Effects of gradient and speed on uphill running gait variability
Padulo, Johnny; Ayalon, Moshe; Barbieri, Fabio A.; Di Capua, Roberto; Doria, Christian; Ardigò, Luca P.; Dello Iacono, Antonio
Published in: Sports Health: A Multidisciplinary Approach
DOI: 10.1177/19417381211067721
E-pub ahead of print: 27/03/2022

Document Version
Peer reviewed version

Link to publication on the UWS Academic Portal

Citation for published version (APA):

General rights
Copyright and moral rights for the publications made accessible in the UWS Academic Portal are retained by the authors and/or other copyright owners and it is a condition of accessing publications that users recognise and abide by the legal requirements associated with these rights.

Take down policy
If you believe that this document breaches copyright please contact pure@uws.ac.uk providing details, and we will remove access to the work immediately and investigate your claim.

Reprinted by permission of SAGE Publications.
Effects of gradient and speed on uphill running gait variability

Johnny Padulo\textsuperscript{a}, Moshe Ayalon\textsuperscript{b}, Fabio A. Barbieri\textsuperscript{c}, Roberto Di Capua\textsuperscript{d,e}, Christian Doria\textsuperscript{a}, Luca P. Ardigò\textsuperscript{f,†}, Antonio Dello Iacono\textsuperscript{g,†}

\textsuperscript{a}Department of Biomedical Sciences for Health, Università degli Studi di Milano, Milan, Italy
\textsuperscript{b}The Academic College at Wingate, Netanya, Israel
\textsuperscript{c}Human Movement Research Laboratory (MOVI-LAB), Department of Physical Education, São Paulo State University (UNESP), Bauru, Brazil
\textsuperscript{d}Department of Physics “E. Pancini”, University of Naples “Federico II”, Naples, Italy
\textsuperscript{e}CNR-SPIN Institute, Naples, Italy
\textsuperscript{f}School of Exercise and Sport Science, Department of Neurosciences, Biomedicine and Movement Sciences, University of Verona, Verona, Italy
\textsuperscript{g}School of Health and Life Sciences, University of the West of Scotland, Glasgow, UK

† These authors share last authorship.

Corresponding author: Luca Paolo Ardigò
School of Exercise and Sport Science, Department of Neurosciences, Biomedicine and Movement Sciences, University of Verona, Via Felice Casorati, 43, 37131 Verona, Italy
Telephone: +393477266814
Fax: +390458425131
Email: luca.ardigo@univr.it
Abstract

Background. The aim of this study was to investigate the effects of gradient and speed on running variability (RV) and local dynamic stability (LDS) during uphill running. Hypotheses. 1) Both gradient and speed increase metabolic effort, in terms of heart rate (HR) and perceived exertion (CR10), in line with the contemporary literature and 2) Gradient increases RV and impairs LDS.

Study design. “Cross-over” observational design. Level of evidence. Level 3. Methods. Twenty-five runners completed 10-min running trials in 3 different conditions and in a randomized order: gradient at 0% (0CON), 2% (2CON) and 2% at iso-efficiency speed (2IES). 0CON and 2CON speeds were calculated as the “best 10-km race performance” minus 1 km.h⁻¹, whereas 2IES speed was adjusted to induce the same metabolic expenditure as 0CON. Heart rate and perceived exertion as well as running kinematic variables were collected across all trials and conditions. Running variability was calculated as the standard deviation of the average stride-to-stride intervals over 100 strides, while LDS was expressed by the Lyapunov exponent (LyE) determined on running cycle time over different running conditions. Results. Increases in HR and CR10 were observed between 0CON and 2CON (P<0.001) and between 2IES to 2CON (P>0.01). Higher RV was found in 2CON compared with 0CON and 2IES (both P<0.001). Finally, the largest LyE was observed in 2IES compared with 0CON and 2CON (P=0.02 and P=0.01, respectively). Conclusion. Whereas RV seems to be dependent more on metabolic effort, LDS is affected by gradient to a greater extent.

Clinical relevance. Running variability could be used to monitor external training load in marathon runners.

Keywords: stride-to-stride; gait; metabolic demand; perceived exertion; endurance runners.
Introduction

Biomechanists have extensively studied complex movements such as running by investigating the underpinning mechanics regulated by the central nervous system (CNS) and motor control mechanisms ruling the coordination across the body segments during motion. Maintaining effective running is essential to reduce metabolic cost (i.e., metabolic expenditure per unit distance travelled) and improve performance. Appropriate local dynamic stability (LDS) reduces running variability (RV) through appropriate adaptations of the motor system to the running task. Moreover, changes in RV occur both as acute responses and chronic adaptations during motor learning tasks under environmental constraints. Indeed, monitoring and quantification of RV and associated LDS during running can be used to assess modifications in movement mechanics among individuals. Therefore, RV and LDS have been suggested as proxies to investigate movement control and regulation and are commonly used in research and applied field measurement.

Running variability is usually defined as a measure of inconsistency of muscular activities or body segmental movements during repeated tasks. Running variability of temporal variables is associated with mechanisms that regulate movement rhythm such as the central pattern generator, whereas RV of spatial variables is more related to balance control mechanisms. These measures can be used to understand the ongoing motor control processes during the task performed. Hence, RV might serve as a relevant and sensitive measure to quantify adjustments of running control.

Running movement is determined by the constant interaction between the runner, the environment and the specific running task. First, the movement is planned by the CNS based upon sensory information characterizing the environment wherein the task is performed. By interpreting this information, the runner adapts motor strategies either voluntarily or automatically to exploit effective running performance. Specifically, basal ganglia are responsible for automatic behaviour, which involves circuitry of motor cortex, cerebellum, striatum, globus pallidus, thalamus and supplementary motor area that are responsible for feedback and are related to internal control of
repeated movements\textsuperscript{13} such as running. Moreover, basal ganglia, \textit{cerebellum} and somatosensory\textit{cortex} are connected to each other\textsuperscript{5} showing their interdependence in managing movement.

Uphill running increases joint work and impairs joint stabilization. Increased demands for mechanical work during uphill running is mirrored by an increase in power output at lower limbs’ joints, particularly at the hip, with consequent greater muscular activity and, in turn, a linear increase in metabolic cost of running.\textsuperscript{19} Changes in biomechanical characteristics of running, such as higher step frequency and shorter swing phase duration are observed over increased gradients\textsuperscript{26}. Inter-segmental organization is necessary to cope with increased gradient during uphill running, which could affect running control especially via changes of RV and LDS. In a previous study, it was observed that different locomotion patterns may result primarily by peripheral factors (i.e., muscle performance), but also as result of modulation of variables of basic network and/or by reconfiguration of neural network.\textsuperscript{11} Therefore, it is reasonable to hypothesize that the greater demands of gradient running on the whole-body position could affect control efficiency of running rhythmicity, which in turn would lead to increase of variability. To test this assumption, in the current study we investigated the effects of speed and gradient on metabolic effort, RV and LDS during uphill running. Our hypotheses were that 1) both gradient and speed increase metabolic expenditure in line with the contemporary literature, 2) gradient increases RV during uphill running and, consequently impairs LDS. Any environmental interference in running, such as gradient (another environmental interference might be air resistance), might increase RV during progression, decreasing LDS and impairing integration in basal ganglia circuitry.

\textbf{Materials and Methods}

\textit{Participants}

Twenty-five runners (3 females and 22 males; age: 38±11 years; body mass: 63±8 kg; height: 1.73±0.07 m) voluntarily participated in this study. Inclusion \textit{criteria} were: 1) Training volume >60 km \textit{per} week; 2) At least 2 running sessions on treadmill \textit{per} week during the last 2
years; 3) More than 3 training sessions per week and a 10-km race best performance with an average speed >14 km·h⁻¹. In addition, participants had to be healthy with no neurological or musculo-skeletal injuries. The experimental protocol was approved by the local ethics committee.

After being informed of procedures, methods, benefits and possible risks related to the study, each participant reviewed and signed an informed consent form to participate in the study.

Experimental setting

Testing was carried out at Human Performance Laboratory (Academic College at Wingate, Netanya, Israel, average temperature 23.5° C) between 3:00 p.m. and 7:00 p.m. To set the experimental speed and gradient, tests were performed on a motorized treadmill (Run Race 500, Technogym, Gambettola, Italy). The treadmill was calibrated before each test according to the instructions of the manufacturer and was regularly checked after tests.24 All participants wore running shoes and performed a standardized 10-min warm-up, which consisted of running at 8 km·h⁻¹.

After the warm-up, each participant performed 5 min of standardized dynamic stretching exercises. Experimental trials included 10 min of running at 3 different speed and gradient conditions: fixed speed at 0% gradient (0CON), same fixed speed at 2% gradient (2CON) and iso-efficiency speed at 2% gradient (2IES). A passive rest of 5 min was given between consecutive running conditions. The experimental investigation followed a randomized protocol (Latin Square) consisting of 0% (0CON) and two different-speed 2% gradients (2CON and 2IES). The speeds during the 0CON and 2CON conditions were 15.4±2.1 km·h⁻¹, and were calculated23 as the average speed of the individual athlete’s best performance in a 10-km race minus 1 km·h⁻¹. The speeds during the 2IES condition corresponded to 13.4±1.70 km·h⁻¹ and were calculated according to the equation of Padulo et al.23 as the reduced speed at a 2% gradient demanding the same metabolic energy as the one chosen for the condition with gradient at 0%. While other authors suggest a different approach to calculate iso-metabolic energy expenditure speed1, the method of Padulo et al.
was preferred for its easier feasibility. After one week, the same experimental investigation was repeated with a different order across conditions to assess the reliability of measures.

**Measurement**

During each running condition, heart rate (HR) – a proxy for metabolic effort – was recorded continuously (Polar RS800, Polar Electro, Kempele, Finland). Participants also reported their perceived exertion (CR10) – as an additional proxy for metabolic effort – immediately after the end of each running condition. An OptoGait device (sampling rate 1000 Hz, Microgate Italy, Bolzano, Italy) was placed on the treadmill trails and used to collect the following kinematic variables: contact time (CT [s]), flight time (FT [s]), stride length (SL [m]) and stride frequency (SF [s⁻¹]). Average stride duration and standard deviation (SD) of the average stride-to-stride intervals over 100 cycles were used as time domain measures to assess RV (SDA100, i.e., SD/average over 100 cycles).²⁵

The Lyapunov exponent (LyE) was calculated to provide indications about LDS of the step frequency of each runner. Local dynamic stability can be quantified by the determination of LyE and is interpreted as the ability to compensate small perturbations to maintain functional locomotion.¹⁵ A higher exponent indicates a reduced ability to maintain LDS. Such analysis indicates whether a dataset resembles a chaotic system rather than a stochastic one. The evolution of a chaotic system is, in general, described by a set of nonlinear differential equations. So, it is a deterministic system like a periodic or a stable system. However, differently from the latter, the evolution of a chaotic system strongly depends on the initial conditions. This difference can be illustrated considering the multi-dimensional space (phase-space) built with the coordinates that identify the state of the system. The evolution of the system is described by the change vs. time of such coordinates. The collection of the points identified by these coordinates represents a curve in the phase space, called orbit. Any initial state is represented by a different starting point in the phase-space, from which an orbit starts. For a stable system, taking two initial states "close enough",
the corresponding orbits will stay close (i.e., the evolution is not "so different" if the system starts from "similar" conditions). Conversely, for a chaotic system, even for starting conditions arbitrarily "close", the corresponding orbits diverge, typically with a multi-exponential law vs. time. The maximum divergence rate dominates the time evolution and constitutes the largest LyE, which is positive for chaotic systems (conversely, for stable systems it is negative, corresponding to a convergence of orbits rather than a divergence). For a stochastic system the situation is still different. For such a system it is not possible to write any equation to describe its evolution, since the stochastic behavior is characterized by random and unpredictable variations. The evaluation of largest LyE from an experimental dataset measured on a complex system is a non-trivial problem and cannot be performed starting from a set of equations, which are in general unknown. Largest LyE was calculated using a custom software following the approach described in Kantz et al.\(^{18}\) for the computation of LyE from finite experimental dataset and the general theory of the analysis of nonlinear time series. Briefly, from the experimental time series delay-embedding vectors were defined\(^{18}\) for the reconstruction of the state vectors in the phase space. The autocorrelation properties of the data-series were used for a first choice of the most suitable delay time and then the largest LyE was evaluated from the initial slope of the natural logarithm of the divergence vs time\(^{15}\) for different choices of the embedding dimensions.

**Statistical analysis**

Results are expressed as mean±SD and standard error. Coefficient of variation (CV [\(\%\)=SD/mean) and 95% confidence interval were calculated after verifying the assumption of normality of the dependent variables distributions using the Shapiro-Wilk test. To assess differences for HR, CR10, CT, FT, SL, SF, SDA100 and LyE across the 3 different running conditions (0CON–2IES–2CON), repeated-measures analyses of variance (ANOVA) were used. When a significant F-value was found, *post-hoc* analysis (Fisher's Least Significant Difference) between conditions was performed. Intra-class correlation coefficient was used to assess test-retest reliability.
of measures, with the significance level set at $P \leq 0.05$. All analyses were conducted using Statistical Package for Social Science software (version 15.0, IBM SPSS Statistics, Chicago, IL, USA).

**Results**

Spatial-temporal variables outputs across the three different running conditions are shown in Table S1. The intraclass correlation coefficients regarding the spatial-temporal variables were 0.97, 0.94, 0.96 and 0.98 for CT, FT, SL and SF, respectively. Repeated-measures ANOVA showed differences over running conditions for HR ($F_{1,23}=8.889$ and $P<0.001$), CR10 ($F_{1,23}=20.007$ and $P<0.001$), CT ($F_{1,23}=3.743$ and $P=0.029$), SF ($F_{1,23}=3.139$ and $P<0.05$) and SL ($F_{1,23}=4.175$ and $P=0.012$), SDA100 ($F_{1,23}=25.161$ and $P<0.0001$) and LyE ($F_{1,23}=8.164$ and $P<0.001$), whereas it were not found any differences regarding FT ($F_{1,23}=2.613$ and $P=0.081$). Following *post-hoc* analysis, significant differences for HR and CR10 (Figure 1) between 0CON and 2CON ($P<0.001$) were observed, while no significant differences were found between 0CON and 2IES ($P=0.987$ and $P=0.798$ regarding HR and CR10, respectively). Similarly, SDA100 resulted significantly higher in 2CON ($P<0.001$) compared with both 0CON and 2IES respectively (Figure 1). Regarding 100-stride SF and its CV, it was found an increase in over 200th–400th cycles (4.36±0.09–5.29±0.09%) but not over 400th–700th cycles (5.19±0.10%) irrespective of the running condition (Figure 2).

Regarding LDS, the 2IES condition resulted in a significantly higher LyE value compared with the two other conditions ($P<0.05$) as shown in Figure 3. Figure 3A reports an example of an assessed dynamical behaviour exhibiting a clear transition between two *regimes* (see legend for details). Figure 3B reports the LyE values calculated as the average of all runners pooled together. It must be acknowledged that some occurrences of stochastic behaviours were observed, as well, but were not considered for calculation of averages. While no differences were observed for LyE between the 0CON and 2CON conditions ($P=0.76$), the 2IES condition resulted in higher LyE as confirmed by the *post-hoc* analysis ($P=0.02$ and $P=0.01$, respectively).
Discussion

The aim of this study was to investigate the effects of gradient and speed on metabolic expenditure, RV and LDS during uphill running. Two main findings emerged: (i) both gradient and speed led to increased metabolic effort and (ii) gradient also influenced RV during uphill running.

Higher metabolic effort is expected due to uphill running.\textsuperscript{19,23} The findings of this study confirmed such evidence as observed from greater HR and CR10 responses in 2CON. Alongside the increased metabolic demands, postural adaptations are also required due the running gradient condition with the consequent increase in the whole system noise (i.e., RV). In mechanical terms, uphill running requires higher mechanical work per stride to increase the body’s potential energy necessary to cope with the upward locomotor pattern.\textsuperscript{20} Accordingly, muscles develop greater positive work to raise the body’s centre of mass height during the stance phase as well as to provide sufficient kinetic energy to reach the highest point during aerial phase.\textsuperscript{19} Finally, the increased mechanical demands lead to greater metabolic load and subjective perception of physical exertion.

On the other hand, 2IES was accompanied by changes in spatial-temporal variables without differences in metabolic effort compared with 0CON and 2CON. This finding is not surprising and can be explained by two main observations. Firstly, changes in spatial-temporal variables, CT in particular, are expected due to the known direct relationship between running speed and CT. As speed and CT are inversely related\textsuperscript{19,23} running at lower speed leads to longer CT as confirmed by the greater CT observed in the 2IES compared to 0CON in current study. Moreover, differences in SF were observed between the two gradient conditions (i.e., 2CON and 2IES) in comparison with 0CON, irrespective of the running speed.\textsuperscript{14} Secondly, differences observed between 2IES and 2CON are the likely result of motor control adaptations primed by the CNS to cope with increased environmental challenges caused by the interaction between gradient and speed. In fact, the interaction of the two variables combined in the 2CON condition may have caused greater locomotor perturbations, thus resulting in an adapted running pattern characterized by shorter CT, shorter SL and higher SDA100 as an overall strategy to improve dynamic balance.\textsuperscript{2} The fact that
spatial-temporal kinematic adjustments induced only by the increased speed (i.e., from 2IES to 2CON) caused greater decreases in LDS compared with the gradient-associated ones (i.e., from 0CON to 2CON) could suggest that the CNS is not able to operate gait adaptations above a certain speed without affecting LDS. On the other hand, when the metabolic demands were kept constant (i.e., from 0CON to 2IES), the CNS apparently handled gradient changes without a concurrent increase in RV (i.e., SDA100; Figure 1) but at the expense of a decrease of LDS (i.e., an increase of LyE; Figure 3).

Increased RV can be interpreted either as an adaptation to keep high performance or as a strategy to contain the system noise due to higher overload of uphill running. Regarding LyE (and LDS), the 2IES condition was significantly greater than the 0CON and 2CON conditions (see results section and Figure 3). This observation suggests a key mediating role of speed rather than gradient on the LDS strategy. Such a finding is not surprising as a previous study showed that changing the speed above or below the preferred value during gait would cause the system to shift from a stable attractor condition to a more unstable behaviour. In particular, during running, speed values lower than the self-selected one seem to induce the greatest increase of the LyE value. The LyE value estimated from the stride frequency is a measure of the capability to perform a reorganization towards a stable pattern of locomotion. The findings of the current study demonstrate that this capability is hindered in the 2IES, which was the experimental condition with the greater constraint in speed. It can be hypothesized that such reduced capability stems from the altered interplay between sensory inputs and motor outputs driving muscle activation whereby an impaired running gait ensues, potentially contributing to musculoskeletal injury and pain during running.

Functional adaptations are necessary to improve running performance. The findings of the current study suggest that athletes adjust different motor control strategies for gradient and speed changes to keep movement efficiency. Increased RV (i.e., alternating high and low impulses) may be necessary to reduce impacts when runners are subjected to greater forces due to the increasing
Bartlett et al.\textsuperscript{3} suggested that increased RV facilitates a reduction of cumulative load on the musculoskeletal structures. This strategy can reduce overuse and, in turn, mitigate the risk of musculoskeletal injuries. In addition to the possibility that a lower RV is related to injury, it is likewise possible that decreased RV found in injured participants was also related to pain.\textsuperscript{12} Tasks requiring larger efforts are characterized by higher RV.\textsuperscript{10} When the CNS, with the basal ganglia in particular, needs to plan a complex task, it sends \textit{stimulus} to effector structures to keep motor efficiency. It seems that some movements variability was a requirement for operating a coordination change as showed in Figure 2 where the participants – after 400 cycles – achieved some sort of variability “steady state” (i.e., about constant CV).\textsuperscript{22}

In the current study, RV increases were also observed during uphill running, thus suggesting greater difficulty to control rhythm and balance facing positive slopes. When running takes places under constant conditions (e.g., on level and at constant speed), the CNS aims to optimize movement efficiency and performance by keeping a constant pace. To this end, it has been demonstrated that both CT and SF should be accurately controlled as they are key factors affecting running mechanics.\textsuperscript{21} In fact, runners able to keep relatively constant SL and SF over any conditions (e.g., at different gradients), may also be able to mitigate fatigue, injuries and falls. It was shown by Kalaïkova\textsuperscript{17} that as soon as the running motor task starts, the subsequent neuromuscular energy expenditure becomes lower. However, when the environmental conditions change further, the CNS modifies the running strategy through responsive adjustments, among which changes in RV seem to be primary and immediate.\textsuperscript{4} Accordingly, an irregular RV increase may be considered as a signal of uncontrolled movement, which could potentially induce a decrease of performance more likely occurring over prolonged running.\textsuperscript{4}

Interestingly, RV did not consistently increase during uphill running as it was only observed in the 2CON but not in the 2IES. Moreover, compared with 0CON, the increase in RV observed during the 2CON condition occurred alongside a concurrent metabolic effort increase, which was absent – as expected – during both the 0CON and 2IES conditions. Saito et al.\textsuperscript{28} showed that
consistent muscle synergies are operated across level and uphill running. Despite that, we observed large spatial-temporal variables changes in response to the gradient increase and the greater metabolic effort required to keep same level speed while running uphill (here in 2CON).

In summary, it appears that the CNS operates two different strategies to control gradient and speed changes during running occurring either separately or concurrently. While uphill running without concurrent increased metabolic demands (i.e., from 0CON to 2IES) is controlled by decreasing LDS the concurrent increase in gradient and speed (i.e., from 0CON to 2CON) require an increase in RV as an adaptative response. It may be assumed that the CNS operate a step-wise approach in controlling environmental changes during running. When metabolic demands are kept constant, an economic strategy is adopted and only a few kinematic adjustments are necessary to preserve dynamic balance during running at higher speed. However, the cumulative demands caused by the concurrent increases of gradient and speed imply a more complex control operated by the CNS, which is reflected by mirroring changes in the RV profile.

**Conclusions**

Whereas both gradient and speed increase metabolic effort during running, gradient impairs LDS during uphill running to a greater extent than speed with consequent increase of RV. Moreover, LDS seems to be dependent more on increase of gradient rather than changes in speed (i.e., in 2IES). Minor running disturbances (e.g., increased slope) can influence movement rhythmicity control increasing RV. Increased RV might be considered as a marker of motor control impairment, which could lead to detrimental effects on performance over prolonged effort. Therefore, moderate uphill training could be useful to familiarize athletes with increased locomotor perturbations, dynamic balance demands and, as consequence, to adapt controlling RV especially in preparation for long-distance running races featured by similar limited slopes (e.g., marathons such as Berlin and Boston ones, with ~2% gradients).
References


Figures legends

Figure 1. Heart rate (HR [%HRMax], expressed as percentage of theoretical maximum value obtained with the equation: 200–age [yrs] for females and 220–age [yrs] for males), perceived exertion (CR10) and running variability (SDA100) across conditions. Fixed speed at 0% (0CON), fixed speed at 2% (2CON) and iso-efficiency speed at 2% (2IES). “*” and “**” P<0.05 and P<0.001 significant differences.

Figure 2. Hundred-stride stride frequency (SF [s⁻¹]) and its coefficient of variation (CV [%]) vs. cycle number. 0CON-CV=0CON 100-stride SF CV, 2IES-CV=2IES 100-stride SF CV and 2CON-CV=2CON 100-stride SF CV.

Figure 3. Non-linear dynamical analysis: A) 3D-projection of reconstructed trajectories in phase-space graph produced by data reported in the left panel. Different symbols highlight presence of local attractors for orbit. Typical plot of natural logarithm of divergence of trajectories as a function of speed for different running conditions using Rosenstein's algorithm. Logarithm reaches a plateau within few s; B) average largest Lyapunov coefficients (LyE) estimated in 0CON, 2IES and 2CON conditions. Statistical significance is denoted as “**”, P<0.05, over running conditions.