Uphill Running at Iso-Efficiency Speed

Article *in* International Journal of Sports Medicine · May 2012

DOI: 10.1055/s-0032-1311588

7 authors, including:

Johnny Padulo
University of Milan
330 PUBLICATIONS 6,057 CITATIONS

Giuseppe Annino
University of Rome Tor Vergata
116 PUBLICATIONS 1,506 CITATIONS

Laura Smith
University of Salford
29 PUBLICATIONS 359 CITATIONS

Gian Mario Migliaccio
CONI Italian Olympic Commitee
78 PUBLICATIONS 978 CITATIONS

Uphill Running at ISO-Efficiency Speed

Authors J. Padulo[1,2], G. Annino[1], L. Smith[3], G. M. Migliaccio[2], R. Camino[2], J. Tihanyi[4], S. D'Ottavio[1]

Affiliations Affiliation addresses are listed at the end of the article

Key words
- running on slope
- kinematics
- energetic cost

Abstract

The purpose of this study was to investigate the effects of slopes (0%, 2% and 7%) on temporal gait kinematics during running at iso-efficiency speed (IES). 65 male marathon runners were selected for this study. A single digital camera (210 Hz) was used to record motion; Dartfish5.5Pro was used to perform 2-dimensional (2D) video analysis and heart rate was recorded during the test. The parameters considered in this study were: step length (SL), flight time (FT), step frequency (SF), contact time (CT) and heart rate (HR). The results showed SL, FT and SF decreased as a result of the increasing treadmill gradient; SL=[(0–2%=8.38%, $p<0.0001$), (0–7%=23.61%, $p<0.0001$)]; FT=[(0–2%=8.92%, $p<0.02$), (0–7%=23.40%, $p<0.0001$)]; SF=[(0–2%=1.18%), (0–7%=4.02%, $p<0.001$)]. The CT and HR however increased with the increasing gradient CT=[(0–2%=9.06% $p<0.0001$), (0–7%=25.64%, $p<0.0001$)]; HR=[(0–2%=1.65%), (0–7%=3.58%)]. These results show a different trend of the footstep's kinematic parameters when running on a slope at IES. Moreover, we can calculate the optimal run speed on a slope without increasing the metabolic demand.

Introduction

Running as a form of locomotion has been extensively researched [4,17,19]. In recent years uphill running has attracted interest for several reasons. Firstly, slight (2%) inclines and gradients are frequently evident during endurance races such as the marathon. During competition, slopes can affect kinematic parameters, such as decreased step length and increased step frequency [16], thus increasing the energy cost of running [9]. Consequently this may affect overall performance.

Secondly, sloping surfaces (~7%) are widely used by coaches in order to improve lower limb muscle strength, thus improving level running performance [9]. Unfortunately most of the studies conducted on uphill running have not shown an improvement in muscle strength as they have primarily only studied the acute effects [6,9,17,19]. Research has identified that running uphill alters kinematic parameters such as decreased step length and increased step frequency, in which the studied differences continue to progress when further increasing slopes, as studied in medium and high level runners [16]. Therefore, training will not only reflect the mechanical effects of the slope, however will presumably also reflect the specificity of the dominant part of training [5].

To this aim, some authors suggested that the training equation (TE) allowed runners to calculate the optimum step length based on the speed, which could be achieved via manipulating the step frequency [16]. Due to the fact that step length plays a crucial role within running TE may be a simple method to gain knowledge on a treadmill when speed is known [(speed ($m \cdot s^{-1}$) in slope)/(step length (m) in level*60 (min)]. Research suggested the TE solved the problem of reduced step length on slope and therefore is very useful for short distances [16].

Using the TE for periods longer than 1 min would cause high energy expenditure without allowing adequate training. This does, however, not take into account kinematic factors but only metabolic factors [13]. For this reason we thought that for the realization of adequate training it is necessary to focus on the kinematic parameters without altering the metabolic response. Uphill running at a constant speed would incur an increase in energy cost and expenditure [3,11,12]. To address this gap iso-efficiency (IES) is ideal where the energy cost of running on a slope is

accepted after revision
February 29, 2012

Bibliography
DOI http://dx.doi.org/10.1055/s-0032-1311588
Int J Sports Med 2012; 33: 1–5 © Georg Thieme Verlag KG Stuttgart · New York
ISSN 0172-4622

Correspondence
Dr. Johnny Padulo, PhD St
Faculty of Medicine and Surgery
University of Rome
00133 Via Columbia s.n.c.
Rome
Italy
Tel.: +39/0620/427 573
Fax: +39/0620/427 258
sportcinetic@yahoo.it

Table 1 Descriptive data of the subjects.

Variable	n = 65
age (years)	32.84 ± 10.69
height (cm)	175.09 ± 5.65
weight (kg)	65.03 ± 6.80
training experience (years)	7.55 ± 1.85
heart rate maximum (beats·min^{-1})	192 ± 4.65

Values are expressed as mean ± SD

matched to that of running on a zero gradient. For this purpose we assume that knowing the increase in energy cost of different slopes [13], by monitoring the heart rate (HR) we can calculate the optimal speed on any slope without altering the metabolic response with respect to level. Furthermore, if the formula is efficient kinematic parameters will have a different pattern than when running at constant speed on slopes and allows calculation of the optimal speed on different slopes.

Material and Methods

Participants

65 male marathon runners participated in the study (▶ **Table 1**). The participants were healthy with no muscular, neurological or tendinous injuries. The group was homogeneous with regard to their training status, in which none of the participants underwent any endurance strenuous activity and/or resistance training outside of their normal endurance training protocol. The experimental protocol was approved by the Ethical Committee of the University of Rome (Italy). After being informed of the procedures, methods, benefits and possible risks involved in the study, each participant reviewed and signed an informed consent to participate in the study in accordance with the ethical standards of the International Journal of Sports Medicine [7].

Experimental setting

Testing was carried out in a Human Performance Laboratory. All the participants were in good health at the time of the study. Research reported a high correlation (r = 0.93) between overground and treadmill running [18]. Within this study, in order to better standardize the slope and the velocity, tests were performed on a motorized treadmill (Run Race Technogym® Run 500, Gambettola, Italy). The treadmill was validated and certified at 0 %, 2 %, 7 % incline for 5 min for each slope condition at a constant velocity. Percent grade was expressed as being equal to the tangent [theta] × 100. The treadmill was calibrated before each test, according to the instructions of the manufacturer, and regularly checked after the tests.

All participants wore running shoes and performed a standardized 10 min warm-up to familiarize themselves with the treadmill, which consisted of running at 10 km·h^{-1} [18]. Following this, each participant performed 5 min of standardized active muscular stretching. Tests included 5 min running at IES on each of the 3 slope conditions. The experiment started with a randomized protocol (Latin Square) consisting of a level gradient (0 %) and 2 slopes (2 % and 7 %). Each session consisted of 5 min running at each slope condition, at one constant speed (IES), with 5 min rest between each condition. IES for each participant at a 0 % gradient (IES_0) was calculated as the average speed during the participant's best performance in a 10 000 m race (recorded within the 6 month period, prior to testing), minus 1 km·h^{-1}. Research suggested this corresponds to ~50 % maximal oxygen consumption ($VO_{2\,max}$) [10] and requires an energy cost (Cr) of 4.0 J/m/kg [4]. Furthermore, according to previous data [13] the increase of Cr as a result of a level gradient is:

$$\text{Cr on slope} = 0.20 \times \text{slope}\ (\%) + Cr_0$$

where Cr_0 is the Cr at level gradient (0 %).

As aforementioned oxygen consumption (VO_2) is proportional to the energetic cost and velocity, for each gradient the velocity was calculated (IES) at which the VO_2 was equal to level running using the following equation:

$$VO_2 = [Cr_0/(21\ (\mathit{J/min}) \times (IES_0/0.06\ (\mathit{m/min}))]$$

$$\text{IES}\ (\text{km·h}^{-1}) = [(VO_2\ \ (\mathit{kJ/min/kg}) \times 21\ \ (\mathit{J/l}) \times 0.06\ \ (\mathit{m/min}))/(0.20\ (\mathit{Cr}) \times \text{slope}\ (\%) + Cr_0)]$$

Measurements

The HR was recorded throughout the experiment and an average computed during the full 5 min for each slope condition (Sport Tester PE 3000; Polar Electro, Kempele, Finland). 2-dimensional (2D) video data were collected of the participants' running on the treadmill using a single high speed digital camera (Casio Exilim FH20) [1] sampled at 210 Hz. 2D data were collected in accordance with a previous study protocol [16]. The camera was positioned on a 1.5 m high tripod, 6 m from the participant and was located perpendicular to the plane of motion at the participant's sagittal plane [1]. The film sequences were analyzed offline using Dartfish 5.5Pro motion analysis software (Dartfish, Fribourg, CH). The following kinematic variables were studied: (i) contact time (ms), (ii) flight time (ms), (iii) step length (m), (iv) step frequency (Hz); for each velocity 400 steps were sampled [14]. Kinematic markers were taped on both feet of each participant. Since the velocity of the treadmill was known, both step length (SL) and step frequency (SF) could be calculated. The contact time (CT) and flight time (FT) were calculated by counting the frames in contact and flight on the 2D data, then dividing by the sampling rate, 210 (1 frame = 210 Hz ≈ 0.0048 s). The CT and FT were calculated for both the left and right foot. The CT was defined and calculated as the time between initial contact with the ground and the last frame of contact before toe-off. The FT was defined and calculated as the time between toe-off and subsequent initial contact of the contralateral foot. Initial contact and toe-off were visually detected.

In accordance with previous studies [15, 16] SF was calculated as SF = [1 000/(CT + FT)], alternatively SL was calculated with the following equation SL = [speed km·h^{-1}/3.6/SF].

The test-retest reliability of this testing procedure was demonstrated through an intraclass correlation coefficient (ICC) and standard error of measurements (SEM) for the following variables: SL (ICC: 0.96–0.98, SEM: 0.04–0.08 m), SF (ICC: 0.96–0.98, SEM: 0.10–0.12 Hz), CT (ICC: 0.97–0.98, SEM: 11–15 ms), and FT (ICC: 0.96–0.98, SEM: 12–15 ms).

Statistical analysis

The results are expressed as mean ± standard deviation (*SD*). Coefficient of multiple determination (R^2) was used to examine correlations between treadmill gradient vs. (i) SL, (ii) SF, (iii) CT, (iv) FT and (v) HR. Subsequently, in order to determine any significant difference between (i) SL, (ii) SF, (iii) CT, (iv) FT, (v) HR on

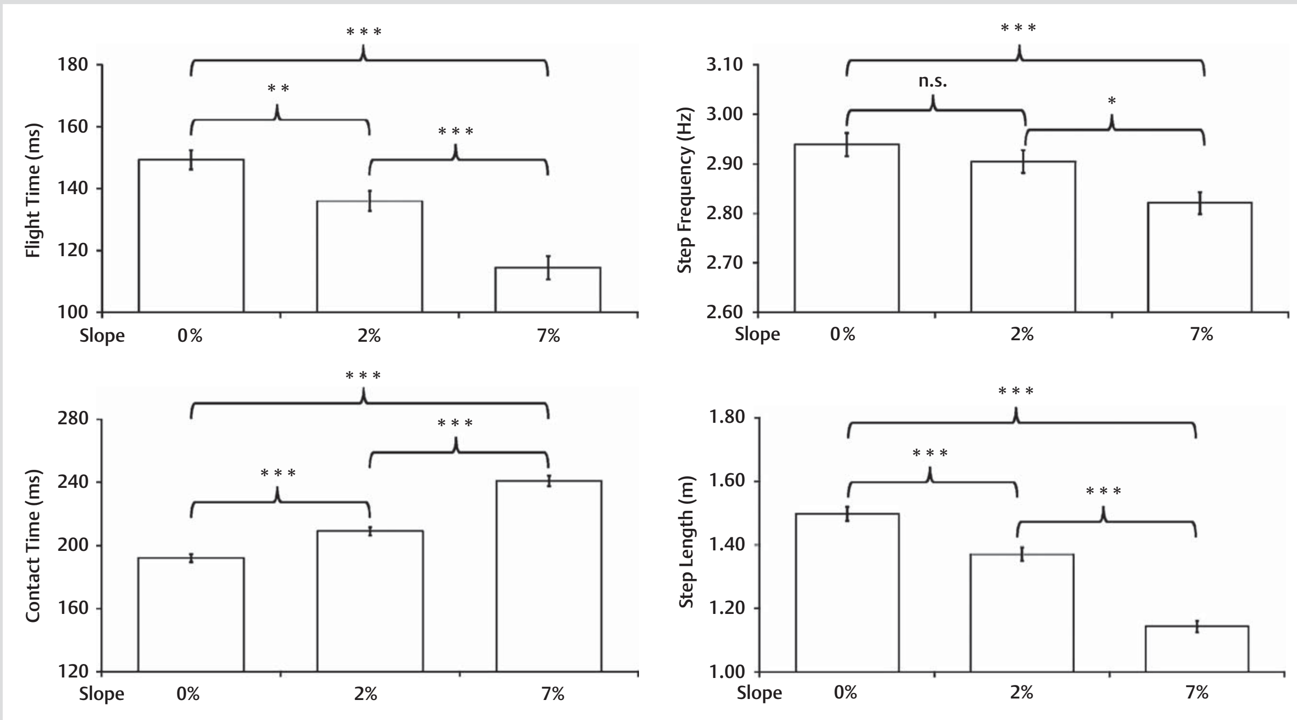

Fig. 1 Flight time, step frequency, contact time and step length on different slopes. Values represent means and error bar for all subjects. Statistical significance is denoted as '*' p<0.05, '**', p<0.02, '***', p<0.001.

Table 2 Effects of uphill gradient on running kinematics.

Condition	0%	2%	7%	p-value
velocity ($km \cdot h^{-1}$)	15.83 ± 1.80	14.33 ± 1.64	11.59 ± 1.28	0.0001
step length (m)	1.50 ± 0.16	1.37 ± 0.15	1.14 ± 0.13	0.0001
step frequency (Hz)	2.94 ± 0.17	2.90 ± 0.17	2.82 ± 0.16	0.001
flight time (ms)	149.33 ± 22.71	136.01 ± 23.94	114.38 ± 27.29	0.0001
contact time (ms)	192.03 ± 18.60	209.43 ± 19.97	241.27 ± 23.71	0.0001
heart rate ($beats \cdot min^{-1}$)	156 ± 13	159 ± 14	162 ± 14	0.114

Means and standard deviation (n = 65). Significant differences between conditions are presented

different slopes a one-way analysis of variance (ANOVA) was applied. Assumption of normality was verified using the Shapiro-Wilk W test. When a significant *F*-value was found least-significant difference (Bonferroni) was chosen as the post-hoc procedure. Statistical analyses were performed using the software IBM® SPSS® Statistic version 15.0, IBM Corporation, Somers, NY, USA). The level set for significance was $p \leq 0.05$.

Results

The SF decreased with increased gradient R^2 0.076 and F = 14.392: there was a decrease of 1.18% with p = 0.842 between 0% and 2%, a decrease of 2.88% with p < 0.03 between 2% and 7% and an overall decrease between 0% and 7% of 4.02% with p < 0.001 (**Fig. 1**). The difference between mean SF was significant when comparing all conditions (p < 0.001) (**Table 2**). Similarly SL significantly decreased with the increased gradient (R^2 0.497 and F = 162.160 with p < 0.0001). A decrease in SL of 8.38% was evident between 0% and 2% with p < 0.0001 and a decrease of 16.62% with p < 0.0001 between 2% and 7%, the overall decrease between 0% and 7% was 23.61% with p < 0.0001. Reflective of the decreases in SF, FT similarly decreased gradually with increased gradient (R^2 0.249 and F = 54.974). The FT decreased 8.92% with p < 0.02 between 0% and 2% gradient, 15.90% with p < 0.0001 between 2% and 7%, with an overall decrease of 23.40% with p < 0.0001 between 0% and 7%. The conditions were significantly different (p < 0.0001). The SL, SF and FT decreased with increased gradient, however CT elicited an increase of R^2 0.486 and F = 153.970 (**Fig. 1**). The CT increased 9.06% with p < 0.0001 between 0% and 2%, 15.20% with p < 0.0001 between 2% and 7%, with an overall increase between 0% and 7% of 25.64% with p < 0.0001. Similarly the difference between conditions was significant (p < 0.0001). The HR showed a slight increase as a result of the increasing treadmill gradient R^2 0.20 and F = 4.259, between 0% and 2% the difference was < 2% with p = 0.992 (**Table 2**), 1.89% with p = 0.778 between 2% and 7% while between 0 and 7% the difference was 3.58% with p = 0.112.

Discussion

In this study we investigated the effects of 3 slopes, 0%, 2% and 7%, on temporal gait kinematics during running at IES. Such empirical research does not currently exist. The primary reason

and rationale for carrying out this study was that the kinematics of running have been studied at different speeds and gradients, however, they have always been researched at a constant speed [16]. In the present study running at 0% gradient elicited a speed of 15.83 $km \cdot h^{-1}$, however at a 2% gradient the speed decreased by 9.48% (14.33 $km \cdot h^{-1}$). With relation to 0%, running at a 7% gradient elicited a decrease in speed of 26.78% (11.59 $km \cdot h^{-1}$).
The decrease in speed may be partly due to the increased gradient and likely produced decreases in both step length and step frequency. As expected step length was greater at 0% gradient compared to the graded running and the corresponding alterations in speed. The present study found step length decreased gradually when the treadmill was elevated from 0% to 2% and 7%. Step length decreased by 8.38% (0–2% gradient) and by 23.61% (0–7% gradient). The present findings support previous research within our research group, which suggests step length at a constant speed (15.8 $km \cdot h^{-1}$) decreases significantly with an increase in running gradient [16]. A previous study found step frequency increased with increased gradient [16], however the current study shows a completely different trend, in which step frequency decreased with the increased gradients (1.18% at 2% gradient and 4.02% at 7% gradient both in regard to 0%). A decrease in step frequency may have occurred due to the decreases in speed and increases in contact time. This notion is supported within the current study, which found contact time increased 9.06% at a 2% gradient and 25.64% at a 7% gradient, both with respect to 0%. These results are contrary to previous research where contact time decreased whilst running at a constant speed with the increased gradients, 1.20% (0–2% gradient) whilst it increased 4.79% at 7% slope in regard to level gradient [16]. This increase in contact time may have occurred as a result of the slower constant speed, as speed and contact time are inversely related, similarly as a result of reduced step frequency.
Considering that the metabolic parameters increased when running uphill at a constant speed, and the heart rate similarly increased when running uphill, this allowed us to determine the effect of the IES equation. Furthermore, research suggests heart rate elicits a response to exercise similar to that of oxygen consumption [8]. It can therefore be used in a similar fashion to measure intensity when work load is maintained reasonably constant for several minutes or more [8]. Previous research has shown that VO_2 is closely correlated with performance in competitive marathon runners [4]. Furthermore, as demonstrated by several authors VO_2 increased with increases in speed [3]. Kinetic energy increases progressively with speed and is representative of a pendulum mechanism [2]. Therefore, the strategy to reduce speed decreases energy cost, however with increases of slope, the energy cost increases [3,13]. This mechanism is important because it allows variation of speed and incline when monitoring the heart rate. During the 3 slope conditions the variable which showed the least variation was heart rate: 0% (81.46% of maximum heart rate (MHR)) and 2% gradient (82.81% of MHR) and overall 7% (84.40% MHR).
The data confirms the validity of the equation for calculating speed at IES for marathon runners at different gradients. However at the higher gradient, 7%, the procedure used in this study overestimated speed. This overestimation could be due to differences in the biomechanics of individual technique; as observed in a previous study [13] and running observed within the current study. Different strategies are employed, based on the different biomechanical demands of each given task. We have demonstrated alterations in kinematic temporal patterns that support the use of 3 different treadmill inclinations. The use of different behaviour strategies is a functional characteristic in the neural control of human movement. These control strategies are likely to be modifications of the existing level of marathon runners' neuromuscular patterns, which could be mediated by changes in peripheral feedback. Such changes in feedback could also cause a switch rather than substantial modifications to the running control strategies level, although it is difficult to make this distinction in humans. Further studies are needed in order to better understand changes in neuronal patterns of marathon runners.
In conclusion, the data in the current study provides a basis for running technique training during uphill locomotion without higher metabolic demand. Therefore, due to its simplicity in use and application and the low cost it would seem suitable for use in both the laboratory and the field. Future studies should address the ground reaction forces generated during contact time at different slopes in order to identify other mechanical aspects that may positively influence the economy of running gait.

Acknowledgements

The authors are grateful to the "Gruppo Sportivo Fiamme Gialle" and in particular to Coach Andrea Ceccarelli, for supporting this research.

Affiliations
[1] Faculty of Medicine and Surgery, University of Rome "Tor Vergata", Rome, Italy
[2] CONI – Italian Regional Olympic Committee, Sardinia, Cagliari, Italy
[3] School of Health, Sport and Rehabilitation Sciences, University of Salford, United Kingdom
[4] Department of Biomechanics, Faculty of Physical Education and Sport Sciences, Semmelweis University, Budapest, Hungary

References

1 *Belli A, Rey S, Bonnefoy R, Lacour JR.* A simple device for kinematic measurements of human movement. Ergonomics 1992; 35: 177–186
2 *Cavagna GA, Thys H, Zamboni A.* The sources of external work in level walking and running. J Physiol 1976; 262: 639–657
3 *Di Prampero PE.* The energy cost of human locomotion on land and in water. Int J Sports Med 1986; 7: 55–72
4 *Di Prampero PE, Capelli C, Pagliaro P, Antonutto G, Girardis M, Zamparo P, Soule RG.* Energetics of best performances in middle-distance running. J Appl Physiol 1993; 74: 2318–2324
5 *Duchateau J, Hainaut K.* Isometric or dynamic training: differential effects on mechanical properties of a human muscle. J Appl Physiol 1984; 56: 296–301
6 *Gottschall JS, Kram R.* Ground reaction forces during downhill and uphill running. J Biomech 2005; 38: 445–452
7 *Harriss DJ, Atkinson G.* Update – ethical standards in sport and exercise science research. Int J Sports Med 2011; 32: 819–821
8 *Hopkins WG.* Quantification of training in competitive sports – Methods and applications. Sports Med 1991; 12: 161–183
9 *Iversen JR, McMahon TA.* Running on an incline. J Biomech Eng 1992; 114: 435–441
10 *Menier DR, Pugh LG.* The relation of oxygen intake and velocity of walking and running in competition walkers. J Physiol 1968; 197: 717–721
11 *Minetti AE, Ardigo LP, Saibene F.* Mechanical determinants of the minimum energy cost of gradient running in humans. J Exp Biol 1994; 195: 211–225
12 *Minetti AE, Ardigo LP, Saibene F.* The transition between walking and running in humans: metabolic and mechanical aspects at different gradients. Acta Physiol Scand 1994; 150: 315–323
13 *Minetti AE, Moia C, Roi GS, Susta D, Ferretti G.* Energy cost of walking and running at extreme uphill and downhill slopes. J Appl Physiol 2002; 93: 1039–1046

14 *Owings TM*, *Grabiner MD*. Measuring step kinematic variability on an instrumented treadmill: how many steps are enough? J Biomech 2003; 36: 1215–1218
15 *Padulo J*, *D'Ottavio S*, *Pizzolato F*, *Smith L*, *Annino G*. Kinematic analysis of soccer players in shuttle running. Int J Sports Med 2012 [Epub ahead of print]
16 *Padulo J*, *Annino G*, *Migliaccio GM*, *D'Ottavio S*, *Tihanyi J*. Kinematics of running at different slopes and speeds. J Strength Cond Res 2011 [Epub ahead of print]
17 *Paradisis GP*, *Bissas A*, *Cooke CB*. Combined uphill and downhill sprint running training is more efficacious than horizontal. Int J Sports Physiol Perform 2009; 4: 229–243
18 *Riley PO*, *Dicharry J*, *Franz J*, *Della CU*, *Wilder RP*, *Kerrigan DC*. A kinematics and kinetic comparison of overground and treadmill running. Med Sci Sports Exerc 2008; 40: 1093–1100
19 *Staab JS*, *Agnew JW*, *Siconolfi SF*. Metabolic and performance responses to uphill and downhill running in distance runners. Med Sci Sports Exerc 1992; 24: 124–127