Control versus self selected gait parameters for passively actuated gait devices

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1 Introduction

For each walking speed, there is an optimal combination of step length and frequency to minimize the energy expenditure of gait. Under normal relaxed walking conditions, the average adult achieves a minimal metabolic rate at a walking speed of 1.25m/s with a step frequency of 0.9Hz (and step-length of 0.7m) [4]. Deviation in these gait parameters from the optimal combination results in an increase of energy consumption [6].

Previous data from [8] showed that the subject group with unforced gait parameters during the walking trials exhibited similar and sometimes lower metabolic expenditure rates with the device in comparison with the subject's normal walking without the device at the same walking speed. Examining the gait parameters of this subject group showed that walking with the device increased step-frequency while the second subject group, with controlled step-frequency, consistently exhibited higher metabolic expenditure rates using the device in comparison to normal walking. The purpose of this study is to examine the metabolic energy expenditure during stride frequency modulated walking between self-modulated and device-modulated stride-frequency. We hypothesize that device modulated stride-frequency will result in a lower metabolic expenditure as the device relieves muscle effort in controlling the lower limbs. Stride frequency is simply half the step-frequency and in this study we use stride frequency instead of step-frequency for clarity of device function in relation to the developed model.

2 Model

A model is developed to represent the passive dynamics of normal walking and provides an estimate of the self-selected stride frequency for the trial conditions. In this model, the swing and stance phase of gait are simplified to the motion of a physical pendulum. Assuming that walking is passive, the resulting equation of motion is:

$$\ddot{\theta} + \omega_n^2 \theta = 0 \tag{1}$$

where $\ddot{\theta}$ is the angular acceleration, ω_n is the natural frequency and θ is the angular displacement of the pendulum from the vertical equilibrium position. Since mass distribution, moment of inertia and pendulum length are different between the swing and stance phase, the period and natural frequency are different between these two phases of gait. During the swing phase the leg acts as a pendulum while during stance the entire body becomes an inverted pendulum. This differs from a simple pendulum model where mass distribution and moment of inertia have no bearing on the swing period of the pendulum. Since a full stride is composed of only half the swing cycle of the inverted and normal pendulum, the stride frequency (T_{stride}) is calculated as half the sum of the stance period (T_{stance}) and swing period (T_{swing}) . Since frequency is the reciprocal of the period ($\omega = 1/T$), the stride frequency, ω_{stride} is determined from the resulting equation:

$$\omega_{stride} = \frac{2(\omega_{stance}\omega_{swing})}{\omega_{stance} + \omega_{swing}} \tag{2}$$

where ω_{stance} and ω_{swing} are the respective natural frequencies of the stance and swing phase determined by the model. The step frequency is simply twice the stride frequency and the step-length, l_{step} is calculated as $l_{step} = v_{walk}/2\omega_{stride}$. The limb segment mass and moments of inertia are estimated using Dempster's equations from [7].

3 Device

The device is similar to that previously presented in [8] except that that the elastic-cable component is modified such that the initial tension is easily adjustable. A depiction of the device from the previous study is shown in Figure 1. The new device includes a lightweight linear rail system to adjust the tension in the spring-cable. The cable links both of the subject's legs such that the spring tension increases at terminal swing until push-off of the contralateral leg. A minimum tension is maintained during the swing phase by the spring-pulley system such that no slack develops in the cable. The routing of the cable is accomplished by using a Bowden cable mounted to a backpack. The cable directly connects the ankle joint to the hip joint such that the effect of the leg is similar to that of a torsion spring acting on a pendulum. A custom foot strap component is worn by the subject like a sock and fits into the subject's shoe. The total weight of the device including the backpack frame is $\simeq 3kg$. This device performs a similar function to that of a simulated exotendon model from [1] that links both legs and crosses all lower limb joints. The effect of the device is included into the model using the following set of equations, where the effective torsion spring constant,

$k_{torsion}$, is determined using Eq.4.

$$\omega_{n1} = \sqrt{\frac{mgL}{I}}, \omega_{n2} = \sqrt{\frac{mgL + k_{torsion}}{I}} \quad (3)$$

where ω_{n1} is the natural frequency without the device (no spring), m is the mass of the pendulum, g is the gravitational constant, L is the length between the pivot and the pendulums center of mass, and I is the mass moment of inertia about the pivot. The second equation is used to estimate the natural frequency, ω_{n2} with the effects of the device.

$$k_{torsion} = k_{linear} * L \quad (4)$$

Figure 1: Depiction of the device used in the previous study.

4 Approach

10 subjects are recruited for the pilot study. The subjects are asked to walking on a force instrumented treadmill (AMTI) at a walking speed of 1.25m/s under four walking conditions: 1) Normal, self-selected stride frequency, 2) Device self-selected stride frequency, 3) Normal - device matched stride frequency, and 4) Device - normal matched stride frequency. Validation of the model is conducted by comparing the model estimated stride frequency with the experimentally measured self-selected stride frequencies. The subjects are exposed to the walking conditions in random order in pairs of conditions ¡1,2¿ and ¡3,4¿. Metabolic data is collected using the COSMED $K4b^2$ system and the kinematic data is captured using a 7 Oqus camera system with QTM Qualysis Software. The treadmill force and motion capture data is synchronized through the Qualisys QTM software and post-filtered using a zero-phase, 2nd order Butterworth with a cut-off frequency of 25Hz using a custom MATLAB script. Contact with the ground is identified using a vertical force threshold of 10N. Metabolic rate is averaged from 2min of data after the 6mins and the gait parameters are averaged from 10 gait cycles within the same 2min mark. Although stride frequency and metabolic data are the only two parameters that we need to test for, more detailed information and a relationship to joint muscle work can be established from the kinetics and kinematics of data which can then relate to the changes in metabolic energy expenditure between trial conditions.

5 Best Outcome

Experimentation is being conducted to confirm that our hypothesis of allowing the subject to self-select their stride frequency when walking with a device will result in lower metabolic expenditure rates than if the subjects were consciously modulating their stride frequency. We expect that the kinetic results will show a reduction in joint power.

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