Short communication

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

Philippe Gimenez [a,*], Pierrick J. Arnal [a], Pierre Samozino [b],
Guillaume Y. Millet [a,c], Jean-Benoit Morin [a]

[a] Université de Lyon, Laboratoire de Physiologie de l'Exercice, F-42023 Saint-Etienne, France
[b] Laboratoire de Physiologie de l'Exercice (EA4338), Université de Savoie, F-73376 Le Bourget-du-Lac, France
[c] Human Performance Laboratory, Faculty of Kinesiology, University of Calgary, Calgary, Canada

## 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 $\pm 8\%$) 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$=-2.51 \pm 1.94$ 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.

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## 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

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 tread-mill 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 ($36.8 \pm 8.3$ yr; $69.1 \pm 6.9$ kg; $1.78 \pm 0.06$ m; $13.1 \pm 2.1\%$ 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 back-ward/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 $\pm 8\%$ as follows:

$$m_h = m_s \times \sin(0.08) \tag{1}$$

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 con-nected 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), gastro-cnemius 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, ADInstru-ments, 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, Simul-Down 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 $\pm$ 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=|(simulated method-actual method) $\times$ actual method$^{-1}$| $\times$ 100. Sta-tistical significance was defined as $P < 0.05$.

## 3. Results

Mean values ($\pm$ 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 sig-nificant 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

to SimulUp with a significant decrease ($P < 0.001$) between Simul-Down ($43.7 \pm 9.7$ BW s$^{-1}$) and LevelRun ($33.3 \pm 7.1$ BW s$^{-1}$) and a tendency ($P = 0.06$) between LevelRun and SimulUp ($28.6 \pm 7.8$ BW s$^{-1}$). The relationships between actual and simulated methods for the RMS values of the five muscles are presented in Fig. 6. For all muscles, linear regressions were significant without significant differences between the two methods (Table 1).

## 4. Discussion

The main results of the present experiment are that SF, rear-foot and leg-treadmill angles and impact shock parameters present good agreement between the two methods, but the simulated method was found to be less appropriate for physiological parameters (EMG and energy cost).

SF was higher in uphill than downhill running in both the simulated and actual running conditions ($P < 0.001$ and $P < 0.01$, respectively), while Chang and Kram (1999) noticed no significant change in SF during simulated uphill/downhill running compared to level running ($P = 0.15$). In the present study, correlations between actual and simulated running for SF were significant for both uphill ($R = 0.94$, $P < 0.001$) and downhill ($R = 0.84$, $P < 0.01$) running, with a dispersion of data very close to the identity line, which indicated a very strong agreement between actual and simulated methods for SF.

Chang and Kram (1999) suggested that subjects' posture could be altered while running with an additional horizontal force. Subject's trunk position was not directly measured here, but the fact that the leg-treadmill angle actually increased when subjects

ran from ActualUp to ActualDown ($85.9 \pm 3.70°$ and $96.9 \pm 2.17°$ respectively) and from SimulUp to SimulDown ($83.8 \pm 3.9°$ and $96.9 \pm 2.7°$ respectively) tends to support the assumption that subjects leaned further forward when they ran uphill and further backward when they ran downhill, in a similar manner with the actual and simulated method.

Linear regression analyses and means comparisons showed a good agreement in tibial impact between actual and simulated conditions. PTA tended to increase from ActualUp to ActualDown ($P = 0.10$) which is in line with the previously shown increase in impact shock as the incline changes from uphill to downhill running (Mizrahi et al., 2000). However, no difference in PTA was shown between SimulUp and SimulDown. This could be explained by the difference in leg orientation with vertical at foot strike, and in turn the difference in the consideration in gravity acceleration in PTA between actual and simulated uphill/downhill conditions. Linear regression analyses and means comparisons supported the good agreement in PHA between the two methods, which was strengthened by the similar increase in this variable with change in slope from uphill to downhill in both method. In the present study, the comparison of loading rate was not possible between the two methods. However, we have shown here that the loading rate increased ($+31\%$) and decreased ($-14\%$) during SimulDown and SimulUp respectively, in comparison with LevelRun. These results are in agreement with the changes ($+23\%$ and $-19\%$, respectively) observed by Gottschall and Kram (2005) who measured the loading rate during actual uphill and downhill treadmill running. These authors explained that the observed decrease in normal impact force peaks between downhill and uphill running was accentuated by a modification of the running pattern that switched from a rear-foot

**Table 1**
Mean values $\pm$ SD of $\dot{V}O_{2net}$, EMG, stride frequency, tibial and heel peak acceleration, rear-foot angle and the angle between the leg and the treadmill in both methods, and characteristics of linear regression between the two methods with the mean bias and mean systematic bias.

| | | Actual uphill/ downhill | Simulated uphill/ downhill | Bias | Systematic bias (%) | Pearson correlation coefficient ($r$) | Slope of the linear regression line | $y$ intercept of the linear regression line |
|---|---|---|---|---|---|---|---|---|
| $\dot{V}O_{2net}$ (ml min$^{-1}$ kg$^{-1}$) | Uphill | $37.2 \pm 4.25$ | $38.6 \pm 2.19$ | $-1.43 \pm 3.88$ | $9.14 \pm 6.47$ | 0.42 | 0.22[a] | 30.6[b] |
| | Downhill | $16.2 \pm 2.77$ | $18.7 \pm 1.53$ | $-2.51 \pm 1.94$[†] | $18.1 \pm 15.8$ | 0.74[**] | 0.41[a] | 12.1[b] |
| EMG (mV) | Uphill | | | | | | | |
| | GL | $0.57 \pm 0.42$ | $0.54 \pm 0.34$ | $0.03 \pm 0.13$ | $21.8 \pm 18.7$ | 0.96[***] | 0.77[a] | 0.10 |
| | BF | $0.25 \pm 0.13$ | $0.23 \pm 0.11$ | $0.02 \pm 0.06$ | $17.0 \pm 10.8$ | 0.88[***] | 0.77 | 0.04 |
| | VL | $0.41 \pm 0.18$ | $0.44 \pm 0.16$ | $-0.03 \pm 0.10$ | $22.7 \pm 17.2$ | 0.84[**] | 0.75 | 0.13 |
| | SOL | $0.68 \pm 0.31$ | $0.63 \pm 0.35$ | $0.05 \pm 0.16$ | $16.7 \pm 14.9$ | 0.89[***] | 1.02 | $-0.06$ |
| | TA | $0.25 \pm 0.11$ | $0.21 \pm 0.18$ | $0.04 \pm 0.11$ | $32.4 \pm 22.5$ | 0.80[**] | 1.27 | $-0.11$ |
| | Downhill | | | | | | | |
| | GL | $0.31 \pm 0.20$ | $0.38 \pm 0.28$ | $-0.07 \pm 0.15$ | $36.7 \pm 37.9$ | 0.87[***] | 1.24 | 0.00 |
| | BF | $0.15 \pm 0.10$ | $0.15 \pm 0.10$ | $0.00 \pm 0.06$ | $31.7 \pm 24.9$ | 0.85[**] | 0.87 | 0.02 |
| | VL | $0.34 \pm 0.19$ | $0.31 \pm 0.14$ | $0.03 \pm 0.09$ | $18.3 \pm 11.5$ | 0.89[***] | 0.64[a] | 0.09 |
| | SOL | $0.43 \pm 0.13$ | $0.51 \pm 0.22$ | $-0.07 \pm 0.12$ | $21.1 \pm 18.3$ | 0.88[***] | 1.52 | $-0.15$ |
| | TA | $0.43 \pm 0.26$ | $0.39 \pm 0.17$ | $0.04 \pm 0.18$ | $22.4 \pm 16.6$ | 0.73[*] | 0.49[a] | 0.18[b] |
| Stride frequency (Hz) | Uphill | $1.38 \pm 0.07$ | $1.38 \pm 0.07$ | $0.00 \pm 0.02$ | $1.42 \pm 1.08$ | 0.94[***] | 1.00 | 0.00 |
| | Downhill | $1.31 \pm 0.05$ | $1.31 \pm 0.05$ | $0.01 \pm 0.03$ | $1.83 \pm 1.30$ | 0.84[**] | 0.80 | 0.25 |
| Peak tibial acceleration (m s$^{-2}$) | Uphill | $-46.5 \pm 10.8$ | $-52.7 \pm 9.93$ | $6.22 \pm 3.95$[†] | $14.9 \pm 10.9$ | 0.93[***] | 0.86 | $-12.9$ |
| | Downhill | $-54.3 \pm 11.3$ | $-54.8 \pm 10.9$ | $0.06 \pm 4.27$ | $6.43 \pm 5.19$ | 0.93[***] | 0.95 | $-2.96$ |
| Peak heel acceleration (m s$^{-2}$) | Uphill | $-59.6 \pm 9.77$ | $-59.6 \pm 11.1$ | $0.09 \pm 8.46$ | $10.5 \pm 10.1$ | 0.70[*] | 0.85 | $-9.27$ |
| | Downhill | $-72.9 \pm 7.36$ | $-75.0 \pm 11.4$ | 2.036.46 | $6.55 \pm 6.25$ | 0.85[**] | 1.31 | 20.4 |
| Rear-foot angle (deg) | Uphill | $-1.18 \pm 6.99$ | $-1.48 \pm 7.86$ | $0.29 \pm 1.75$ | $21.5 \pm 20.3$ | 0.98[***] | 0.87 | 0.10 |
| | Downhill | $12.6 \pm 3.51$ | $12.6 \pm 3.67$ | $-0.03 \pm 1.73$ | $11.5 \pm 7.88$ | 0.89[***] | 0.92 | 0.98 |
| Leg-treadmill angle (deg) | Uphill | $85.9 \pm 3.70$ | $83.8 \pm 3.92$ | $2.15 \pm 1.84$[†] | $2.81 \pm 1.63$ | 0.88[***] | 0.94 | 3.30 |
| | Downhill | $96.9 \pm 2.17$ | $96.9 \pm 2.68$ | $-0.09 \pm 2.06$ | $1.73 \pm 1.13$ | 0.66[*] | 0.81 | 18.3 |

† showed a significant bias between actual and simulated uphill/downhill running.

<sup>a</sup> showed a significant difference between unity and the slope of the linear regression.

[a] showed a significant difference between unity and the slope of the linear regression.

[b] showed a significant difference between 0 and the intercept of the linear regression line between actual and simulated uphill/downhill running. * showed a significant linear regression between actual and simulated uphill/downhill running.

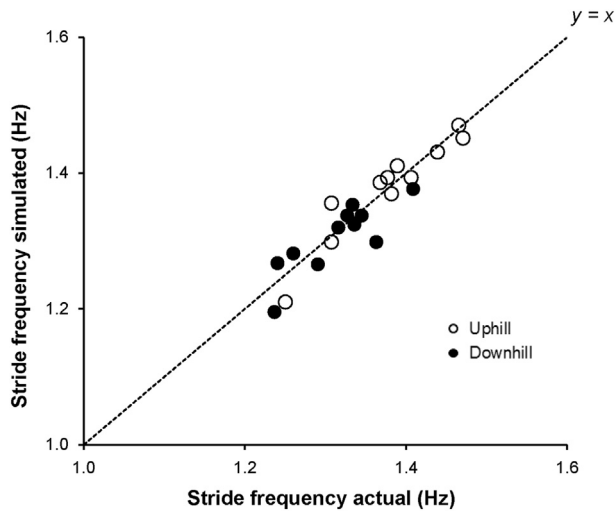* $P < 0.05$.
** $P < 0.01$.
*** $P < 0.001$.
† $P < 0.05$.

**Fig. 1.** Relationship between stride frequency in actual and simulated conditions in downhill (filled black circles) and uphill (open circles) running. The dashed line represents the identity line ($y=x$).
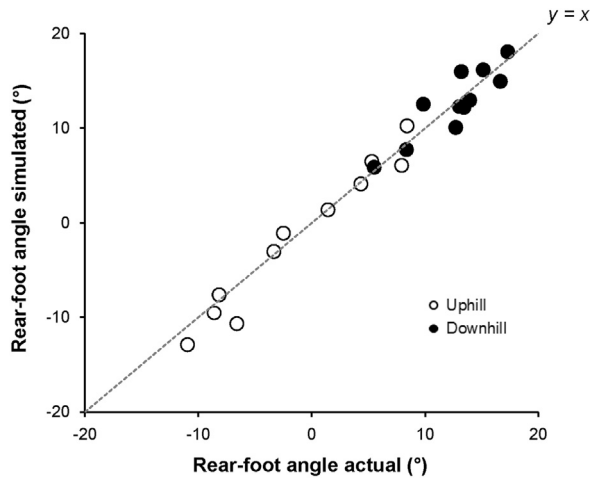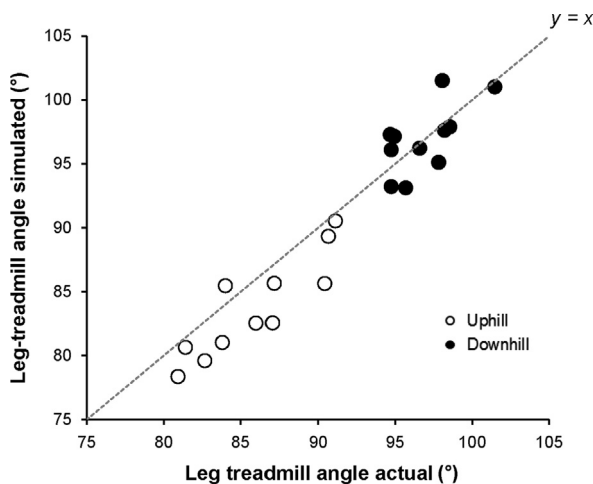


**Fig. 2.** Relationship between rear-foot angle determined when the foot struck the treadmill in actual and simulated conditions in downhill (filled black circles) and uphill (open circles) running. The dashed line represents the identity line ($y=x$).
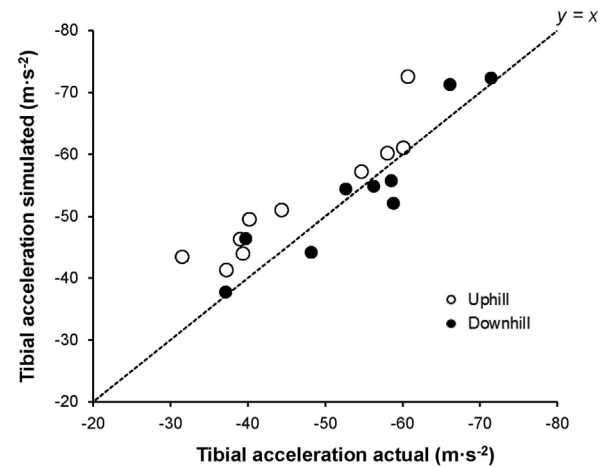


**Fig. 3.** Relationship between leg-treadmill angle determined when the foot struck the treadmill in actual and simulated conditions in downhill (filled black circles) and uphill (open circles) running. The dashed line represents the identity line ($y=x$).



**Fig. 4.** Relationship between tibial acceleration in actual and simulated conditions in downhill (filled black circles) and uphill (open circles) running. The dashed line represents the identity line ($y=x$).
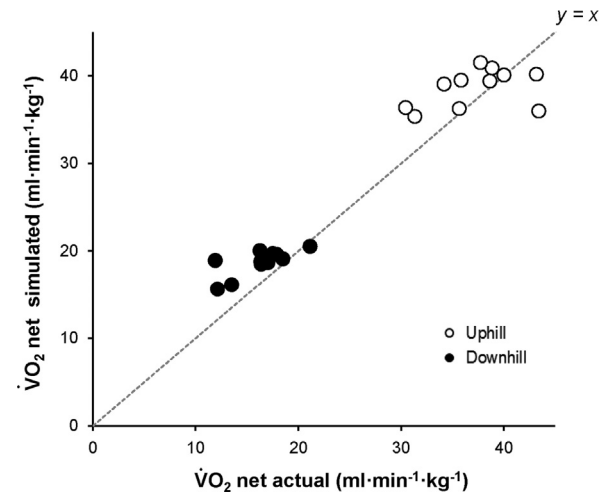


**Fig. 5.** Relationship between $\dot{V}O_{2\ net}$ in actual and simulated conditions in downhill (filled black circles) and uphill (open circles) running. The dashed line represents the identity line ($y=x$).

strike to a midfoot strike. The present study confirms this change in running pattern, with the rear-foot angle decreasing when subjects ran from downhill to uphill, for both the actual and simulated uphill/ downhill running methods ($P < 0.001$). The significant linear regression very close to the identity line for rear-foot angle between actual and simulated running strengthens the similarity of running pattern between the two methods.

The comparison of $\dot{V}O_{2\ net}$ showed a significant bias between actual and simulated method during downhill running, i.e. adding a horizontal aiding force led to a higher energy cost compared to actual downhill running, which was also shown by the nonhomogeneous dispersion for $\dot{V}O_{2\ net}$ (Fig. 5) and the fact that the linear regression was different from the identity line. This significant difference for $\dot{V}O_{2\ net}$ could come from the additional normal component of bodyweight in the SimulDown condition. Indeed, during actual uphill/downhill running, the normal force is lower than body weight while when adding an horizontal force to simulate uphill/downhill running, the normal force is equal to body weight and so the resulting force was higher than during actual uphill/ downhill running. The difference can also be explained by the increase in the system inertia (body mass+suspended mass, i.e. the total mass to be accelerated/decelerated at each step) during simulated conditions. Furthermore, a change in muscular activity
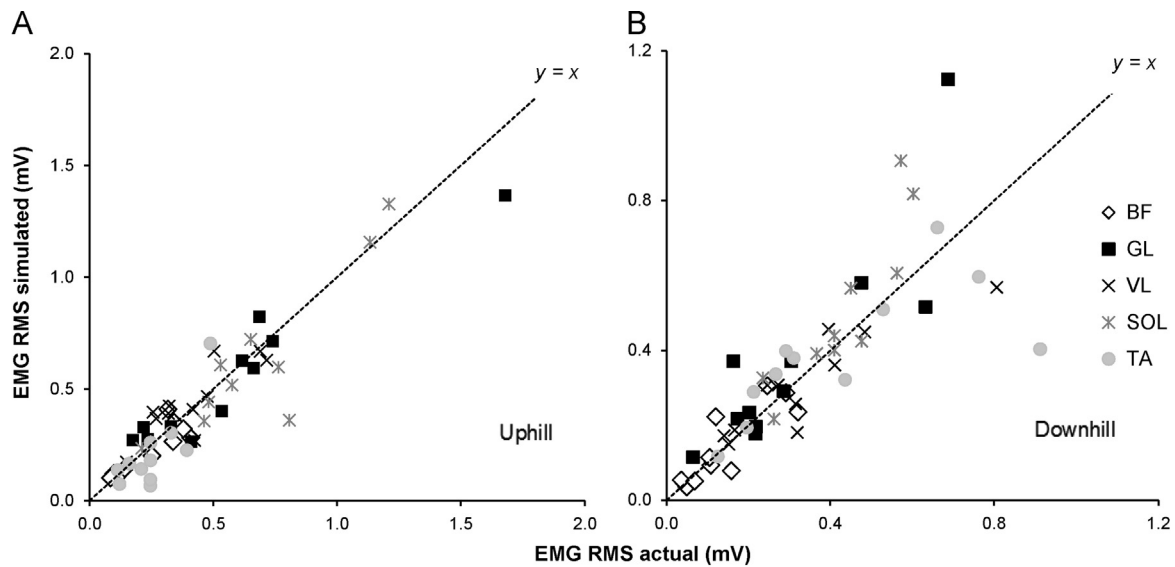
**Fig. 6.** Relationship of EMG for BF, GL, VL, SOL and TA muscles in actual and simulated uphill (panel A) and downhill (panel B) running. The dashed line represents the identity line ($y=x$).

could be related to these differences in $\dot{V}O_{2\,net}$. Inter-individual differences in muscular activity were the same between actual and simulated uphill/downhill running and the overall muscular activity tended to be consistent between the two modalities tested. However, the dispersion of EMG values around the identity line is quite large (i.e. the systematic bias is elevated) and substantial differences existed between simulated and actual running conditions, e.g. regarding the highest RMS values during downhill running, for GL during uphill running and for VL and TA during downhill running.

Note that the comparison between methods was performed at only one speed/slope condition (i.e. 2.5 m s$^{-1}$ and $\pm 8\%$). Thus the present study does not allows to conclude on whether or not the effect of a change in speed and/or slope on the mechanics and energetics of running is different in actual and simulated uphill and downhill running.

In conclusion, the simulation and actual methods showed good agreement for SF, impact shock and rear-foot and leg-treadmill angles. However, this method was found to be less appropriate for physiological variables. The interest of making it possible to study uphill/downhill running mechanics in laboratory conditions (when a tilting and force-measuring treadmill is not available) outweighs the few limitations discussed above, as these mainly concern the metabolic variables.

## Conflict of interest statement

None of the authors have financial or other conflicts of interest in regards to this research

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