range of speeds tested. This change in kinematics provides for increased use of metabolically economical energy exchanges to assist in limb movement, which subsequently allows for maintenance of metabolic cost per-distance.

The kinematic-based no transfer algorithm (14), within segment only algorithm (15), and the complete transfer algorithm (16) were employed in this study. While within-segment energy exchanges have been demonstrated (21,22), the extent to which exchanges occur between non-adjacent segments is unknown. Unaccounted for in the current methodology was the contribution of elastic energy storage and utilization. Researchers have suggested that stored energy in the elastic components of muscles contribute to positive external work generation without additional metabolic cost (23). Therefore, elastic energy could contribute to positive energy level change. The inability to account for the influence of elastic energy could lead to an overestimation of the work performed. Limitations of the kinematic-based approach for calculating mechanical work and power have been sufficiently discussed elsewhere (24,25).

In summary, it was our objective to assess the response of the per-distance metabolic and mechanical cost of running across a range of submaximal running speeds. It appears that the metabolic cost to run a given distance is independent of running speed. However, the magnitude of the per-distance metabolic cost may have been overestimated in previous reports. Mechanically, the per-distance cost decreases as speed increases. The consistency in per-distance metabolic cost may be a result of changes in running kinematics as speed is increased. In human locomotion, constancy of cost to travel a given distance appears to be caused by kinematic and kinetic alterations in running pattern with increasing running speed.

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