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Walking at the preferred stride frequency minimizes muscle activity

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ABSTRACT

This study determined whether walking at the preferred stride frequency minimizes muscle activity compared with other cadences at the same speed. Anthropometric measurements were recorded from 10 subjects and used to estimate their predicted resonant stride frequency. The preferred walking speed and stride frequency were determined from freely adopted walking on a treadmill. For the experimental trials the treadmill was set at each individual's preferred walking speed. Participants walked for 6 min at eight cadences prescribed by an auditory metronome: preferred stride frequency and −35, −25, −15, 0, +15, +25, +35% of predicted resonant stride frequency. Oxygen consumption was measured via gas analysis. Muscle activity of the right leg gastrocnemius (GA), tibialis anterior (TA), biceps femoris (BF) and rectus femoris (RF) muscles was recorded via electromyography (EMG). On average, participants preferred to walk with a stride frequency .07 Hz lower than their predicted resonant stride frequency, however a strong positive correlation was observed between these variables. Stride frequency had a significant and large quadratic effect on VO$_2$ ($R^2_{LR} = .76$), and activity of the GA ($R^2_{LR} = .66$), TA ($R^2_{LR} = .83$), BF ($R^2_{LR} = .70$) and RF ($R^2_{LR} = .78$) muscles. VO$_2$, GA and TA activity were all minimal at the preferred stride frequency and increased for faster or slower cadences. BF and RF activity were minimal across a broad range of slow frequencies including the preferred stride frequency and increased for faster frequencies. The preferred stride frequency that humans readily adopt during walking minimizes the activation of the GA, TA, BF and RF muscles, which in turn minimizes the overall metabolic cost.

1. Introduction

Humans freely adopt a stride frequency when walking [1] which minimizes overall oxygen consumption for a given speed [2–5]. Given that the primary metabolic cost during walking arises from contractions of skeletal muscles, muscle activity is expected to be minimal at the preferred cadence. This may be achieved by exploiting passive dynamics from the gravitational field and elastic energy stored in the muscles and tendons [1,6]. The preferred locomotion frequencies across species are related to the mass and length properties of the limbs [7,8], indicating that the gravitational field has a strong influence on cadence, similar to the oscillation of a pendulum. However, the preferred stride frequency of walking is faster than predicted by a simple pendulum model [1,8]. The contribution of muscles, ligaments and tendons can be added to this model by representing them globally as a spring of stiffness k set at a perpendicular distance b from the axis of rotation. The resonant frequency of this hybrid spring-pendulum model (ω_n) can then be calculated via:

$$\omega_n = \frac{1}{2\pi\sqrt{mL_e^2/(mL_e g + kb^2)}}, \qquad (1)$$

where m is the mass of the leg, g is the acceleration due to gravity (=9.81 m s^{-2}) and L_e is the equivalent pendulum length. This model predicts the preferred frequency of hand-held pendulum and arm swinging [5,8]. The resonant frequency (ω_n) coincides with the preferred stride frequency of walking when the generative torque of the spring (kb^2) equals the restoring torque due to gravity ($mL_e g$) and Eq. (1) can be reduced to [1]:

$$\omega_n = \frac{1}{2\pi\sqrt{L_e/2g}}. \qquad (2)$$

This resonant frequency has been found to predict the preferred stride frequency of children and adults walking [1,9].

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Physical systems moving at resonance have the benefit of requiring the smallest amount of forcing for the same amplitude of oscillation. If walking at the preferred stride frequency can be understood as moving at resonance, then muscles, such as the gastrocnemius, which play a significant role in forcing the center of mass during gait to compensate for loss of energy at heel strike, would be expected to be minimal at the preferred/predicted stride frequency and to increase for higher or lower cadences. This predicted pattern of muscle activity with walking cadence has yet to be tested because previous electromyographical (EMG) studies of walking focused on understanding the influence of speed on muscle activity [10,11]. Another limitation of these studies for present purposes is the use of mean muscle activity during phases of the gait cycle, which do not represent the total amount of activity when stride duration differs across conditions.

The overall goal of this study was to determine if the minimal oxygen consumption at the preferred stride frequency could be explained by minimal activity of the muscles involved in walking. EMG was used to quantify activity of four muscles involved in controlling motion of the ankle, knee and hip in walking: gastrocnemius (GA), tibialis anterior (TA), biceps femoris (BF), and rectus femoris (RF) [10,11]. The total amount of activity of each muscle for a constant time and distance was determined in order to relate the EMG findings with metabolic cost. The hybrid spring-pendulum model of walking was tested by comparing the predicted resonant stride frequency with the freely adopted preferred cadence, and assessing whether each muscle displayed a concave up pattern, with the minimum at the preferred and resonant stride frequencies.

2. Methods

2.1. Subjects

A convenience sample of five men and five women, aged 18–32 years volunteered to participate in this study. All participants were free from any neuromuscular or musculoskeletal disorders that may have caused abnormal gait patterns. All participants were in good physical condition and had previous experience walking on a treadmill. Informed consent was granted by participants in accordance with the university institutional review board.

2.2. Anthropometric measurements

For each individual, their predicted resonant frequency was computed according to the hybrid spring-pendulum model using anthropometric measurements and proportional estimates from Dempster [12]. Body height and mass were recorded from all participants using a balance beam scale with height rod (see Supplementary Material). Thigh length, shank length and foot length were all measured by the same experimenter, who had previous experience palpating appropriate anatomical landmarks and measuring the distances with an anthropometric tape measure. The description of the measurements and the computation of L_e in Eq. (2) have been previously described by Holt and colleagues [1] (see Supplementary Material).

2.3. Procedures

Prior to attaching the surface EMG electrodes the skin sites were shaved if necessary, abraded and cleaned with an alcohol solution. Disposable Ag–AgCl pre-gelled snap electrodes (EL501; BIOPAC Systems, Inc., Goleta, CA) were placed in pairs (electrode center distance = 3.75 cm) over four muscles of the right leg. The GA electrodes were placed 1/3 of the distance from the head of the fibula to the heel, while the TA electrodes were placed 1/3 of the distance from the lower margin of the patella to the lateral malleolus [13]. The RF electrodes were placed 2/3 of the distance from the iliac crest to the superior margin of the patella, and the BF electrodes were placed 2/3 of the distance from the head of the femur to the posterior of the lateral condyle of the femur. Ground electrodes were placed on bony prominences of the right leg. The electrodes were connected to an amplifier (TEL100M-C; BIOPAC Systems, Inc.), with 2 MΩ impedance and common mode rejection ratio of 110 dB. A heel-toe strike transducer (SS28A; BIOPAC Systems, Inc.) was attached using athletic tape under the sole of the participant's right shoe. All wires were secured with underwrap and athletic tape. This data was collected at 500 Hz, the maximum equipment setting. Previous research has shown that this sample rate is sufficient for accurately determining the amplitude of EMG as well as other parameters [14,15].

Participants wore a nose clip and breathed through a non-rebreathing T-valve (AFT21; BIOPAC Systems, Inc.). The flow rate of the inspired air was measured by a pneumotach transducer (TSD107B; BIOPAC Systems, Inc.) at 250 Hz, while the proportion of oxygen and carbon dioxide in expired air was determined by gas analyzers (O2100C and CO2100C; BIOPAC Systems, Inc.). All data was acquired using the MP100 data acquisition and analysis system using AcqKnowledge software (version 3.73 for Windows; BIOPAC Systems). Gas measurements were adjusted according to the lab temperature and barometric pressure immediately preceding data collection.

Each individual's preferred walking speed and cadence were determined on a treadmill (TM65, Quinton, Bothell, WA) with the display occluded. Participants instructed the experimenter to speed up or slow down the treadmill until they were walking at their "most comfortable" speed [2,3]. When the same speed (±3%) was selected on three consecutive trials the procedure was stopped and the average of these values was used as the preferred speed. Participants then walked at this preferred speed for three trials of 60 s each. The time of each heelstrike was used to determine stride frequencies which were averaged within and across the three trials to compute the preferred stride frequency.

Participants completed eight experimental stride frequencies of: preferred stride frequency (Mean: $\Delta\omega = -7.32\%$), predicted stride frequency ($\Delta\omega \equiv 0$), and ±15%, ±25% and ±35% of the predicted stride frequency. The treadmill was maintained at the originally determined preferred speed and participants were instructed to match their right heel strike with an auditory metronome at the prescribed cadence. Participants walked for 6 min at each cadence to allow a steady cadence and physiological state to be achieved. One trial was performed at each condition in random order.

2.4. Data analysis

The raw EMG signal from each muscle was amplified by a gain of 1000 by the amplifier. The amplified signals were then filtered digitally using a 10 Hz high pass filter. The filtered EMG signals were then rectified and smoothed by calculating the root mean square for a 30 data sample moving window (.06 s). The total activity of each muscle was then calculated as the area under this curve for the last minute of each 6 min trial. The volume of inspired air during the last minute of each trial was determined by integrating the flow rate. Using the measurements of the proportion of oxygen and carbon dioxide exhaled and making adjustments for temperature, barometric pressure and body mass, the volume of oxygen (VO_2) consumed was computed. These analysis procedures were performed in the AcqKnowledge software. For each trial the total EMG activity of a single muscle was normalized by dividing it by the total EMG activity for that same muscle under the predicted resonant stride frequency trial.