ARTICLE IN PRESS

Journal of Biomechanics ∎ (∎∎∎∎) ∎∎∎–∎∎∎

Contents lists available at ScienceDirect

Journal of Biomechanics

journal homepage: www.elsevier.com/locate/jbiomech
www.JBiomech.com

Short communication

Simulation of uphill/downhill running on a level treadmill using additional horizontal force

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ARTICLE INFO

Article history:
Accepted 2 April 2014

Keywords:
Running
Uphill/downhill
Methods
Kinetics
Kinematics
Impact shock

ABSTRACT

Tilting treadmills allow a convenient study of biomechanics during uphill/downhill running, but they are not commonly available and there is even fewer tilting force-measuring treadmill. The aim of the present study was to compare uphill/downhill running on a treadmill (inclination of ± 8%) with running on a level treadmill using additional backward or forward pulling forces to simulate the effect of gravity. This comparison specifically focused on the energy cost of running, stride frequency (SF), electromyographic activity (EMG), leg and foot angles at foot strike, and ground impact shock. The main results are that SF, impact shock, and leg and foot angle parameters determined were very similar and significantly correlated between the two methods, the intercept and slope of the linear regression not differing significantly from zero and unity, respectively. The correlation of oxygen uptake ($\dot{V}O_2$) data between both methods was not significant during uphill running (r=0.42; P>0.05). $\dot{V}O_2$ data were correlated during downhill running (r=0.74; $P<0.01$) but there was a significant difference between the methods (bias = −2.51 ± 1.94 ml min^{-1} kg^{-1}). Linear regressions for EMG of vastus lateralis, biceps femoris, gastrocnemius lateralis, soleus and tibialis anterior were not different from the identity line but the systematic bias was elevated for this parameter. In conclusion, this method seems appropriate for the study of SF, leg and foot angle, impact shock parameters but is less applicable for physiological variables (EMG and energy cost) during uphill/downhill running when using a tilting force-measuring treadmill is not possible.

1. Introduction

Previous studies showed the effects of uphill/downhill running on a treadmill on energy cost (e.g. Minetti et al., 2002), electromyographic activity (EMG) (e.g.Wall-Scheffler et al., 2010) and stride frequency (SF) (e.g. Minetti et al., 1994). Only a few studies have investigated ground reaction forces (GRF) in such conditions, probably because developing appropriate measurement devices (tilting instrumented treadmills) is challenging (Buczek and Cavanagh, 1990; Iversen and McMahon, 1992). Using an advanced tilting and force-measuring treadmill, Gottschall and Kram (2005) were the first to quantify normal and parallel GRF components during uphill/downhill running.

From a mechanical standpoint, uphill/downhill running overground was shown to be not different from uphill/downhill running on a treadmill (van Ingen Schenau, 1980). Furthermore uphill/downhill running has been simulated by applying a force to the runner that pulls backward/forward and reproduces the gravitational force component acting parallel to the slope (Avogadro et al., 2004; Chang and Kram, 1999). Avogadro et al. (2004) measured GRF with an instrumented treadmill that could not be tilted, with subjects pulled forward to simulate downhill running, but this methodology and design have not been validated. Chang and Kram (1999) hypothesized that actual uphill/downhill running on a treadmill and the corresponding backward/forward-pulled simulation would induce

Abbreviations: ActualDown, actual downhill running at 2.5 m s^{-1} (with an actual slope of −8%); ActualUp, actual uphill running at 2.5 m s^{-1} (with an actual slope of +8%); BF, biceps femoris; EMG, electromyographic activity; GL, gastrocnemius lateralis; GRF, ground reaction forces; LevelRun, level running at 2.5 m s^{-1} (without actual or simulated slope); PHA, peak heel acceleration; PTA, peak tibial acceleration; RMS, root mean square; SF, stride frequency; SimulDown, level running at 2.5 m s^{-1} (with a simulated slope of −8%); SimulUp, level running at 2.5 m s^{-1} (with a simulated slope of +8%); SOL, soleus; TA, tibialis anterior; VL, vastus lateralis; $\dot{V}O_{2\ net}$, net oxygen consumption (steady state $\dot{V}O_2$ during running minus $\dot{V}O_{2\ stand}$); $\dot{V}O_{2\ stand}$, oxygen uptake stand at rest

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http://dx.doi.org/10.1016/j.jbiomech.2014.04.012
0021-9290/© 2014 Published by Elsevier Ltd.

similar changes in external work and metabolic cost but that the work efficiency, stride frequency and posture would differ.

Although previous studies have used this type of system, none of them clearly showed that pulling subjects backwards/forwards on a level treadmill is an accurate simulation of uphill/downhill running conditions. Thus, the aim of the present study was to compare uphill/downhill running on a treadmill with level treadmill running using backward/forward horizontal pulling force, with a specific focus on SF, energy cost of running, muscular activity, leg and foot angle, and ground impact shock. These classical variables have been chosen to compare energetics and mechanics between both conditions because of their sensitivity to uphill and downhill running and their importance in running related performance, fatigue or injury risk.

2. Methods

2.1. Subjects

Eleven healthy men (36.8 ± 8.3 yr; 69.1 ± 6.9 kg; 1.78 ± 0.06 m; 13.1 ± 2.1% body fat) gave their written consent and participated in this study, which was approved by the local ethical committee.

2.2. Experimental design

2.2.1. Familiarization session.

The participants were given full details of the experimental procedures and then warmed up for about 15 min. We ensured that these well-trained participants were exercising below the intensity corresponding to the lactate threshold of 4 mmol L^{-1} during the most difficult condition of 2.5 m s^{-1} with +8% slope.

2.2.2. Experimental session

Two weeks after the familiarization session, subjects ran for 4 min on a tilting (not instrumented) treadmill (Gymrol S2500, HEF Tecmachine, Andrezieux-Boutheon, France) at 2.5 m s^{-1} with an actual slope of +8% (ActualUp) and −8% (ActualDown). They also ran on a non-tilting dynamometric treadmill (ADAL3D-WR, Medical Development-HEF Tecmachine, Andrézieux-Bouthéon, France) with simulated slopes of +8% (SimulUp) and −8% (SimulDown) and with zero slope (LevelRun). Conditions were randomized and separated by 3 min of rest.

2.3. Uphill/downhill simulation

While running on the instrumented treadmill, participants were pulled backward/forward by a rope that was connected to a belt fastened around the waist with the other end connected to a suspended weight in order to generate a horizontal pulling force. A simple low-friction pulley was used to redirect the weight force vector from the vertical to the horizontal. This pulley was free to rotate allowing both horizontal movements of the subjects and vertical movement of the suspended mass. The height of the pulley axis was adjusted for each subject so as be at the same height as the subject's waist. The mass was calculated to induce a horizontal force corresponding to the tangential component of body weight during uphill/downhill running for a slope of ±8% as follows:

$$m_h = m_s \times \sin(0.08) \quad (1)$$

with m_h the suspended mass (kg), m_s the subject's mass (kg), and 0.08 rad the angle of the simulated slope corresponding to a slope of 8%.

2.4. Measurements and data analysis

2.4.1. Gas exchange

Pulmonary gas exchange and ventilation were determined breath by breath throughout the tests using a gas analyzer and pneumotachograph system (Medisoft Ergocard, Sorinnes, Belgium). Participants breathed through a mouthpiece connected to the gas analyzer system calibrated using reference gas mixtures and a 3-L syringe. Before starting to run, the participants stood for 4 min while we determined oxygen uptake stand at rest ($\dot{V}O_{2\ stand}$). Net oxygen consumption (corresponding to the steady state $\dot{V}O_2$ minus $\dot{V}O_{2\ stand}$) was calculated during the last 90 s of each running condition and noted as $\dot{V}O_{2\ net}$.

2.4.2. Electromyography

EMG activity of the right vastus lateralis (VL), biceps femoris (BF), gastrocnemius lateralis (GL), soleus (SOL) and tibialis anterior (TA) muscles was recorded using bipolar silver chloride surface electrodes, 30 mm in diameter (Meditrace 100, Tyco healthcare, Mansfield, Canada). Skin preparation and electrodes placements were performed following SENIAM guidelines (Hermens et al., 2000). EMG data were recorded at 2000 Hz using the PowerLab system (16/30-ML880/P, ADInstruments, Bella Vista, Australia), and EMG signal was amplified (Octal Bioamp, ML138, ADInstruments) with a bandwidth frequency ranging from 5 to 500 Hz transmitted to a PC and analyzed with LabChart 7.3 software (ADInstruments). The EMG activity of each muscle was quantified using the root mean square (RMS) smoothed using a 50-ms moving averaging window. The EMG bursts onset and offset were identified using a threshold value of 10% of the maximum value recorded over 20 cycles and a minimum burst duration of 50 ms. Activity of each muscle was averaged between the identified burst onset and offset over 20 running cycles. SF was determined as 20 divided by the total time of 20 consecutive EMG bursts on GL.

2.4.3. Accelerometer analysis

Subjects were equipped with two uniaxial accelerometers (ADXL150, Analog Device, USA) fixed with Dual Lock™ (3M, St Paul, USA); one was fixed on the anteromedial aspect of the distal third of the tibia (from the medial malleolus to the great trochanter), with the skin shaved and cleaned beforehand, and the other at the heel just above the midsole (on the shoe). The acceleration signal was sampled at 2000 Hz (A/D 12-bit acquisition card, DAS8, 284 National Instruments, USA) and low-pass filtered (30-Hz). Peak tibial acceleration (PTA) and peak heel acceleration (PHA) during each condition were calculated for every subject using the averaged values from 10 consecutives steps.

2.4.4. Running mechanics

Mechanical parameters were measured for each step during SimulUp, SimulDown and LevelRun, using the instrumented treadmill. Vertical and antero-posterior GRF signals were recorded at 1000 Hz over 20 s and low-pass filtered (30 Hz). The mean vertical loading rate (in BW s^{-1}) was computed as the mean value of the time-derivate of the vertical GRF signal over the first 50 ms of the support phase and then averaged for 10 consecutive steps. Each running condition was filmed in the sagittal plane with a video camera (Basler scA640-120gc, Germany) operating at 100 Hz. Reflective markers were placed on the lateral malleolus, head of the fibula, and tip of the right shoe, and two other markers were positioned at the front and back of the treadmill, in order to determine the following sagittal angles at foot strike: rear-foot angle between the treadmill (axis between the two treadmill markers) and the foot (axis between the lateral malleolus and the tip of the shoe markers), and leg-treadmill angle between the treadmill and the leg (axis between the lateral malleolus and the head of the fibula markers). After appropriate calibration, the two-dimensional coordinates of the markers were digitized using SIMI Motion software (SIMI Reality Motion Systems, Unterschleissheim, Germany). Rear-foot and leg-treadmill angles were determined for each condition as the average angles for five consecutive steps.

2.5. Statistical analysis

Descriptive statistics are presented as mean ± SD. After checking data normal distributions (Shapiro–Wilk normality test) and variance homogeneity (Fisher *F* test), correlations and linear regressions were performed to test the agreement between parameters obtained during actual and simulated uphill/downhill running. For all parameters, the two methods were compared using a *t*-test for paired samples and the mean difference between the actual and simulated method (bias) was computed. The systematic bias (expressed in %) was also calculated for each subject as follows: systematic bias $= |(\text{simulated method-actual method}) \times \text{actual method}^{-1}| \times 100$. Statistical significance was defined as $P < 0.05$.

3. Results

Mean values (± SD) of the considered parameters are presented in Table 1. SF, rear-foot angle, leg-treadmill angle, PTA, and PHA determined during actual and simulated methods were significantly correlated (Table 1, Figs. 1–4). The intercept and the slope of the linear regressions between the two methods for SF, rear-foot angle, leg-treadmill angle, PTA, and PHA were not significantly different from zero and unity, respectively. The two methods present significant different values only for PTA and leg-treadmill angle during the uphill running condition.

The correlation between $\dot{V}O_{2\ net}$ values obtained in actual and simulated conditions was not significant during uphill running (Fig. 5) and significant during downhill running with a significant difference between the two methods. The intercept and the slope of the linear regression between the two methods for $\dot{V}O_{2\ net}$ were significantly different from zero and unity, respectively. The loading rate decreased with the change in slope from SimulDown