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A treadmill control protocol combining nonlinear, equally smooth increases in speed and gradient: Exercise testing for subjects with gait and exercise limitations

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Abstract

Incremental exercise testing with a linear increase in work rate is the recommended method for clinical exercise testing. A recent protocol (A), incorporating a linear increase in speed and a nonlinear increase in gradient, has been developed which addresses some limitations of traditional testing methods. It does not account for those with an impaired gait pattern. We propose and assess a novel protocol (B) incorporating nonlinear increases in both speed and gradient.

We theoretically develop a new treadmill control protocol (B), determine oxygen uptake response linearity, initial metabolic rate and cardiopulmonary response parameters (peak oxygen uptake, lactate threshold, dynamic O_2 cost) and compare the outcome measures with two previously verified IET protocols (A and C (constant speed with linear increase in gradient)). Feasibility and outcomes were explored with a subject with incomplete spinal cord injury.

The average initial metabolic rate ($\dot{V}O_2$) was substantially lower during protocol A (0.49 (±0.12) $\mathrm{l\,min^{-1}}$) and protocol B (0.52 (±0.05) $\mathrm{l\,min^{-1}}$) than during protocol C (1.35 (±0.04) $\mathrm{l\,min^{-1}}$). The average linearity of the $\dot{V}O_2$ response during protocols A and B (correlation co-efficients 0.97 (±0.00) and 0.95 (±0.02), and co-efficients of determination 0.94 (±0.01) and 0.91 (±0.02), respectively) were higher than during protocol C (correlation co-efficient 0.91 (±0.02) and co-efficient of determination 0.84 (±0.02)). The average dynamic O_2 cost for protocol C (6.53 (±0.46) $\mathrm{ml\,min^{-1}\,W^{-1}}$) was lower than that of protocol A (10.02 (±1.16) $\mathrm{ml\,min^{-1}\,W^{-1}}$) and protocol B (10.03 (±0.91) $\mathrm{ml\,min^{-1}\,W^{-1}}$). No differences were found in these parameters between protocols A and B.

The new protocol B performs better than protocol C and is comparable with protocol A. When testing subjects with an impaired gait pattern, it may be advantageous to use the new protocol B due to the gradual increases in both speed and gradient throughout the test.

Keywords: Exercise physiology; Treadmill exercise; Incremental exercise testing; Gait impairment; Spinal cord injury

1. Introduction

An incremental exercise test (IET), with a linear increase in work rate to the limit of tolerance, is the recommended procedure for assessment in clinical exercise testing [1,2]. Following a short delay, oxygen uptake ($\dot{V}O_2$) increases linearly at a rate of $\sim 10\,\mathrm{ml\,min^{-1}\,W^{-1}}$ during a cycle IET [3–5] and $\sim 11\,\mathrm{ml\,min^{-1}\,W^{-1}}$ during a treadmill IET [5]. This rate of increase in $\dot{V}O_2$ with respect to work rate, or the dynamic O_2 cost of the exercise, has been shown to deviate in impaired subjects. A reduction in O_2 cost is indicative of cardiovascular dysfunction and has been shown to occur in those with peripheral or pulmonary vascular disease ($8.29 \pm 1.17\,\mathrm{ml\,min^{-1}\,W^{-1}}$) [3] and hypertrophic cardiomyopathy ($9.2 \pm 1.3\,\mathrm{ml\,min^{-1}\,W^{-1}}$) [4]. Using peak values obtained from IETs to determine disease is not recommended as they can be decreased with detraining and can be symptom limited [4]. Therefore, the linearity of the $\dot{V}O_2$ response is a discriminating factor in the assessment of disease. For accurate diagnosis it is therefore essential that the linearity of the work rate profile during an IET be guaranteed.

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A low initial metabolic rate is also important when designing an IET, particularly for impaired subjects, to ensure that key parameters of aerobic fitness, such as the lactate threshold (LT), are captured in the data obtained. Standard treadmill exercise testing protocols do not account for this. When the treadmill gradient remains constant and the speed increases linearly a high initial metabolic rate occurs if a steep gradient is chosen. However, if a low initial gradient is chosen to ensure a low initial metabolic rate then the speed is increased so quickly that the limit of tolerance may be determined by the subject's ability to move their legs quickly and/or efficiently enough. If the treadmill speed remains constant and the gradient is increased, a low speed will result in a low initial metabolic rate. However, the treadmill inclination may increase to a very steep gradient before the limit of tolerance is reached. If a high speed is chosen a large initial metabolic cost will result.

These limitations of standard IETs have been investigated [5]. A new treadmill exercise test was developed which produced a low initial metabolic rate and, through a linear increase in speed and a nonlinear increase in gradient, resulted in a linear increase in work rate with the subject fatiguing at a comfortable walking speed. We refer to this here as protocol A. This test was designed for subjects with cardiovascular impairment and did appear to address the problems associated with clinical exercise testing. However, it does not account for those with an impaired gait pattern who may be required to perform such a test. In patients with an impaired gait, such as those with an incomplete spinal cord injury (SCI), the ability to cope with the sharp initial increase in gradient during this test may be limited. They may be more able to adapt their gait to more gradual changes in speed and gradient.

The aim of this work was therefore to derive a new treadmill control protocol (B) for incremental exercise testing which incorporates nonlinear, equally smooth increases in both speed and gradient and to experimentally assess its associated oxygen uptake response linearity and initial metabolic rate. The results obtained using the new protocol with an incomplete SCI subject were compared to those achieved when performing protocol A [5] and a modified Balke protocol (C) [6,7], incorporating a constant speed and a linear increase in gradient.

2. Methods

2.1. Theory

In protocol A [5] the algorithm for the incremental phase guarantees a linear increase in work rate by combining a linear increase in treadmill speed with a nonlinear increase in slope. A low initial metabolic rate is achieved using low initial values of speed and slope. A limitation of protocol A is that, since the increase in speed is constrained to be linear, the rate of change of speed is constant, which in turn results in a relatively high rate of change in slope near the start of the incremental phase and a low rate of change in slope towards the end of the test (see example in Fig. 1). Here a new protocol (B) is derived which guarantees a linear increase in work rate while speed and slope are constrained to increase in the same relative proportion, i.e. equally smoothly, to achieve the desired linear increase in work rate.

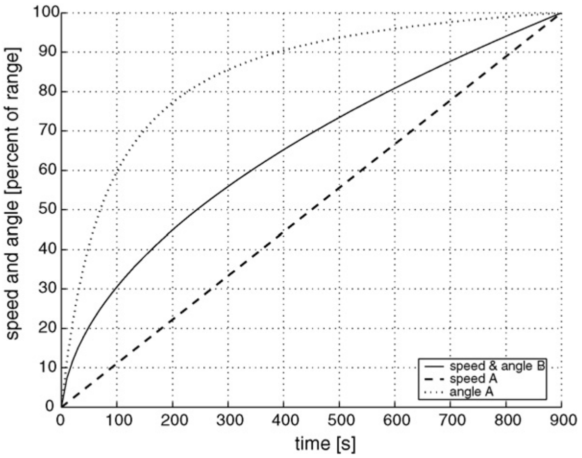

Fig. 1. Speed and angle profiles obtained using the protocol A (speed: dashed line; angle: dash-dot line) and the new method, protocol B, proposed here (both speed and angle given by the solid line). Speed and angle are scaled to represent a percentage of their respective min–max ranges.

The exercise work rate P, above the "unloaded" walking condition at zero slope, is given by

$$P(t) = mgv(t)\sin\theta(t) \tag{1}$$

where m is net mass (i.e. the unsupported component of body mass), g is the gravitational field strength, v is speed, and θ is the inclination angle. For an IET, where a linear increase in work rate is required, we have

$$P(t) = k^P t + P_0, \tag{2}$$

where P_0 is the initial work rate and k^P is the rate of change of work rate. Given a pre-specified final work rate P_f and test duration t_f, the work rate slope is $k^P = (P_f - P_0)/t_f$.

Taken together, Eqs. (1) and (2) imply that, to achieve a linear increase in work rate, speed and inclination angle are constrained in general to satisfy

$$v(t)\sin\theta(t) = \frac{k^P t + P_0}{mg} \tag{3}$$

The algorithm for protocol A [5] considers the special case where treadmill speed is constrained to increase linearly, i.e. $v(t) = k^v t + v_0$, where the rate of change of speed is $k^v = (v_f - v_0)/t_f$, with v_0 and v_f the initial and final speeds, respectively. With this algorithm, therefore, the appropriate treadmill angle at any time t is obtained exactly as

$$\theta(t) = \arcsin\frac{k^P t + P_0}{mg(k^v t + v_0)} \tag{4}$$