Mechanical Efficiency of Treadmill Running Exercise: Effect of Anaerobic-Energy Contribution at Various Speeds

Daniel A. Keir, Raphaël Zory, Céline Boudreau-Larivière, and Olivier Serresse

Objectives: Mechanical efficiency (ME) describes the ratio between mechanical ($P_{\text{MECH}}$) and metabolic ($P_{\text{MET}}$) power. The purpose of the study was to include an estimation of anaerobic energy expenditure (AnE) into the quantification of $P_{\text{MET}}$ using the accumulated oxygen deficit (AOD) and to examine its effect on the value of ME in treadmill running at submaximal, maximal, and supramaximal running speeds. Methods: Participants ($N = 11$) underwent a graded maximal exercise test to determine velocity at peak oxygen uptake ($v_{\text{VO2peak}}$). On 4 separate occasions, subjects ran for 6 min at speeds corresponding to 50%, 70%, 90%, and 110% of $v_{\text{VO2peak}}$. During each testing session, $P_{\text{MET}}$ was measured from pulmonary oxygen uptake ($V_{O2p}$) using open-circuit spirometry and was quantified in 2 ways: from $V_{O2p}$ and an estimate of AnE (from the AOD method) and from $V_{O2p}$ only. $P_{\text{MECH}}$ was determined from kinematic analyses. Results: ME at 50%, 70%, 90%, and 110% of $v_{\text{VO2peak}}$ was 59.9% ± 11.9%, 55.4% ± 12.2%, 51.5% ± 6.8%, and 52.9% ± 7.5%, respectively, when AnE was included in the calculation of $P_{\text{MET}}$. The exclusion of AnE yielded significantly greater values of ME at all speeds: 62.9% ± 11.4%, 62.4% ± 12.6%, 55.1% ± 6.2%, and 64.2% ± 8.4%; $P = .001$ (for 50%, 70%, 90%, and 110% of $v_{\text{VO2peak}}$, respectively). Conclusions: The data suggest that an estimate of AnE should be considered in the computation of $P_{\text{MET}}$ when determining ME of treadmill running, as its exclusion leads to overestimations of ME values.

Keywords: metabolic power, accumulated oxygen deficit, aerobic, internal work

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**Effect of Anaerobic Energy on Mechanical Efficiency**

$P_{\text{MECH}}$ is determined as the sum of the external ($W_{\text{EXT}}$) and internal ($W_{\text{INT}}$) work components. $W_{\text{EXT}}$ is represented by the changes in kinetic and potential energy associated with the body’s center of mass ($\text{COG}_{\text{BW}}$), while $W_{\text{INT}}$ is described by changes in the kinetic (rotational and translational) and potential energy of each segment (in a body of N segments) due to its movement relative to $\text{COG}_{\text{BW}}$. Therefore, the exercising muscles are required to produce $P_{\text{MET}}$ to sustain both $W_{\text{EXT}}$ and $W_{\text{INT}}$ components during running.

$P_{\text{MET}}$ during constant-speed exercise has typically been quantified from pulmonary oxygen uptake ($\text{VO}_2\text{p}$). The use of this method assumes that energy requirements are solely met by means of oxidative metabolism. At the onset of constant-speed exercise, the $\text{VO}_2\text{p}$ profile does not increase instantaneously; rather, it projects toward a new steady state (reflecting the muscle ATP demand). While the energy demand is instantaneous, the slower rate of $\text{VO}_2\text{p}$ adjustment is mediated by substrate-level phosphorylation and phosphocreatine breakdown (anaerobic-energy provision, $\text{AnE}$). As intensity increases, the reliance on $\text{AnE}$ to meet the imposed energy demand becomes greater. It is tenable that methods reported previously may have inaccurately determined $P_{\text{MET}}$ by ignoring the $\text{AnE}$ contributions to running exercise. For this reason, documented values of running ME may not be as accurate as previously thought, given that the denominator in the ME model (ie, $P_{\text{MET}}$) may have been underestimated.

To create a more complete model of running ME, the current investigation aimed to include an estimation of $\text{AnE}$ using the accumulated-oxygen-deficit (AOD) method in addition to $\text{VO}_2\text{p}$ in the quantification of $P_{\text{MET}}$ and to examine the effect of its inclusion on ME at submaximal, maximal, and supramaximal running speeds. The AOD method involves comparing the total $\text{O}_2$ demand (linearly estimated from the $\text{VO}_2\text{p}$–speed relationship) with the $\text{VO}_2\text{p}$ measured during constant-speed exercise. Our hypothesis was that ME would decrease at maximal and supramaximal running speeds with the inclusion of $\text{AnE}$ and this would cause ME values to more closely approximate the theoretical maximal efficiency of muscle locomotion (ie, 30%).

**Preliminary Measurements**

Subjects were instructed to avoid any vigorous training for 48 hours before testing and to avoid foods and beverages containing caffeine and alcohol for 24 hours prior. During preliminary sessions, each subject performed a continuous graded exercise test (GXT) to exhaustion on a treadmill (Quinton Model 640, Series 90) to determine peak oxygen uptake ($\text{VO}_2\text{peak}$) and velocity associated with it ($v\text{VO}_2\text{peak}$). The GXT protocol was similar to that outlined by Billat et al, whereby running tests were performed on a motorized treadmill kept at 0% grade. Speed was increased by 0.56 m/s from 2.75 m/s every 3 minutes. $\text{VO}_2\text{peak}$ was identified as the highest 20-second average of $\text{VO}_2\text{p}$ according to the following 3 criteria: no increase in $\text{VO}_2\text{p}$ despite increase in workload (plateau), subject could no longer sustain the workload, and respiratory-exchange ratio ≥ 1.0.

**Experimental Protocol**

Subjects underwent 4 additional experimental testing sessions after preliminary testing. Each testing session consisted of a single 6-minute exercise bout at treadmill speeds representing 50%, 70%, 90%, and 110% of $v\text{VO}_2\text{peak}$ (0% grade). Exercise bouts were randomized and were separated by a minimum of 24 hours. A warm-up period of 5 minutes (30% $v\text{VO}_2\text{peak}$) preceded each session, after which subjects were given a 15-minute rest.

**Data Collection**

**Metabolic Data.** Breath-by-breath pulmonary gas exchange ($\text{VO}_2\text{p}$, $\text{VCO}_2\text{p}$) and ventilation were measured using an open-circuit spirometry system ($\text{Vmax}$, Sensormedics, USA). Before each test, the device was calibrated according to the manufacturer’s instructions. $\text{O}_2$ and $\text{CO}_2$ analyzers were calibrated using ambient air and sample gas references of 16% $\text{O}_2$ and 4% $\text{CO}_2$. The flow sensor was also calibrated using a syringe of known volume (3.00 L).

Blood lactate ([La], in mM) was collected before and after each bout of exercise at 4 and 10 minutes. A LactatePro [La] analyzer (Arkay Inc, Kyoto, Japan), was used to analyze blood samples taken from capillaries at the distal end of the finger.

**Kinematic Data.** Kinematic data were recorded for the last 20 seconds of every minute during each 6-minute bout. Three-dimensional video was used to estimate $P_{\text{MECH}}$ for 6 minutes based on the last video recording for each bout. A total of 10 strides (corresponding to the last 10 strides recorded in the last minute before bout completion) was analyzed for each subject, at all relative speeds. Three-dimensional kinematic data were collected using the Vicon System (Vicon Motion Systems, CO). Images were recorded via 6 infrared cameras (Philips LTC 0325 Series Monochrome, Amsterdam, Netherlands) sampled at 60 Hz and synchronized using the Peak system.

**Methods**

**Subjects**

Eleven men without any known orthopedic, neuromuscular, or cardiovascular problems volunteered to participate in this investigation (mean age 21.1 ± 2.3 y, height 179.1 ± 6.9 cm, mass 76.3 ± 1.8 kg). Subjects read and signed a consent form before participating in the study as per the policies of the university research ethics committee. All experimental procedures were conducted according to the code of ethics of the World Medical Association (Declaration of Helsinki).
(Peak Performance Technologies, Englewood, CO). Before each test, cameras were calibrated in a space equal to 2 m. A 9-segment body model was defined using rigid links to represent the following 9 segments: right and left upper arm (shoulder-joint center to elbow-joint center), right and left forearm and hand (elbow-joint center to third metacarpal joint), right and left thigh (hip-joint center to knee-joint center), right and left shank (knee-joint center to ankle-joint center), and trunk. The rigid link segments were assumed to be connected by pin joints with no translation possible between links. Body-segment parameters (mass, COG, and inertial parameters) for the upper arm and the forearm and hand were estimated using the equations of Zatsiorsky modified by de Leva.13 To redefine the trunk segments using alternate planes of segmentation as defined above, the method reported by Larivière and Gagnon14 was used to calculate mass, length, and COG location for the lumbar segment (L5/S1–T12/L1) and the thoracic segment (T12/L1–C7/T1). Inertial parameters for the trunk segments were determined using the equations reported by de Leva13 with these adjusted segment lengths. The principal axes of rotation were assumed to coincide with the defined anatomical axes for the segments. Anatomical axes were defined as follows: positive x-axis directed anteriorly, positive y-axis directed from right to left, positive z-axis directed superiorly. Through this model, the angulations (position) of the joints in space were derived.

Subjects were outfitted with 3 noncollinear retro-reflective markers on each of the 9 segments to track segment kinematics during each trial using a Peak Motus system. These tracking markers were related to internal joint locations using a calibration trial with additional markers used to demarcate specific anatomical landmarks.14,15 In this way, segment COG positions could be marked by Larivière and Gagnon14 used to define mass, length, and COG location for the lumbar segment (L5/S1–T12/L1) and the thoracic segment (T12/L1–C7/T1). Inertial parameters for the trunk segments were determined using the equations reported by de Leva13 with these adjusted segment lengths. The principal axes of rotation were assumed to coincide with the defined anatomical axes for the segments. Anatomical axes were defined as follows: positive x-axis directed anteriorly, positive y-axis directed from right to left, positive z-axis directed superiorly. Through this model, the angulations (position) of the joints in space were derived.

**Data Analysis**

**Metabolic Data.** For each bout of treadmill running, \( P_{\text{MET}} (\text{J/s}) \) was obtained while considering contributions from both aerobic-energy (\( \Delta E \); from \( \text{VO}_{2p} \)) and \( \text{AnE} \) (from AOD) metabolism. The \( \Delta E \) was determined through indirect calorimetry using the nonprotein caloric equivalent of \( \text{O}_2 \) intake based on the 20-second average of the respiratory-exchange ratio during each 6-minute bout. The total caloric value of \( \Delta E \) was equal to the sum of the 6-minute total and converted to J/s. \( \text{AnE} \) was derived from the AOD as outlined by Medbo et al.11 For each participant, a linear submaximal \( \text{VO}_{2p} \)-speed relationship was determined from the GXT. The mean of the last 2 minutes of each exercise stage during the GXT (six 20-second average \( \text{VO}_{2p} \) measurements) was used to plot the steady-state \( \text{VO}_{2p} \) attained for each submaximal speed. The linear relationship was used to estimate the total \( \text{O}_2 \) demand of exercise. \( \text{AnE} \) during each exercise bout (50%, 70%, 90%, and 110% \( \text{vVO}_{2\text{peak}} \)) was determined by subtracting the total estimated \( \text{VO}_{2p} \) requirement from the accumulated \( \text{VO}_{2p} \) measured during the bout (Figure 1). Multiplication of the \( \text{VO}_{2p} \) (in L/min) by the duration of exercise (min), produced a value for the AOD that was used to represent \( \text{AnE} \). \( \text{AnE} \) (in J) was estimated using the indirect calorimetry method described previously.

**Kinematic Data.** All mechanical data were obtained using a custom-designed program (Matlab, Mathworks, Natick, MA) from raw kinematic data exported by the Peak Motus software. \( P_{\text{MECH}} (\text{J/s}) \) was assumed to be the sum of external (\( W_{\text{EXT}} \)) and internal (\( W_{\text{INT}} \)) work divided by time. \( W_{\text{EXT}} \) was derived from a point-mass model concept,16 whereby the energy of the entire body was quantified from the linear kinematics of the COG of the whole body (COGBW). The total energy of the point mass was determined by the sum of its gravitational potential energy (\( E_{\text{PE}} \)) and translational kinetic energy (\( E_{\text{KE}} \)) per step. The variations of said energies (J) were calculated as follows:

\[
\Delta E_{\text{PE}} = m_{wb} \times g \times \Delta h
\]

\[
\Delta E_{\text{KE}} = 0.5m_{wb} \times (v_{\text{max}}^2 - v_{\text{min}}^2)
\]

where \( m_{wb} \) is the mass of the whole body (kg), \( g \) is the acceleration due to gravity (9.81 m/s²), \( \Delta h \) is the change in position of the COGBW (m) on the vertical axis, and \( v_{\text{max}} \) and \( v_{\text{min}} \) are the maximal and minimal horizontal velocities of COGBW (m/s) during 1 step. Thus,

\[
W_{\text{EXT}} = \Delta E_{\text{PE}} + \Delta E_{\text{KE}}
\]

\( W_{\text{INT}} \), or the work rate needed to accelerate the limbs with respect to the body’s center of mass (J), was calculated as previously described by Slawinski and Billat.17 The internal mechanical work was calculated to represent the sum of the kinetic and potential energy changes at each segment’s COG, per step. The change in internal mechanical cost was considered in absolute value,

\[
W_{\text{INT}} = 0.5 \sum m_{s} v_{s}^2 + I_{s} \omega_{s}^2
\]

where \( s \) represents a segment, \( m_{s} \) is the mass of the segment (kg), \( v_{s} \) is the velocity of the segment COG (m/s) with respect to the COGbw, \( I_{s} \) is the moment of inertia of the segment (kg·m²), and \( \omega_{s} \) is the angular velocity of the segment COG (rad/s) with respect to the COGbw.

Step rate was computed by dividing 20 steps by the time it took to complete 20 steps as subjectively identified by the number of frames (sampled at 60 Hz) in Peak.
The step length, in meters, was obtained by dividing the running speed by the step rate.

Both \( W_{\text{EXT}} \) and \( W_{\text{INT}} \) were taken as the absolute value in their variation during approximately 20 steps (J). Mechanical work \( (W_{\text{TOT}}) \) was computed as (J):

\[
W_{\text{TOT}} = |W_{\text{EXT}}| + |W_{\text{INT}}|
\]

\( W_{\text{TOT}} \), \( W_{\text{EXT}} \), and \( W_{\text{INT}} \) (J) were multiplied by the step rate (Hz) to obtain \( P_{\text{MECH}} \), \( P_{\text{EXT}} \), and \( P_{\text{INT}} \) (J/s).

\( P_{\text{MET}} \) was obtained from the sum of the AE and AnE contributions (J/s). Thus, the gross ME (%) is

\[
\text{ME} = \frac{P_{\text{MECH}}}{P_{\text{MET}}} \times 100
\]

Statistical Analyses

Normality of the data sample was checked for all variables using a 1-sample Kolmogorov-Smirnov test. A 1-way ANOVA with repeated measures was used to detect significant differences among the 4 conditions of speed with respect to ME, energy contributions, and mechanical variables, as well as the differences between \( P_{\text{MET}} \) and \( P_{\text{MECH}} \) for each relative velocity. Post hoc pairwise analyses were performed on variables displaying statistically significant influence at all levels of speed.

Statistical significance was established at a \( P \) level of .05 for all analyses. All results are presented as mean ± SD.

Results

Anthropometric data, as well as preliminary results from the GXT, are presented in Table 1. Table 2 shows the mean treadmill velocities that subjects were required to sustain for each relative speed and the computed metabolic and mechanical variables obtained during those bouts. The steady-state \( VO_2p \), \( P_{\text{MET}} \), \( P_{\text{MECH}} \), and \( P_{\text{EXT}} \) were significantly \((P < .01)\) different between all speed bouts. \( P_{\text{INT}} \) displayed some significant changes as relative speed increased, but no discernable trend was observed. Peak \([La] \) became significantly elevated at the 90% \( v_{VO_2\text{peak}} \) protocol \((P = .021)\) and further increased at 110% \( v_{VO_2\text{peak}} \) \((P = .006)\).

Figure 2 shows that ME for all relative speeds is significantly less when both AE and AnE are included in the calculation of \( P_{\text{MET}} \) than when AE alone is considered in the computation \((P = .001, P = .000, P = .380, P = .001 \text{ for } 50\%, 70\%, 90\%, \text{ and } 110\% \text{ of } v_{VO_2\text{peak}} \text{, respectively})\). When AnE was accounted for in the model, the ME–speed relationship displayed significantly lower values at speeds corresponding to 90% and 110% of \( v_{VO_2\text{peak}} \) than 50%
Table 1  Subject Characteristics and Results From Preliminary Graded-Exercise Test

<table>
<thead>
<tr>
<th>Subject</th>
<th>Age (y)</th>
<th>Height (cm)</th>
<th>Mass (kg)</th>
<th>VO2peak (mL · kg⁻¹ · min⁻¹)</th>
<th>vVO2peak (L/min)</th>
<th>vVO2peak (km/h)</th>
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<tbody>
<tr>
<td>1</td>
<td>22</td>
<td>178</td>
<td>76.5</td>
<td>52.0</td>
<td>3.98</td>
<td>18</td>
</tr>
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<td>2</td>
<td>22</td>
<td>175</td>
<td>74.8</td>
<td>52.5</td>
<td>3.93</td>
<td>18</td>
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<tr>
<td>3</td>
<td>18</td>
<td>176</td>
<td>74.5</td>
<td>46.7</td>
<td>3.48</td>
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<tr>
<td>4</td>
<td>19</td>
<td>191</td>
<td>90.0</td>
<td>54.3</td>
<td>4.89</td>
<td>18</td>
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<tr>
<td>5</td>
<td>21</td>
<td>189</td>
<td>78.0</td>
<td>55.4</td>
<td>4.32</td>
<td>18</td>
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<td>6</td>
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<td>79.0</td>
<td>57.6</td>
<td>4.55</td>
<td>18</td>
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<tr>
<td>7</td>
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<td>171</td>
<td>63.0</td>
<td>55.5</td>
<td>3.54</td>
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<td>10</td>
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<td>172</td>
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<td>51.7</td>
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<tr>
<td>Mean</td>
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<td>178.8</td>
<td>76.3</td>
<td>53.3</td>
<td>4.07</td>
<td>17.4</td>
</tr>
<tr>
<td>SD</td>
<td>2.4</td>
<td>7.2</td>
<td>6.6</td>
<td>2.9</td>
<td>0.43</td>
<td>1.0</td>
</tr>
</tbody>
</table>

Abbreviations: VO2peak, peak oxygen uptake; vVO2peak, velocity at VO2peak.

Table 2  Physiological and Performance Values Achieved During Relative Speed Bouts, Mean ± SD

<table>
<thead>
<tr>
<th>% vVO2peak</th>
<th>50</th>
<th>70</th>
<th>90</th>
<th>110</th>
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</thead>
<tbody>
<tr>
<td>Velocity (m/s)</td>
<td>2.41 ± 0.13*</td>
<td>3.34 ± 0.22*</td>
<td>4.30 ± 0.32*</td>
<td>5.26 ± 0.34*</td>
</tr>
<tr>
<td>Oxygen uptake (L/min)</td>
<td>2.40 ± 0.23*</td>
<td>3.07 ± 0.29*</td>
<td>3.79 ± 0.35*</td>
<td>4.45 ± 0.43*</td>
</tr>
<tr>
<td>Metabolic power (J/s)</td>
<td>847 ± 97*</td>
<td>1086 ± 113*</td>
<td>1398 ± 170*</td>
<td>1655 ± 194*</td>
</tr>
<tr>
<td>Mechanical power (J/s)</td>
<td>510 ± 118*</td>
<td>597 ± 123*</td>
<td>722 ± 113*</td>
<td>851 ± 134*</td>
</tr>
<tr>
<td>External power (J/s)</td>
<td>279 ± 46*</td>
<td>351 ± 58*</td>
<td>434 ± 58*</td>
<td>516 ± 84*</td>
</tr>
<tr>
<td>Internal power (J/s)</td>
<td>231 ± 46d</td>
<td>245 ± 82c,d</td>
<td>288 ± 84b</td>
<td>334 ± 112ab</td>
</tr>
<tr>
<td>Peak blood lactate (mM)</td>
<td>2.1 ± 0.8c,d</td>
<td>2.7 ± 1.1c,d</td>
<td>5.6 ± 2.0ab,d</td>
<td>9.7 ± 1.7abc</td>
</tr>
</tbody>
</table>

Abbreviations: vVO2peak, velocity at peak oxygen uptake.

*Significantly different from all other relative speeds (P < .05).
Significantly different from 50% vVO2peak (P < .05). Significantly different from 70% vVO2peak (P < .05). Significantly different from 110% vVO2peak (P < .05).

VO2peak (P = .027 and P = .041). However, the ME values associated with 70%, 90%, and 110% vVO2peak running bouts were not significantly different from each other (P > .05).

PMET significantly increased with relative speed: 847 ± 92, 1085 ± 107, 1384 ± 167, and 1638 ± 198 J/s for 50%, 70%, 90%, and 110% of vVO2peak, respectively (Figure 3). AE significantly increased as speed progressed from 50% to 90% of vVO2peak (P = .000 for all pairwise comparisons). However, there was no difference in AE measured in the 90% and 110% vVO2peak conditions (P = .749). The difference in PMET observed between 90% and 110% vVO2peak was explained, rather, by a significant increase in AnE between these 2 speeds (67.7 to 308.9 J/s; P = .000) Approximately, 95.9% of PMET was attributed to AE and 4.1% to AnE for 50% vVO2peak, 95.9% and 4.1% for 70% vVO2peak, 95.3 and 4.7% for 90% vVO2peak, and 81.7% and 18.3% for 110% vVO2peak.

Discussion

The aim of the current study was to develop and test a methodology for calculating treadmill-running ME by including AnE estimated from the AOD. The key findings are that including AnE to PMET significantly reduces the ME values at all relative running speeds and the ME values obtained remain considerably greater than the estimated maximal efficiency of locomotion (30%) despite the inclusion of AnE in the model of running ME.
Effect of Anaerobic Contribution

The relative contributions of energy release from $\text{AnE}$ and $\text{AE}$ that were observed for each percentage of $v\text{VO}_{2\text{peak}}$ (Figure 2) are consistent with previous reports.\textsuperscript{18} Estimating the AOD is a noninvasive indirect method of obtaining $\text{AnE}$ during running bouts\textsuperscript{11} and has been used in the past to determine $\text{AnE}$ during brief exercise sessions.\textsuperscript{19} While it is acknowledged that the AOD method used in the current study is not without shortcomings, it remains the best noninvasive method to quantify $\text{AnE}$ during a bout of constant-speed exercise.\textsuperscript{20}

As expected, the gross value of $\text{AnE}$ became significantly greater as relative speed increased. As a result, $\text{ME}$ was significantly reduced at all relative speeds when $\text{AnE}$ was included in the computation (Figure 2). When $\text{AnE}$ was expressed relative to total metabolic requirement ($\text{AnE}/P_{\text{MET}}$), its relative contribution was significantly greater at the speed corresponding to 110% $v\text{VO}_{2\text{peak}}$: 18.1% than at 4.1%, 4.1%, and 4.7% for 50%, 70%, and 90% $v\text{VO}_{2\text{peak}}$, respectively (Figure 3). At this speed, excluding $\text{AnE}$ from the calculation resulted in an inflation of $\text{ME}$ because a large proportion of $P_{\text{MET}}$ was not taken into account. Indeed, a difference in $\text{ME}$ of 12.3% (64.2% vs 52.1%) was noted. This finding underscores the importance of adding $\text{AnE}$ to the $\text{ME}$ model, especially during supramaximal running. Previous studies examining $\text{ME}$ of running have assumed that $P_{\text{MET}}$ was met by respiration alone, even though $P_{\text{MECH}}$ was recorded for speeds ranging from 2 to 9 m/s.\textsuperscript{3-5,21,22} The fastest speed used in the current study was only 5.6 m/s. It is therefore likely that subjects in previous studies were exercising at both maximal and supramaximal running speeds sufficient to require a significant contribution from $\text{AnE}$ to total energy expenditure.

**ME**

Using the proposed model, $\text{ME}$ was significantly different from 50% $v\text{VO}_{2\text{peak}}$ at the 90% and 110% relative speeds; however, no other differences were observed with respect to speed (Figure 2). The $\text{ME}$ values for treadmill running obtained in the current investigation are similar in magnitude to those obtained in the literature to date.
Keir et al (~40–75%).22–26 It is generally accepted that ME is sensitive to running speed.4 However, the effect of speed on ME reported in the literature has been inconsistent. Specifically, ME has been found to increase,5,25 decrease,4 and remain the same3,22 as speed increases. The discrepancy is likely due to the variety of methods used to quantify both \( P_{\text{MET}} \) and \( P_{\text{MECH}} \) components of ME. Inconsistencies in the methodological approaches used to measure running ME make it difficult to determine how efficiency might change with increasing speed.

The maximal value of ME of the contracting muscle during locomotion has been considered to be approximately 30%.6 The high values of ME (~50–60%) obtained in the current study may stem from the kinematic method applied in quantifying \( P_{\text{MECH}} \). This kinematic model is limited in that conservation of energy through passive energy transfers within and between body segments are not accounted for.10 Furthermore, the phenomenon of elastic work produced by the stretch-shortening cycle of the muscle–tendon units is not considered in the model. It has been reported that activities requiring greater emphasis on the stretch-shortening cycle of movement patterns that rely purely on concentric contractions are more efficient.27 In running, the storage and subsequent release of elastic energy may help preserve force.28 For these reasons, our results may be an overestimate of \( P_{\text{MECH}} \) for each relative speed, which may explain why our ME values for running remain higher than what has been previously proposed.6

**Practical Applications**

The study attempted to analyze the relationship between the mechanical and metabolic power produced in treadmill running. Understanding this relationship is important in order to optimize athletic and, in particular, running performance. Future research should take into account all components of both metabolic and mechanical power to ensure that they are represented in the ME model. Certainly, the contribution of \( \text{AnE} \) expenditure cannot be overlooked when calculating the \( P_{\text{MET}} \) component of treadmill running and likely other forms of human locomotion.

**Conclusion**

We demonstrated in the current study that estimates of \( \text{AnE} \) should be taken into account when calculating the \( P_{\text{MET}} \) component of the ME model. \( \text{AnE} \) contributes a significant amount of energy to perform \( P_{\text{MECH}} \) in treadmill running at speeds ranging from submaximal to supra-
maximal. We found that AnE significantly increased as constant-speed treadmill-running bouts progressed from 2.4 to 5.3 m/s and higher. The inclusion of AnE to $P_{\text{MET}}$ increases the magnitude of the denominator in the ME model (at all relative speeds), which in turn reduces the ME values for treadmill running. The inherent assumptions of the kinematic model, however, make it difficult to explain the relationship between ME and speed.

References


