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The correlation between metabolic and individual leg mechanical power during walking at different slopes and velocities

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ABSTRACT

During level-ground walking, mechanical work from each leg is required to redirect and accelerate the center of mass. Previous studies show a linear correlation between net metabolic power and the rate of step-to-step transition work during level-ground walking with changing step lengths. However, correlations between metabolic power and individual leg power during step-to-step transitions while walking on uphill/downhill slopes and at different velocities are not known. This basic understanding of these relationships between metabolic demands and biomechanical tasks can provide important information for design and control of biomimetic assistive devices such as leg prostheses and orthoses. Thus, we compared changes in metabolic power and mechanical power during step-to-step transitions while 19 subjects walked at seven slopes (0°, +/−3°, +/−6°, and +/−9°) and three velocities (1.00, 1.25, and 1.50 m/s). A quadratic model explained more of the variance (R^2=0.58–0.61) than a linear model (R^2=0.37–0.52) between metabolic power and individual leg mechanical power during step-to-step transitions across all velocities. A quadratic model explained more of the variance (R^2=0.57–0.76) than a linear model (R^2=0.52–0.59) between metabolic power and individual leg mechanical power during step-to-step transitions at each velocity for all slopes, and explained more of the variance (R^2=0.12–0.54) than a linear model (R^2=0.07–0.49) at each slope for all velocities. Our results suggest that it is important to consider the mechanical function of each leg in the design of biomimetic assistive devices aimed at reducing metabolic costs when walking at different slopes and velocities.

1. Introduction

To walk, humans utilize metabolic energy to perform mechanical tasks such as generating force to support weight and performing work to redirect/accelerate the center of mass (COM) from step-to-step. COM dynamics have been well represented by an inverted pendulum model during single leg support for level-ground walking at constant velocities (Cavagna et al., 1977; Gottschall and Kram, 2006). This model suggests minimal mechanical work to sustain steady-speed locomotion because of a constant phasic exchange of potential and kinetic energy (Cavagna et al., 1977, 2000). However, during step-to-step transitions, the leading leg absorbs mechanical work to slow downward movement of the COM while the trailing leg generates mechanical work to redirect the COM upward and forward (Alexander, 1980; Donelan et al., 2002a, b; Kuo, 2007; Adamczyk and Kuo, 2009).

Individual leg mechanical power during step-to-step transitions changes with velocity over level-ground (Donelan et al., 2002a, b; Adamczyk and Kuo, 2009; Franz et al., 2012), such that the leading leg absorbs and trailing leg generates work simultaneously during step-to-step transitions. However, both legs generate work while walking on uphill slopes greater than 0° and absorb work when walking on downhill slopes less than 0° at 1.25 m/s (Franz et al., 2012). Similarly, metabolic power increases with uphill slopes greater than and decreases with downhill slopes less than −3° (Kang et al., 2002; Minetti et al., 2002; Sawicki and Ferris, 2009; Silder et al., 2012). However, step-to-step transition work and metabolic demands for the combined effects of slope and velocity have not been examined.

Previous research has shown strong correlations between metabolic power and individual leg mechanical power performed during step-to-step transitions for level-ground walking at 0.72–1.97 m/s with varying step lengths (Donelan et al., 2002a). Donelan et al. found that when step length is varied, 79–89% of the variance in metabolic power is explained by individual leg mechanical power during the step-to-step transition (Donelan et al., 2002a). This strong

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correlation between metabolic and individual leg step-to-step transition power during level-ground walking suggests a correlation may exist when walking uphill and downhill at different velocities. However, these correlations have not been established. Further, because previous research has shown that the ankle accounts for 46–89% of the external power required for level-ground walking (Winter, 1983; Farris and Sawicki, 2012), understanding the correlations between metabolic and mechanical power is important for design, development, and control of robust biomimetic assistive devices such as leg prostheses and orthoses (Ferris et al., 2007). Previous studies suggest that prosthetic ankle power plays an important role in reducing metabolic demands during level-ground walking (Herr and Grabowski, 2012; Caputo and Collins, 2014).

Our purpose was to determine the correlations between metabolic power and individual leg step-to-step transition mechanical power during walking across a wide range of slopes and velocities. We sought to better understand the basic biomechanics and metabolic costs of unimpaired human walking. Metabolic power increases and leading (P_{lead}) and trailing (P_{trail}) leg mechanical powers are more positive on steeper uphill slopes compared to level-ground walking. Metabolic power decreases, and P_{lead} and P_{trail} are more negative on steeper downhill slopes compared to level-ground walking. Further, metabolic power increases, P_{lead} is more negative and P_{trail} is more positive at faster velocities (Minetti et al., 1993, 2002; Franz et al., 2012). We hypothesized that metabolic power would be correlated with P_{lead} and P_{trail} for all slopes ($-9°$ to $9°$) and velocities (1.00 m/s, 1.25 m/s and 1.50 m/s). We also hypothesized that the ratio of individual leg mechanical power during step-to-step transitions to the overall metabolic power, indicated as the individual limb power ratio (ILPR), would be similar across all slopes and velocities.

2. Methods

Nineteen subjects with no lower extremity or neurological injuries or pathologies volunteered [13 M, 6 F, mean 29.2 years (8.4 years); 69.6 kg (13.2 kg)] and gave informed written consent prior to participating in accordance with a protocol approved by the Department of Veteran Affairs' Human Subjects Institutional Review Board. Subjects walked on a dual-belt force-measuring treadmill (Bertec Corp., Columbus, OH) at seven slopes (0°, +/−3°, +/−6°, and +/−9°) and three velocities (1.00, 1.25, and 1.50 m/s). We used constant speeds for comparisons across conditions and with other studies (Franz et al., 2012). First, we measured each subject's mass and metabolic rate while standing. Then, we measured metabolic rates and ground reaction forces during each six-minute walking trial. Trial order was randomized, and at least two minutes rest was enforced between trials. Data collection occurred over three sessions at the same time each day to account for potential day-to-day variability in metabolic rates. Seven walking conditions were tested each day.

2.1. Metabolic power

We measured rates of oxygen consumption ($\dot{V}O_2$; ml/min/kg) and carbon dioxide production ($\dot{V}CO_2$; ml/min/kg) using indirect calorimetry (Parvo Medics TrueOne 2400, Sandy, UT). We averaged $\dot{V}O_2$ and $\dot{V}CO_2$ from the last two minutes of each trial and calculated metabolic power using a standard equation (Brockway, 1987). We determined net metabolic power by subtracting standing from each trial's metabolic power.

2.2. Step-to-step transition power

We measured ground reaction forces (F) at 1500 Hz from each leg and normalized all data to body mass (m). We filtered F with a fourth order low-pass Butterworth filter and 20 Hz cutoff frequency using a custom program (Matlab, Natick, MA). COM acceleration (a) with respect to time (t) was calculated as follows:

$$a_{\mathrm{ML}}(t) = \frac{F_{\mathrm{ML}}(t)}{m} \tag{1}$$

$$a_{parallel}(t) = \frac{F_{parallel}(t) - mg_{*}\sin(\theta)}{m} \tag{2}$$

$$a_{\mathrm{perp}}(t) = \frac{F_{\mathrm{perp}}(t) - mg_{*}\cos(\theta)}{m} \tag{3}$$

where medio-lateral (ML), parallel ($parallel$), and perpendicular ($perp$) components of force were calculated relative to the treadmill slope (θ). COM velocity (v) was calculated as the integral of acceleration with respect to time

$$v(t) = \int_0^t a(t)\,dt + v_0 \tag{4}$$

We determined integration constants (v_0) for perpendicular (v_{perp}) and medio-lateral (v_{ML}) velocities by assuming that average v over a stride equaled zero. We determined v_0 for parallel velocity ($v_{parallel}$) by assuming that average v over a stride equaled treadmill velocity. We calculated external mechanical power performed by each leg during step-to-step transitions using the method described by Donelan et al. (2002a). We calculated step-to-step transition power absorbed and generated by each leg (P_{lead} and P_{trail}) on the COM as the sum of the products of ground reaction force (F) and COM velocity (v_{com}) during the step-to-step transition

$$P_{\mathrm{lead}} = F_{\mathrm{ML,lead}} \cdot v_{\mathrm{ML,com}} + F_{\mathrm{parallel,lead}} \cdot v_{\mathrm{parallel,com}} + F_{\mathrm{perp,lead}} \cdot v_{\mathrm{perp,com}} \tag{5}$$

$$P_{\mathrm{trail}} = F_{\mathrm{ML,trail}} \cdot v_{\mathrm{ML,com}} + F_{\mathrm{parallel,trail}} \cdot v_{\mathrm{parallel,com}} + F_{\mathrm{perp,trail}} \cdot v_{\mathrm{perp,com}} \tag{6}$$

We defined step-to-step transition as the time when both legs were on the ground (Donelan et al., 2002a). We detected heel-strike and toe-off with a force threshold of twice the average signal noise when nothing was in contact with the treadmill. Step-to-step transitions may extend beyond double support (Adamczyk and Kuo, 2009), but our primary interest was to understand correlations between metabolic power and mechanical power absorbed at initial contact and produced during late stance, thus we defined the step-to-step transition as the time of double support. We calculated each subject's average individual leg powers during step-to-step transitions from approximately 75 steps per subject. Then, we calculated the average and standard deviation of individual leg power from all subjects.

2.3. Relationship between individual leg mechanical power and metabolic power

Based on research by Donelan et al. (2002a, b), we quantified correlations between metabolic and individual leg mechanical power using linear models. Because leg muscles must produce force to move the COM forward during walking and thereby incur a metabolic cost, musculoskeletal models have optimized muscle activation squared to accurately predict biomechanical data for a walking gait cycle (Crowninshield and Brand Richard, 1981; Anderson and Pandy, 2001; Thelen, et al., 2003) and approximate metabolic cost (Umberger and Rubenson, 2011). Based on this research, we also investigated quadratic models when correlating metabolic power and individual leg mechanical power. Further, we analyzed data for all slopes at individual speeds based on work by Farris and Sawicki (2012) that demonstrated a quadratic change in individual leg work with faster constant speed.

2.4. Individual limb power ratio (ILPR)

We quantified ILPR as the ratio between average individual leg mechanical power during step-to-step transitions and average metabolic power for the entire walking task. We acknowledge that other mechanical tasks account for the metabolic power required during the entire gait cycle, but sought to specifically understand how relative changes in step-to-step transition power affected metabolic power at different slopes and velocities. As such, ILPR shows the effect of each leg's step-to-step transition power on overall metabolic power, but underestimates ILPR for the entire walking task

$$\mathrm{ILPR}_{lead} = P_{\mathrm{mech,lead,S2S}}/P_{\mathrm{met}} \tag{7}$$

$$\mathrm{ILPR}_{trail} = P_{\mathrm{mech,trail,S2S}}/P_{\mathrm{met}} \tag{8}$$

2.5. Statistics

We used two-way repeated measures ANOVAs ($P < 0.05$) to compare metabolic power and step-to-step transition power of each leg at different slopes and velocities. Our within subject variables were slope with seven levels: 0°, ±3°, ±6°, and ±9° and velocity with three levels: 1.00, 1.25, and 1.50 m/s. We correlated average metabolic power with average step-to-step transition power of each leg using linear and quadratic curve fitting regression models (RStudio, Boston, MA), where the strongest correlation delineated the best model.