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Assessing the metabolic cost of walking: the influence of baseline subtractions

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Partitioning locomotor metabolic rates into resting and locomotor components is a common practice that has both basic and applied value. Here, we evaluated the quantitative influence of the specific baseline value subtracted (quiet standing vs. resting metabolic rates) from the gross metabolic rates measured during walking. We quantified resting, standing and gross metabolic rates during horizontal treadmill walking at six speeds from 0.2 through 1.9 m•s^{-1} in 6 healthy, adult subjects. We found that standing metabolic rates were significantly greater than resting values (1.25 ± 0.03 vs. 1.08 ± 0.02 W•kg^{-1}) and that both constituted large fractions of the gross metabolic rate while walking at all speeds examined (range 16-58%). Differences in the respective net metabolic rates obtained by subtracting standing vs. resting values differed most at the slowest speed measured (16.0% at 0.2 m•s^{-1}) and least at the fastest one (2.9% at 1.9 m•s^{-1}). Standing metabolic rates, like walking metabolic rates, include the metabolic cost of muscular activation for balance and maintaining an upright posture. Therefore, the net metabolic rates determined by subtracting standing from gross rates underestimate the total muscular costs that walking requires. We suggest that the net walking metabolic rates obtained by subtracting resting metabolic rate values are more representative of the total metabolic energy that walking requires.

I. INTRODUCTION

THE metabolic energy expended by humans and other animals during physical activity is measured as a single entity, but often partitioned into two components. The first is a maintenance component meant to represent the minimum rate of metabolism required by the body. The remainder is used to estimate the metabolic energy required to perform the physical activity.

This conceptualization and practice has been of considerable scientific value. Minimum rates of metabolism, termed basal or standard, were investigated at length for a variety of mammals early in the last century (1). Kleiber's classic studies demonstrated that standard or basal metabolic rates (E_{metab}) expressed per kg body mass (M_b) are greater in smaller vs. larger animals ($E_{metab} / M_b \alpha M_b^{-0.25}$). Similar investigations into the locomotor metabolism of mammals and birds were undertaken by Taylor and Schmidt-Nielsen and colleagues in the mid- to latter portions of the last century (2,3). These investigators found that the metabolic energy required to transport a unit body mass a unit distance (E_{trans}) was also greater for smaller vs. larger animals. Taylor's scaling relationship between body mass and the mass-specific metabolic cost of terrestrial locomotion ($E_{trans} / M_b \alpha M_b^{-0.32}$) is also considered a classical contribution to the scientific literature.

Although similar trends exist for both the basal and locomotor metabolic rates of humans who differ in body size, equivalent scaling relationships have not come forth. There are numerous potential explanations for this, most of which are beyond what can be considered in a single investigation. Here, we focus simply on quantifying the metabolic cost of human walking. Our objective was to specifically consider one potential factor: the quantitative effect of baseline subtractions on estimating the metabolic energy that walking requires. Walking on firm, level surfaces is a relatively low-intensity activity, typically elevating the body's metabolic rate only 1.5 to 5 times above resting levels. Given these relatively small elevations, the baseline quantity subtracted could have a significant impact on the estimates obtained for the metabolic cost of this activity.

Although this issue is technical in nature, walking baseline subtractions are of considerable potential importance. Efforts to explain, predict, and monitor physical activity and energy expenditure directly depend on how the total metabolic cost is partitioned between basal and activity requirements. Thus, for both basic purposes such as understanding how gait and muscle mechanics incur the metabolic costs observed during locomotion (4,5), and applied purposes such as developing predictive equations for estimating metabolic costs in the field (6,7,8,9) or prescribing exercise intensities in clinical settings (6), valid baseline subtractions are a prerequisite for accuracy.

The most common contemporary approach (10,11) to this issue is to measure and subtract the metabolic cost of quiet standing. However, some of the earliest investigators working on human and other animal subjects concluded that subtracting basal, rather than standing or "postural" metabolic rates, was equally (3) or more valid (12). Here, we compared the quantitative influence of two different baseline subtractions on estimating the metabolic cost of level human walking. We predicted that the baseline

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quantity subtracted would alter estimations of the metabolic energy that walking requires by as much as 20%.

II. METHODS

A. Experimental Design

To test the quantitative influence of baseline subtractions on estimations of the net metabolic rates required for level walking, we subtracted two baseline values from the gross rates measured: 1) standing metabolic rate, and 2) resting metabolic rate. We then compared the two net values obtained across a broad range of walking speeds.

B. Subjects

Six subjects, 3 male (means ± sem, mass = 79.6 ± 3.0 kg; height = 178.6 ± 4.5 cm; age = 25.7 ± 2.2 years) and 3 female (mass = 60.7 ± 4.8 kg; height = 165.7 ± 5.4 cm, age = 27.7 ± 5.7 years) between 21 and 39 years of age volunteered to participate and provided written informed consent in accordance with the guidelines of the institutional review board of Southern Methodist University. All subjects were in good health and had no major contraindications to exercise. Subjects reported to the laboratory in the early morning immediately after waking. They were instructed to refrain from eating and caffeine use within 12 hours of reporting to the laboratory.

C. Gross Metabolic Rates

Metabolic rates were determined from indirect calorimetry using measurements of expired gases during standing and steady-state treadmill walking at six different speeds. Resting, standing and walking measures were collected using a modular metabolic system (Parvo Medics TrueOne 2400, Sandy, Utah). Expired gases were collected via a one-way breathing valve and tubing that directed flow through a pneumotach and into a mixing chamber. Volume flow rates were measured by the pneumotach while of O_2 and CO_2 fractions in aliquots drawn from the mixing chamber were analyzed using paramagnetic and infrared gas analyzers, respectively. Rates of oxygen uptake were averaged over a minimum of two minutes under steady-state conditions. All oxygen uptake values were converted into metabolic rates using an energetic equivalent for oxygen of 20.1 joules per milliliter oxygen.

Resting metabolic rates were determined from the lowest consecutive 10-minute average over the last 30 minutes of a 60-minute bout of supine resting. Standing values were determined from the lowest consecutive 5-minute average during the last 10 minutes of a 15-minute bout of quiet standing. Walking metabolic rates were determined from the average measured over the last two-minutes of each walking trial.

D. Treadmill Testing Protocol

Walking trials were administered on a level treadmill at speeds of 0.2, 0.4, 0.7, 1.0, 1.3, 1.6 and 1.9 $m•s^{-1}$. Each trial lasted six minutes to ensure steady-state conditions during the last two minutes of each trial. The protocol began at 1.0 $m•s^{-1}$ and was administered continuously in a staggered-speed fashion until all the walking speeds were completed once. After a break of zero to 20 minutes, the protocol was completed in the same speed order a second time. Steady-state rates of oxygen uptake were averaged from the duplicate trials completed at each speed.

E. Estimated Net Metabolic Requirements of Walking

Estimated net metabolic rates (E_{net}) at each walking speed were determined by subtracting one of two baseline quantities from the gross metabolic rates measured, either: 1) the measured rate of standing metabolism (E_{stand}) to obtain ($E_{net\text{-}stand}$), or 2) the measured rate of resting metabolism (E_{RMR}) to obtain ($E_{net\text{-}RMR}$). The metabolic cost of walking per unit distance (E_{trans}) was determined by dividing the gross metabolic rate, and the two estimates of the net metabolic rate, by walking speed to obtain: $E_{trans\text{-}gross}$, $E_{trans\text{-}stand}$ and $E_{trans\text{-}RMR}$, respectively.

III. RESULTS

A. Gross Metabolic Rates

The gross metabolic rates measured during standing (1.25 ± 0.03 $W•kg^{-1}$) exceeded the resting metabolic rates (1.08 ± 0.02 $W•kg^{-1}$) by a factor of 1.16 (Figure 1A). The mean gross metabolic rates of our 6 subjects during walking increased with speed in a curvilinear fashion over a 3.2-fold range from the slowest speed of 0.2 $m•s^{-1}$ to the fastest speed of 1.9 $m•s^{-1}$ (2.14 ± 0.09 to 6.90 ± 0.21 $W•kg^{-1}$; Figure 1A). Per unit distance, the measured maximum gross metabolic energy expended was 10.69 ± 0.44 $J•kg^{-1}•m^{-1}$ at 0.2 $m•s^{-1}$. Gross transport costs were approximately one-third this value at intermediate and faster walking speeds, exhibiting a minimum of 3.04 ± 0.07 $J•kg^{-1}•m^{-1}$ at 1.3 $m•s^{-1}$ (Figure 1B).

B. Estimated Net Metabolic Requirements of Walking

Both standing and resting baseline values constituted a large percentage of the gross metabolic rates measured at different walking speeds (Figure 2). At the slowest speed of 0.2 $m•s^{-1}$, measured standing and resting rates were 58.3 and 50.4%, respectively of the measured gross values. These percentages decreased with walking speed, falling to 18.1 and 15.6%, respectively at the fastest speed of 1.9 $m•s^{-1}$. The average respective percentages across all six speeds measured were 38.0 and 32.9%.

Differences in our three E_{trans} variables were speed-dependent, being roughly two-fold at the slowest speed of 0.2 $m•s^{-1}$ (4.45 ± 0.32 [$E_{trans\text{-}stand}$] and 5.30 ± 0.39 [$E_{trans\text{-}RMR}$], respectively vs. 10.69 ± 0.44 $J•kg^{-1}•m^{-1}$ [$E_{trans\text{-}gross}$]) and considerably less at the fastest speed of 1.9 $m•s^{-1}$ (2.98 ± 0.11 [$E_{trans\text{-}stand}$] and 3.06 ± 0.11 [$E_{trans\text{-}RMR}$], respectively vs. 3.63 ± 0.11 $J•kg^{-1}•m^{-1}$ [gross]). The percentage differences in the estimates of net walking transport costs obtained by subtracting measured standing rates vs. resting rates ranged from a maximum of 16.0% at 0.2 m•s^{-1} to a minimum of 2.9% at 1.9 m•s^{-1}.

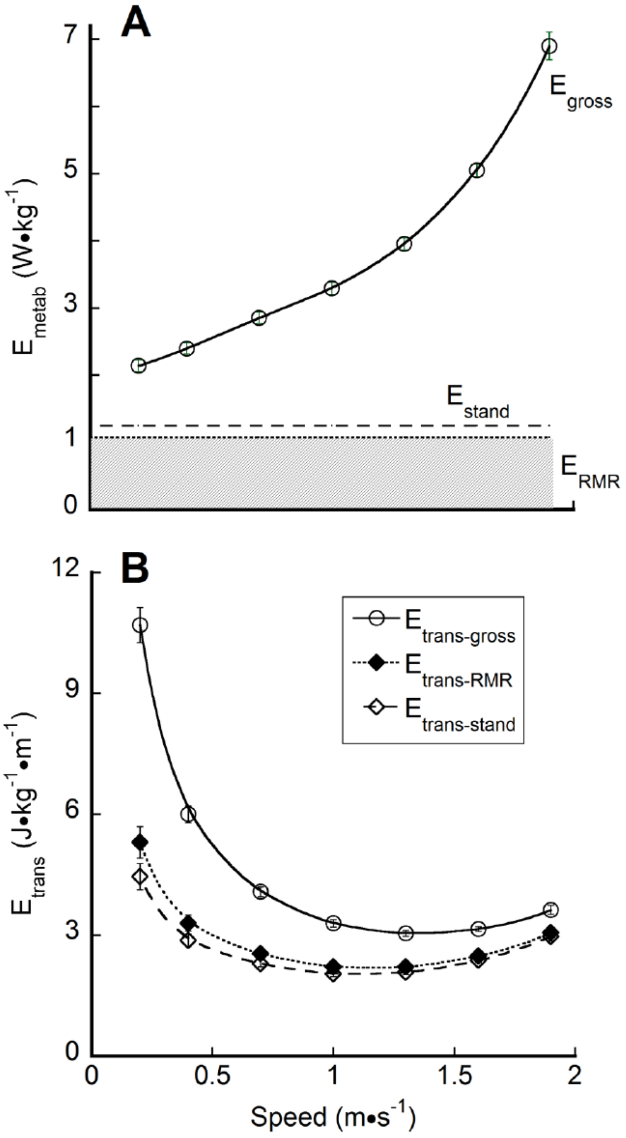

Fig 1. A. Mass-specific, gross metabolic rates as a function of walking speed. Resting (E_{RMR}) and standing metabolic rate values (E_{stand}) are illustrated as constants. B. Mass-specific, gross ($E_{trans-gross}$) and respective net transport costs ($E_{trans-RMR}$ and $E_{trans-stand}$) in relation to walking speed.

IV. DISCUSSION

The sensitivity of estimates of the net metabolic requirements of walking to the particular baseline value subtracted (standing vs. resting) from the gross metabolic rates measured were marginally less than we expected at the outset of the study. Rather than the maximum difference of 20% predicted, we found a speed-dependent differences that ranged from 2.9% at the fastest speed to 16.0% at the slowest one. This slightly more limited effect resulted, in part, from a smaller than anticipated difference between standing and resting rates. Specifically, our standing values were only 1.16 times greater than our resting estimates, whereas previous investigators have generally reported larger offsets in these (13) and similar measures (11,14). The degree of speed-dependency resulted from the curvilinear increases in gross metabolic rates with walking speed (Fig 2). These increases caused the fractional contributions of both baseline rates to drop from over one-half at 0.2 m•s^{-1} to approximately one-sixth at 1.9 m•s^{-1}.

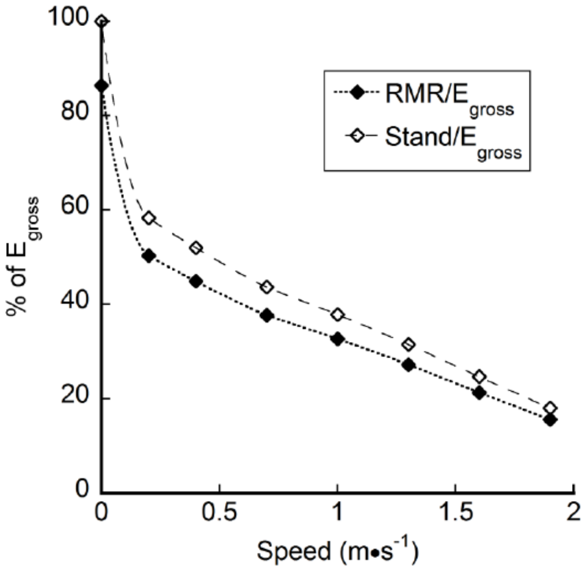

Fig 2. The respective percentage contributions of standing and resting metabolic rates to the gross metabolic rates measured at different walking speeds.

A. Relative Validity of Baseline Subtractions

A problem inherent in partitioning gross metabolic rates into resting and locomotor portions is that the two components cannot be measured independently at the time of the activity. As such, a direct evaluation of whether the baseline value subtracted provides a valid representation of the body's minimum non-locomotor metabolic requirements is not possible. However, the factors responsible for the differences between basal and standing values can be identified and used to guide decisions about appropriate baseline subtractions. Standing metabolic rates typically exceed basal metabolic rate values by a factor of 1.15 to 1.5 (11,13,14,15,16). The additional metabolic cost incurred above basal values while standing is due largely to the activation of the leg and trunk muscles to balance, maintain posture and to support the weight of the body (17,18,19). Because the same balance, postural and support requirements are present during walking, subtracting standing metabolic rates eliminates a small, but appreciable portion of the muscular costs incurred during this activity. In contrast, subtracting resting metabolic rate does not.

Although the current literature does not provide the exact proportion of the metabolic cost incurred by walking that can be attributed to balance, posture and support, the existence of these costs is widely, if not completely recognized (16,19,20,21). For example, a close relationship between the weight supported and the walking metabolic costs incurred has appeared in load carriage experiments (16,20) under pre- and post-weight loss conditions (21) and in comparisons of obese and non-obese individuals (15). These results agree with Taylor's classic studies (2,5,22) on running that concluded that supporting the weight of the body is a primary determinant of the metabolic cost of terrestrial locomotion.

The reasons for the current convention of subtracting standing metabolic rate are not fully clear, but may be partially pragmatic. Standing metabolic rates can be measured relatively easily in treadmill experiments while resting and basal metabolic rates are typically more difficult. The comparative studies on locomotor metabolism (2,3) that originally framed the issue did so appropriately, correctly concluding that their analyses were minimally affected by the inclusion of "postural" vs. resting metabolic costs. The much greater factorial elevations in the metabolic rates of the running and hopping animals examined in the classic studies led to a large insensitivity to the baseline quantity subtracted. The size effect of different baseline subtractions here, although not that large, could nonetheless substantially influence basic conclusions regarding muscular efficiency (23,24) and economy (16) during walking.

B. *Recommendations and Conclusions*

The results we have reported here identify the moderate sensitivity of estimates of the metabolic energy required for walking to the baseline metabolic rate subtracted. For reasons that are difficult to discern in the scientific literature, the predominant current convention is to use the metabolic rate during quiet standing as the standard baseline quantity subtracted from the gross rates measured. However, because standing metabolic rate measurements include balance, postural and support costs that also comprise a small but appreciable portion of the metabolic cost of walking, more accurate estimates of the total metabolic energy that walking requires are likely to be provided by subtracting resting metabolic rates.

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