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# Kinematics and performance on uphill and downhill trail running in elite and well-trained athletes

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## Abstract

This study investigated the impact of uphill (UP) and downhill (DH) sections and their relative running gross kinematics on trail running performance in athletes with different competitive levels. Data were collected during the 2023 Dolomyths Skyrace (22 km, ± 1750 m elevation gain/loss). Split times for UP and DH sections were analyzed for the top100 male finishers. Running kinematics (stride duration, contact time, stride frequency, and stride length) was assessed via video analysis on four-course segments (two UP, two DH). Athletes were grouped by performance level, and ANCOVA was used to analyze kinematic differences. Athletes spent more time on UP (62.5 ± 1.3%) than DH (37.5 ± 1.3%), making UP the strongest predictor of overall time ($p < 0.001$). However, percentage time differences among runners were greater in DH, where time loss from the best split was higher (21.6 ± 0.3%) than in UP (18.5 ± 0.3%, $p < 0.001$). The relationship between time loss and performance varied between sections ($p < 0.001$). Across race sections, speed decreased from elite to well-trained athletes, accompanied by longer CT and SD and lower SF and SL in both UP and DH ($p < 0.001$). After adjusting for speed, no significant group differences in kinematics remained ($p > 0.05$). In DH, SL and SD increased in the second segment. SF explained 38–39% of speed variability in UP, while SL explained 66–73% in DH. Between-group differences in DH performance exceed those in UP, significantly impacting trail-running outcomes and highlighting the need for targeted descent training. Kinematic variations were mainly driven by speed, with stride frequency driving ascent speed and stride length facilitating faster descents.



### Keywords

Mountainous terrain, split times, stride length, skyrunning


## Introduction

Trail running has surged in popularity over the past two decades.[1] Defined as a foot race set in natural environments—such as mountains, deserts, forests, and plains—trail running covers varied terrains like dirt roads, forest trails, single tracks, and beach sand, with paved sections comprising no more than 20–25% of the course.[2] Unlike road races, trail running occurs in unpredictable, complex settings, requiring runners to adapt biomechanically and physiologically. Sky-running, a high-altitude form of trail running, often involves technical mountain terrain, including glaciers, moraines, and scrambling sections with ropes.[2] Additionally, trail running and sky-running races are characterized by significant elevation changes, with uphill and downhill sections of varying lengths that further challenge athletes. These challenging conditions demand adjustments in running patterns, impacting neuromuscular requirements and energy expenditure.[3]

Due to all these characteristics, researchers have tried in recent years to develop performance models that could better describe trail running and sky-running performance compared to classical endurance performance models.[4–6] As proposed by Ehrström and co-authors, the predictive power of the classic endurance running model is enhanced by introducing elements specific to trail running, such as local muscle endurance and running economy on a positive

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slope.[6] These elements address the unique demands of trail running, distinguishing it from traditional endurance running on level surfaces. Theoretically, trail running model could be further refined by identifying the predictive factors for uphill and downhill performance separately, as demonstrated by Lemire and colleagues.[5]

Running velocity at $VO_{2max}$ ($vVO_{2max}$) appears to be the major performance factor in both UP and DH conditions in short trail running, with BMI and maximal strength playing an essential role in completing the UP predictive model.[5] $VO_{2max}$,[7] high $vVO_{2max}$, and low BMI[5] are crucial for UP performance outcomes. In contrast, the prediction of performance for DH trail running appears to be more complex, with $vVO_{2max}$, maximal strength and musculotendinous leg stiffness in the lower limbs playing a critical role in DH performance outcomes.[5] However, the physiological model proposed by Lemire and co-authors has 84% of predictive power, indicating that some factors are still missing for a comprehensive analysis of running downhill on trails.[5] Downhill sections occur in challenging environmental conditions, such as uneven terrain, steep slopes and unpredictable surfaces, and it was speculated that individual DH running technical abilities and the impact on running biomechanics[8] could be crucial for overall performance outcomes, although these factors are difficult to assess.

In such demanding conditions and prolonged efforts, running biomechanics continuously adapt.[8] These adaptations can be indicative of the onset of fatigue,[9] serve as protective mechanisms against injuries,[9,10] and influence the energy cost of running (Lemire et al., 2021a), ultimately affecting performance. Research on running kinematics in trail running highlights the impact of varying terrains and slopes on stride patterns and biomechanical adjustments. Uphill running typically demands greater muscular effort and energy expenditure, with less pronounced kinematic differences between performance levels, as observed by Genitrini et al.[11] and Besson et al.[12] However, when accounting for running speed, variations in stride length and frequency may emerge.[8] Downhill running, by contrast, presents unique biomechanical challenges, including greater braking forces[5,6] and the need to optimize stride length and contact time to maintain control and minimize energy loss.[13,14] These adaptations are crucial for managing fatigue and preventing injuries, particularly in prolonged efforts and steep descents.[5,10] Furthermore, Genitrini et al.[11] suggest that efficient downhill running involves enhanced swing leg mechanics to optimize propulsion, while Lemire et al.[5] emphasize the protective role of reduced stride length and contact time in minimizing mechanical stress over extended downhill sections. Collectively, these findings underscore the importance of terrain-specific biomechanical adjustments and their direct influence on fatigue, injury prevention, and overall performance outcomes in trail running.

Therefore, the aim of this study was twofold: *i)* to investigate how uphill (UP) and downhill (DH) performances affect overall trail running race results; *ii)* to analyze running kinematics during UP and DH segments in athletes of different performance levels, while considering the potential effects of fatigue as the race progresses. These objectives were addressed in the context of a Skyrunning competition with a specific elevation profile, characterized by a continuous 10 km uphill section followed by a 12 km downhill section.

We hypothesized that i) the downhill section could be the most decisive factor influencing the race outcome, and ii) better-performing athletes would demonstrate better maintenance of elevated speed throughout the race, longer cycle lengths, and a reduced duty cycle.

## Methods

### Research design

The data were collected during the 2023 Dolomyths Skyrace, a 22 km Skyrunning race with a total elevation gain and loss of 1750 m. Starting and finishing at 1450 m, the race reaches its highest point at 3152 m. The first 10 km consists of a continuous uphill section, followed by a 12 km downhill section that leads to the finish line.

The race took place in July in the Italian Alps under sunny and dry conditions, which allowed athletes to perform at their best without the influence of adverse weather or terrain.

The race featured 825 ranked participants (694 male and 131 female athletes) representing different performance levels. The first athlete finished the race in 02:04:39, while the last athlete finished in 05:44:11 (hh:min:ss).

We collected split times for each athlete from the official timing system, both for the uphill and downhill sections. In addition, we filmed the athletes on four different segments of the course during the race: two on the UP section and two on the DH section. All segments were chosen in advance during a route reconnaissance carried out by the research team one week before the event and were characterized by comparable inclines (about ±35% incline). All the participants were recorded during the race on the four segments of interest. Segments were selected to be representative of the overall uphill and downhill sections, while avoiding overly technical terrain that could introduce excessive variability in running patterns. Similar slopes and surface conditions were prioritized to ensure comparability across segments. Their distribution along the course also allowed us to explore potential fatigue-related changes in running mechanics. The permission to record videos was obtained from the organizing committee, as the participants had previously granted their consent to the committee, which extended this permission to third parties.

### Split time analysis

For each participant, overall race time, uphill and downhill split times were collected from the official timing system and analyzed. To determine whether the uphill or downhill section was the primary determinant of overall race performance, we focused on the top 100 male finishers to obtain a more complete analysis of elite and well-trained athletes. For each athlete, we calculated the percentage time loss in both the uphill and downhill sections relative to the best split in each section to explore the linear relationship between section-specific performance and overall race outcome.

## Running kinematic analysis

For the kinematic analysis of running, four segments were selected, as previously described. These segments were chosen to have similar slopes (±35%), with two located in the uphill section and two in the downhill section of the race, at approximately 3.5 km (UP1), 9 km (UP2), 10.5 km (DH1), and 18 km (DH2) of the racecourse. Additionally, all selected segments featured comparable surface types, ensuring that the technical demands across the segments were consistent. For each of the selected segments, a 12 to 15-meter was precisely measured, with the start and end points clearly marked on both sides of the path using four colored cones.

To capture the athletes' horizontal displacement during both uphill and downhill running, a high-frequency camera (GH5S LUMIX, Panasonic Corp., Osaka, Japan) was employed, set to a 100 Hz acquisition frame rate and FHD recording quality. The camera was positioned laterally in each segment to ensure visibility of the cones and allow clear observation of the athletes' foot positions.

Additionally, At the beginning of each segment, a smartphone mounted on a tripod recorded the athletes from a frontal view, allowing investigators to identify their bib numbers.

Although the analyzed segments were relatively short (12–15 meters), this choice allowed for precise kinematic assessment under controlled conditions in a mountain environment. These segments were selected to reflect the typical characteristics of the uphill and downhill sections, while minimizing variability due to extreme terrain. Nonetheless, we acknowledge that this may only partially reflect the full range of technique variability over the entire race course.[15]

## Participants/athletes selection

Male athletes were categorized into different performance groups, and a performance coefficient (PC) was calculated for each athlete by dividing their final race time by the winner's time. This coefficient ranged from 0 to 1, with 1 representing the winning performance.[7] Performance groups were created at every 5% decrease in the performance coefficient. For the kinematic analysis, we included the top ten athletes from the first five performance groups who: i) were identified in all four segments and ii) completed at least three visible steps within each segment. This allowed us to analyze five groups of runners with progressively lower performance levels, each composed of 10 participants. To better assess the performance level of each group, we collected the individual ITRA score of each participant (ITRA).[16] Given the selection criteria, the athletes involved in this study are primarily elite, sub-elite, and well-trained runners, with all participants finishing within the top 90 positions in the race (race time of the last athlete included in the analysis: 02:41:20). Table 1 reports the ITRA score, age, race time, and uphill (UP) and downhill (DH) running time for the five groups of runners investigated.

## Tracking procedures and analysis

All selected athletes were analyzed using Kinovea software (v.2023.1.2) in each segment. The time taken by the athletes to travel each selected segment was calculated through video analysis, measuring the duration between the athletes crossing a virtual line perpendicular to the path, connecting the first two cones and the final two cones. Mean speed was then calculated as the distance between the cones divided by the time taken to cross that segment. Foot ground contact and toe-off frames of each stride recorded from the selected athletes were visually identified and used to calculate the following metrics: mean stride duration (SD: the time between consecutive ground contacts of the same foot), mean contact time (CT: the time between ground contact and toe-off of the same foot), mean duty cycle (percentage of time the foot spends in contact with the ground during a stride), mean stride frequency ($SF = 1 * \text{stride duration}^{-1}$) and mean stride length ($SL = \text{mean speed} * \text{stride frequency}^{-1}$).

All gait events were identified manually by two experienced operators, who followed a standardized set of visual criteria to determine ground contact and toe-off frames. The operators were aligned on definitions and worked independently but in agreement on event detection guidelines, minimizing potential subjectivity. Based on the video frame rate (100 Hz), the potential error in event identification was limited to ±1 frame (0.01 s), ensuring a high level of temporal accuracy.

## Statistical analysis

Data distribution was assessed with the Shapiro-Wilk test and presented as mean ± standard deviation (SD). Where necessary, data were log-transformed to meet the assumptions of normality. An ANCOVA was performed on the top 100 participants for the time percentage difference data, with overall race time as a covariate and section (uphill vs downhill) as a factor. The interaction between race time and section was also included to determine if the relationship between race time and percentage difference varied between uphill and downhill sections. A significance level of $p < 0.05$ was used.

**Table 1.** Groups characteristics – the table reports the characteristics of the performance groups (1–5). ITRA score, age, overall race time, and split times for uphill and downhill are reported. Data are expressed as mean ± standard deviation (SD).

| Mean ± SD | | Performance Groups | | | | |
|---|---|---|---|---|---|---|
| | | 1 | 2 | 3 | 4 | 5 |
| PC | — | 1–0.95 | 0.95–0.90 | 0.90–0.85 | 0.85–0.80 | 0.80–0.75 |
| ITRA Score | — | 905.4 ± 20.5 | 871.7 ± 26.8 | 861.4 ± 26.7 | 779.1 ± 26.8 | 754.8 ± 58.1 |
| Age | years | 29.5 ± 4.6 | 28.5 ± 4.7 | 30.2 ± 6.2 | 28.6 ± 4.8 | 28.9 ± 4.4 |
| Race time | min | 126.7± 1.4 | 136.5 ± 2.3 | 142.4 ± 2.0 | 149.1 ± 0.9 | 158.8 ± 1.4 |
| Uphill time | min | 79.9 ± 1.2 | 85.9 ± 1.4 | 89.6 ± 2.5 | 92.7 ± 2.2 | 98.8 ± 2.2 |
| Downhill time | min | 46.9 ± 0.9 | 50.6 ± 1.7 | 52.8 ± 2.0 | 56.4 ± 2.3 | 60.0 ± 2.5 |

For the kinematic data, two separate analyses were conducted for uphill and downhill segments. A two-way ANOVA was used to assess the effects of group and segment, as well as their interaction, on the kinematic parameters. Since speed was significantly different between groups, an ANCOVA was also performed, including speed as a covariate, to control for its influence on the kinematic variables. Bonferroni correction was applied for post-hoc tests to compare specific groups. Effect sizes were reported using eta squared ($\eta^2$), with 0.01, 0.06, and 0.14 representing small, medium, and large effects, respectively. A stepwise multiple linear regression was used to explore the relationship between stride frequency, stride length, and running speed variability, with $p < 0.05$ indicating statistical significance.

## Results

### Split time analysis

Although the total race time is primarily influenced by the time spent on the uphill (UP) section ($R^2 = 0.90$), which accounts for a greater percentage of the overall race time (62.5 ± 1.3%) compared to the downhill (DH) section (37.5 ± 1.3%), the analysis of the percentage difference from the best split time in both uphill and downhill running revealed a significant effect of overall race time ($p < 0.001$, $\eta^2 = 0.882$) and section (uphill vs downhill) ($p < 0.001$, $\eta^2 = 0.008$) on the percentage difference, referring to the variation in an athlete's split time relative to the best time recorded for each section. Additionally, a significant interaction between race time and section was observed ($p < 0.001$, $\eta^2 = 0.010$) (Figure 1), indicating that the relationship between race time and the percentage difference differed between the UP and DH sections. The marginal means showed that the percentage difference was higher in the DH section (21.572 ± 0.325) compared to the UP section (18.533 ± 0.325).

### Kinematic analysis

*Uphill running.* The kinematic analysis of uphill running demonstrated significant differences across performance groups for several parameters, including speed, CT, SD, SF, and SL. Specifically, speed significantly decreased from Group 1 to Group 5 ($p < 0.001$, $\eta^2 = 0.601$). All these parameters showed clear trends corresponding to the runners' performance group ($p < 0.001$ for most parameters). No significant segment*group interactions were found, indicating that these effects were consistent across both uphill segments. However, ANCOVA results, with tract-specific speed added as a covariate, revealed no significant differences in any kinematic parameters across groups after adjustments ($p > 0.05$). No significant differences were found between the two uphill segments (Figure 2).

*Downhill running.* The kinematic analysis of downhill running revealed significant differences across performance groups in several parameters. Speed decreased progressively from Group 1 to Group 5 ($p < 0.001$, $\eta^2 = 0.704$), while CT, duty cycle, and SD increased with lower performance groups ($p < 0.001$ for each parameter). SF and SL both showed a decreasing trend across groups. The absence of significant segment*group interactions indicates that these trends were consistent across both downhill segments. When controlling for speed in the ANCOVA, no significant differences were found in any of the kinematic parameters across groups ($p > 0.05$) and no significant interaction segment*group was found ($p > 0.05$). However, significant differences between the two segments remained. Specifically, SD and SL increased in the second sector. CT and duty cycle both showed a tendency toward a significant effect of the segment ($p = 0.065$ and $p = 0.066$, respectively), with both parameters decreasing in the second segment (Figure 3).

*Stepwise linear regression analysis.* The stepwise multiple linear regression analysis (Figure 4) revealed that SL and SF contribute differently to the variation in speed during uphill and downhill running, with adjusted $R^2$ values of 1 in all segments ($p < 0.001$). In uphill running, SF alone accounted for 38–39% of the variance in speed, while the addition of SL increased the explained variance to 100%. In downhill running, SL was a stronger individual predictor, explaining 66–73% of the variance in speed.

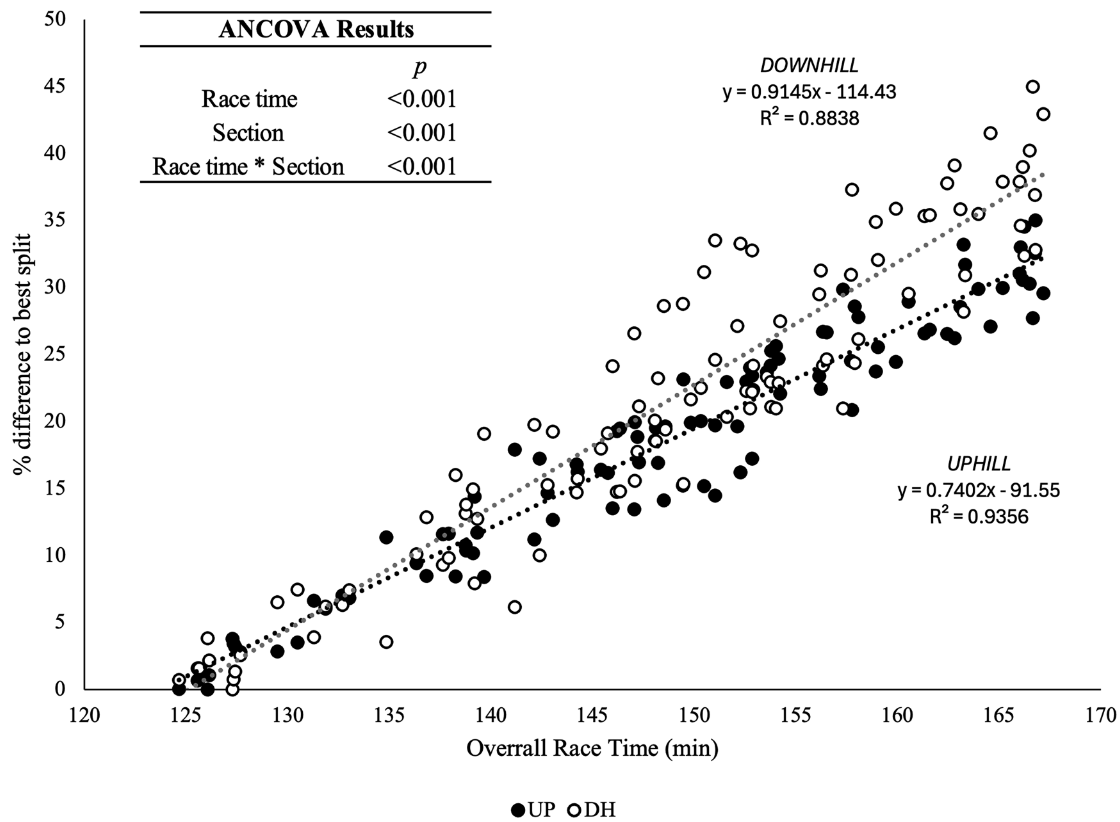



**Figure 1.** Relationship between overall race time (min) and percentage difference to the best split time for both uphill (UP) and downhill (DH) sections. The dotted lines represent linear trends for each section. ANCOVA results show significant effects of race time.

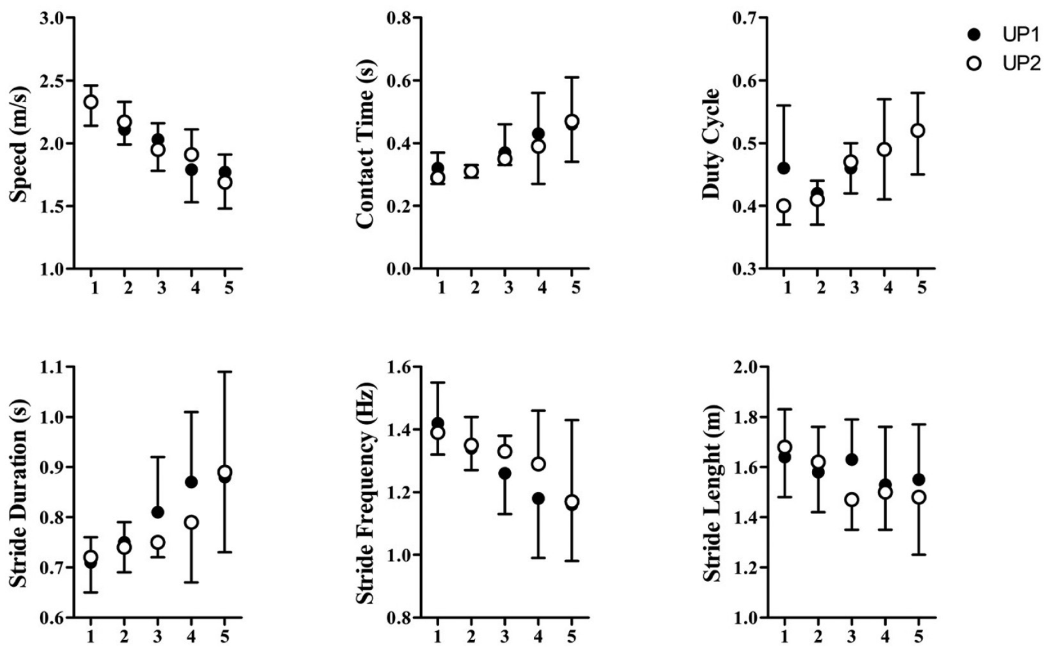
## Discussion

Our study aimed to address two main objectives within the context of a Skyrunning race. Before presenting the main findings, it is important to acknowledge that the analysis was conducted on a selected sample of high-performing male athletes (top 100 finishers). This choice was motivated by the aim of exploring performance and kinematic differences within a competitive field, to better understand where elite athletes are able to make the difference compared to those finishing immediately behind. Female athletes were excluded solely due to the limited sample size available, which would not have allowed for a robust statistical comparison.

First, to investigate whether uphill or downhill running performance plays a different role in determining the overall trail running performance. Second, to analyze running kinematics during the UP and DH segments across athletes of different performance levels, while considering how fatigue may influence kinematic patterns as the race progresses. The results showed that: *i)* despite the uphill section has the most important relative weight in determining the overall race outcome, as performance level decreases, athletes tend to lose a greater percentage of time in the downhill section compared to the uphill section, indicating a larger margin for improvement in their downhill performance; and ii) kinematic analysis reveals that differences between performance groups (from elite to well-trained athletes) are mainly driven by speed, with subsequent kinematic differences being primarily related to speed variations. Interestingly, in the uphill sections, stride frequency appears to be the primary factor driving the increase in ascent speed, while in the downhill sections, faster descent speeds are mainly achieved through an increase in stride length. Running kinematics was not significantly affected by fatigue in the uphill segment, while specific kinematic changes in the downhill section, such as an increased stride length and a decreased stride frequency from DH1 to DH2, may reflect either accumulated fatigue from the ascent or a strategic adjustment to manage technical race demands.

### *Split time analysis*

While total race time is mainly determined by the time spent uphill, which also represents a larger portion of the overall




**Uphill - ANOVA Results**

| | Speed | Contact Time | Stride Duration | Stride Frequency | Stride Lenght | Duty Cycle |
|---|---|---|---|---|---|---|
| | *p* | *p* | *p* | *p* | *p* | *p* |
| Segment | 0.778 | 0.348 | 0.238 | 0.183 | 0.238 | 0.566 |
| Group | <0.001 | <0.001 | <0.001 | <0.001 | <0.001 | <0.001 |
| Segment*Group | 0.352 | 0.944 | 0.730 | 0.781 | 0.491 | 0.872 |
| **Uphill - ANCOVA Results** | | | | | | |
| Segment | - | 0.344 | 0.240 | 0.180 | 0.183 | 0.619 |
| Group | - | 0.327 | 0.738 | 0.854 | 0.890 | 0.164 |
| Segment*Group | - | 0.841 | 0.649 | 0.703 | 0.654 | 0.698 |

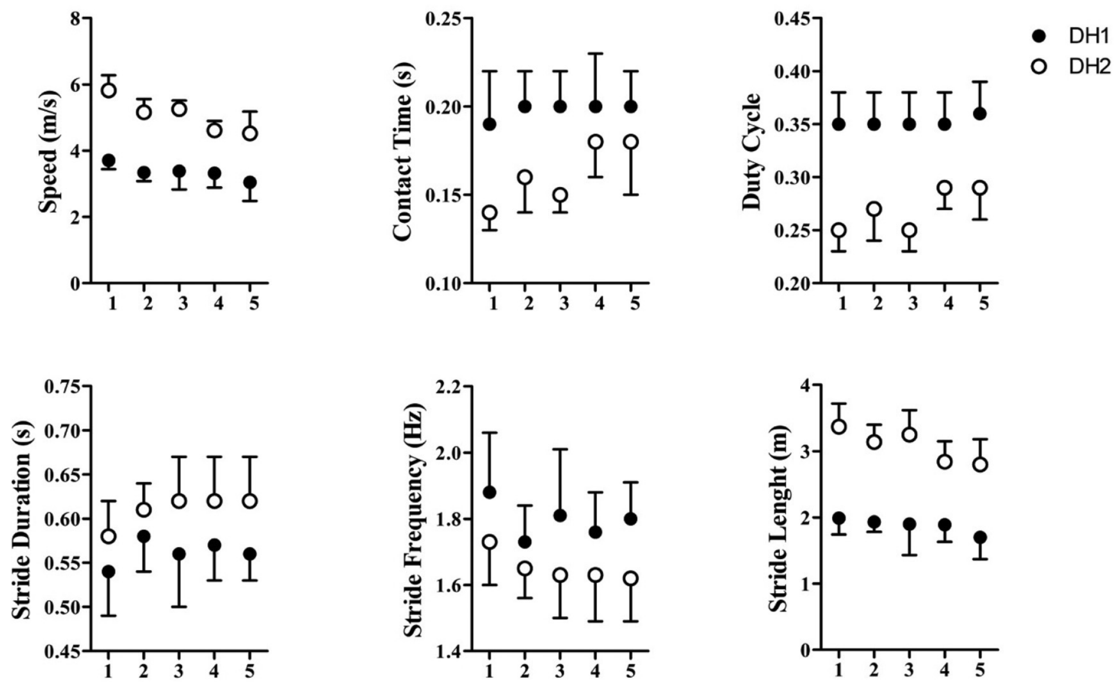
**Figure 2.** Kinematic parameters (speed, contact time, duty cycle, stride duration, stride frequency, and stride length) across performance groups (1 to 5) for two uphill segments (UP1 and UP2). Filled circles represent values for UP1, and open circles represent values for UP2. Data are presented as means ± standard deviation. The table below presents the statistical results.

race duration, our analysis showed that downhill performance significantly impacted the final outcome. Larger percentage split time differences were observed in downhill sections, increasing as performance level decreased. As race time increased, the percentage difference from the best split grew more in downhill, suggesting its greater influence on overall race time, particularly for slower runners. Higher marginal means in downhill further support this, indicating greater time loss relative to the best split, especially in lower-performing athletes.

Elite athletes maintained higher speeds throughout the entire race, which may be attributed to a combination of higher metabolic capacities, superior downhill running skills, as well as other factors such as strength, leg stiffness, and reduced exercise-induced muscle damage, which are likely to mitigate the impact of fatigue on performance.[5,6]

In this first analysis, we included the top 100 finishers, because including only the athletes selected for the kinematic analysis would have been limiting and resulted in data distribution gaps; however, the data distribution for the subset of athletes included in the kinematic analysis showed a similar trend, with comparable linear relationships observed in both sections (slope values for uphill: 0.915 vs. 0.912, slope values for downhill: 0.740 vs. 0.742, for the top 100 and the kinematic subgroup respectively).

This insight into uphill and downhill performance in trail running is relatively novel, as comprehensive analyses are still lacking, with only a few studies addressing these aspects in short-distance races.[5,6,14] Ehrström et al.[6] reported that finish time was more strongly correlated to split times in uphill than in downhill sections during a short trail running race (27 km), while Björklund et al.[14]




| Downhill - ANOVA Results | | | | | | |
|---|---|---|---|---|---|---|
| | Speed | Contact Time | Stride Duration | Stride Frequency | Stride Lenght | Duty Cycle |
| | *p* | *p* | *p* | *p* | *p* | *p* |
| Segment | <0.001 | <0.001 | <0.001 | <0.001 | <0.001 | <0.001 |
| Group | <0.001 | 0.002 | 0.096 | 0.050 | <0.001 | 0.020 |
| Segment*Group | 0.029 | 0.506 | 0.770 | 0.777 | 0.196 | 0.077 |

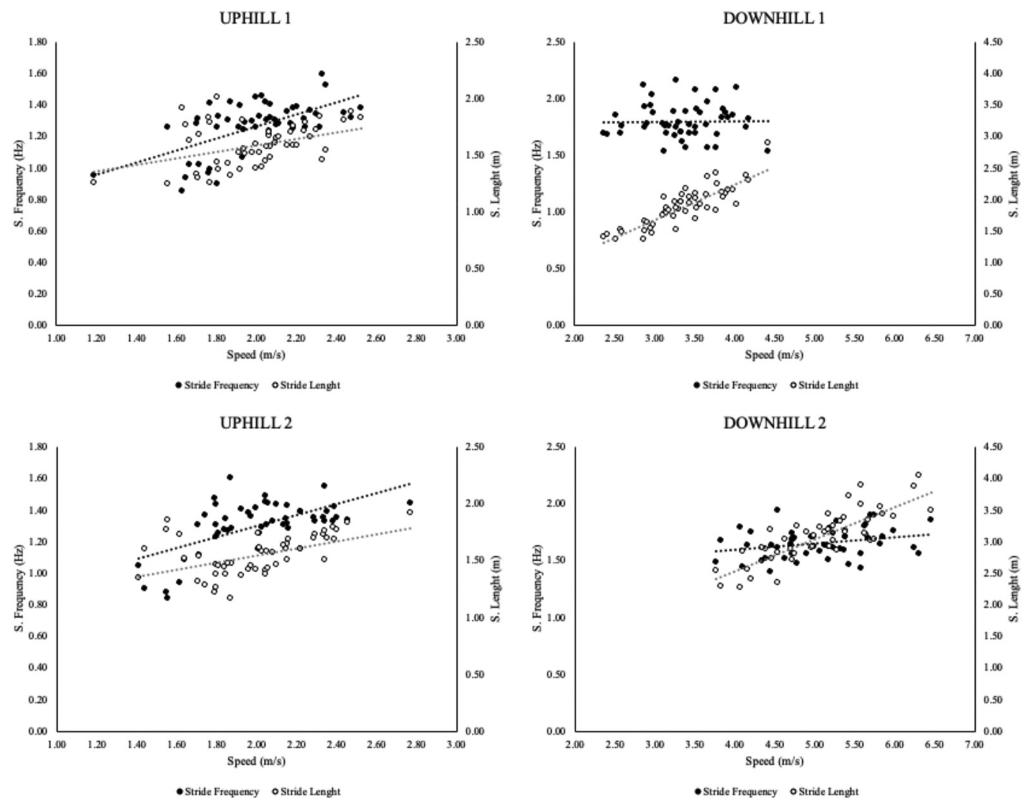
| Downhill - ANCOVA Results | | | | | | |
|---|---|---|---|---|---|---|
| Segment | - | 0.065 | 0.027 | 0.032 | 0.032 | 0.066 |
| Group | - | 0.739 | 0.209 | 0.126 | 0.153 | 0.293 |
| Segment*Group | - | 0.933 | 0.773 | 0.781 | 0.858 | 0.470 |

**Figure 3.** Kinematic parameters (speed, contact time, duty cycle, stride duration, stride frequency, and stride length) across performance groups (1 to 5) for two uphill segments (DH1 and DH2). Filled circles represent values for DH1, and open circles represent values for DH2. Data are presented as means ± standard deviation. The table below presents the statistical results.

found the greatest time loss in uphill sections of a 7 km trail running trial. Both studies, however, considered split times in absolute terms, which inherently reflects the greater amount of time spent in uphill sections compared to downhill. Moreover, the races analyzed in those studies featured varied elevation profiles, with multiple uphill and downhill sections, unlike the continuous 10 km uphill and 12 km downhill sections present in the race analyzed in our study. Recent research has focused on pacing strategies in ultra-trail races (>50 km),[17,18] where faster finishers show higher speeds in downhill sections compared to slower competitors.[17] Our results align with this trend, indicating that top athletes lose less time downhill, likely due to superior descent skills[19] and less muscle damage from frequent downhill exposure.[20] The present study offers a new approach by analyzing the percentage difference relative to the best split time, which minimizes the influence of absolute time differences between the uphill and downhill sections. Our findings suggest that downhill performance is more influential on race outcomes. This highlights the importance of the chosen analytical method and race profile, as these factors can shape how uphill and downhill performance contributions are interpreted. Further, focusing on elite athletes in short-distance races with varying elevation profiles can provide deeper insights into how pacing strategies affect overall performance.

## *Running kinematics*

To our knowledge, this study remains one of the few that investigated running kinematics in trail runners under ecological conditions, focusing on a large cohort of elite and well-trained athletes. Many other previous studies have compared different levels of athletes using treadmill running tests at the same speed and incline.[12,21–23] In




**Stepwise multiple linear regression analysis**

| Section | Dependent Variable | Predictors | R | $R^2$ | Adjusted $R^2$ | $R^2$ change | p Change | Linear relation |
|---|---|---|---|---|---|---|---|---|
| Uphill 1 | Speed | SF | 0.62 | 0.38 | 0.37 | 0.39 | **<.001** | *Speed* = 2.161**SF* + 0.241 |
| Uphill 2 | Speed | SF | 0.63 | 0.39 | 0.58 | 0.39 | **<.001** | *Speed* = 2.399*SF + 0.014 |
| Downhill 1 | Speed | SL | 0.85 | 0.73 | 0.72 | 0.73 | **<.001** | *Speed* = 1.282*SL + 0.950 |
| Downhill 2 | Speed | SL | 0.81 | 0.66 | 0.66 | 0.66 | **<.001** | *Speed* = 1.308*SL + 1.046 |

**Figure 4.** Figure reports the relationships between stride frequency and stride length with speed for all the segments analyzed (UP1, UP2, DH1, and DH2). The table shows stepwise multiple linear regression results showing the contribution of stride SF and stride SL to speed in both uphill and downhill segments.

contrast, fewer studies have explored performance differences under ecological conditions.[8,11] When comparing these works, caution is necessary, as running speed differences between athletes in ecological setups can introduce a significant bias that must be considered when analyzing kinematic differences. While treadmill running controls this variable, it limits the athlete's ability to self-regulate their running speed, which is a typical feature of overground running and competition.[13,24]

In our analysis of the kinematic data, some interesting findings emerged. We initially hypothesized that higher-performing athletes would maintain higher speeds, have longer stride lengths, exhibit a reduced duty cycle, and possibly experience less fatigue in both final segments. The best-performing athletes consistently showed higher speeds throughout the course. Kinematic differences occurred between different performance levels; however, these kinematic differences appeared to be attributed to variations in running speed rather than differences inherent to the athletes' performance levels. While fatigue had minimal impact on uphill running mechanics, the kinematic adjustments observed in the downhill segments may reflect strategic adaptations or the cumulative effects of the preceding uphill effort.

## *Uphill running*

Our findings on uphill running kinematics emphasize the critical role of speed in influencing kinematic characteristics across groups of different performance levels. The significant decrease in speed from higher- to lower-performing groups, together with increases in CT and changes in stride parameters, suggests that higher-performing runners sustain greater speeds by minimizing CT and optimizing stride mechanics. These results align with previous literature, which shows that as speed increases, athletes adapt their running kinematics.[21,25]

The absence of significant differences after adjusting for speed indicates that the observed variations in kinematic parameters are primarily attributable to differences in running speed itself. This suggests that interventions aimed at improving uphill running performance in high-level athletes should focus more on strategies to enhance speed, as technique-related factors do not appear to distinguish between performance levels. Additionally, the lack of significant differences between the two analyzed uphill segments suggests that all athletes maintained a relatively steady pace throughout the climb, reinforcing the idea that the key differentiator in uphill performance is the ability to sustain a higher running speed rather than changes in running mechanics over time. This aligns with previous research highlighting the importance of athlete's metabolic profile in uphill trail running performance.[7]

Similar kinematics results have been found in previous studies. Genitrini et al.[11] reported no significant differences in running kinematics between more proficient and less proficient trail runners during uphill trail running. Vermand et al.[8] observed kinematic differences during uphill running in a 40 km trail race, with these differences being attributed to variations in running speed. Additionally, Garcia-Pinillos et al.[22] found no differences in running kinematics between groups of amateur and elite runners when running at the same speed. Besson et al.[12] also found no biomechanical differences between elite and experienced trail runners during treadmill uphill running, although the elite runners demonstrated a lower cost of running at the same speed.

Additionally, we observed in the present study that SF appears to play a critical role in uphill running, as runners tend to increase their cadence to maintain speed despite the limited SL imposed by the incline. This suggests that SF is a compensatory mechanism for overcoming the physical constraints of uphill movement, which is consistent with previous literature showing significant differences in SF as speed or gradient increased.[25]

### Downhill running

Regarding downhill running, we observed differences in running speed and kinematic parameters between performance levels, in accordance with previous literature,[11] but our results emphasize the critical role of speed in influencing kinematic characteristics. After adjusting for speed, there were no differences between performance groups for the parameters analyzed. However, clear distinctions emerged between the two downhill segments in the downhill section. The changes between segments could be attributed to various factors, such as a deliberate shift in strategy to manage the technical terrain or a response to accumulated fatigue due to the previous uphill portion of the course, or the progressive exposure to downhill running.

The tendency towards reductions in contact time and duty cycle in the second segment suggests that runners adapt their running kinematics not only due to speed but also to possibly reduce braking forces or maintain momentum. While downhill running involves greater braking forces compared to uphill running,[5,6] uphill running requires greater propulsive forces, primarily concentric in nature, whereas downhill running is dominated by eccentric muscle actions with differing metabolic efficiencies. Reducing the duty cycle may, therefore, represent a way to minimize the force impulse during contact, helping runners better tolerate the mechanical demands of downhill running.

We also observed that in downhill running, stride length becomes a dominant factor in explaining speed differences in maintaining speed, as the slope enables runners to extend their stride more freely. Townshend et al.[13] found that stride length when running downhill increased by 16.2% compared to level running, further supporting the idea that stride length plays a critical role in regulating speed during downhill segments. This observation is also in line with findings from Genitrini et al.,[11] outlined previously. Adjustments in stride frequency and stride length allow runners to accommodate the technical demands of varied terrain while managing the forces involved in the descent. These adaptations suggest that athletes adjust their running patterns in a consistent manner as they progress through the course. This consistency among high-level athletes may indicate that runners at this performance level have developed similar strategies to cope with the demands of the race and downhill sections.

## Conclusion

Our study contributes to the limited research on trail running performance and kinematics under ecological conditions, focusing on a large cohort of elite and well-trained athletes. The findings may be of practical relevance for coaches and athletes aiming to optimize performance through a better understanding of kinematic strategies in real-world conditions. In particular, our results highlight the critical role of downhill sections in Skyrunning competitions, where greater time losses in the descent—compared to the uphill—had a stronger impact on race outcomes. This underscores the importance of prioritizing downhill running in training, as it plays a substantial role in determining final rankings. Frequent exposure to downhill running can enhance technique, help athletes manage braking forces, and adapt to the mechanical demands of these sections.

When kinematic parameters were normalized for speed, no significant differences emerged between athlete levels, suggesting that metabolic factors, along with specific neuromuscular and technical abilities, play a primary role in differentiating performance in both uphill and downhill sections.

Regarding uphill running, our results show that speed is the main factor driving differences in running kinematics, as there were no significant differences across groups after controlling for speed.

In the downhill section, all athletes, regardless of performance level, adjusted their running patterns similarly, notably increasing stride length and reducing stride frequency as the descent progressed. These changes likely reflect a combination of factors, including the accumulation of fatigue from the prior uphill section, adaptation to the technical demands of the terrain, and shifts in technique to manage the steep descent effectively.

### Study limitations

This study has some limitations that should be acknowledged. First, sample size is limited to elite and well trained athletes and while this approach provides insight into performance determinants among well-trained and elite male athletes, it limits the generalizability of the findings to female and recreational runners. This limitation should be considered when interpreting the results.

While physiological or neuromuscular tests before or after the race could have offered deeper insights into athletes' capacities and performance, these were not included in the protocol. Our primary focus was to analyze a large number of athletes in a real race scenario, prioritizing kinematic analysis. Additionally, it was not possible to predict which athletes would provide high-quality video data for analysis, making such additional measurements impractical. Second, the kinematic analysis was limited to short segment of around 15 meters, which may not fully capture variability in running patterns across the course. Third, potential sources of error in the video-based kinematic analysis should be acknowledged. Although efforts were made to standardize video acquisition and minimize measurement error, minor inaccuracies in stride parameter detection cannot be entirely excluded. Lastly, while multiple linear regression was used to explore the contribution of stride length and stride frequency to running speed, we acknowledge that this approach assumes linear relationships between variables. Although this assumption is supported by previous treadmill-based studies,[21] real-world trail running conditions may involve more complex and non-linear interactions, particularly due to terrain variability and individual adaptation strategies.[25] Future research could focus on analyzing the relationship between stride frequency and stride length in real-world conditions across a range of slopes and speeds, potentially using non-linear or mixed-model approaches to better reflect the biomechanical complexity of trail running.

### Perspectives

Future research should explore trail running performance in real-world conditions by integrating physiological, biomechanical, and neuromuscular factors. Special focus should be placed on downhill running, where greater time losses suggest potential for improvement. Increased exposure to downhill terrain may enhance adaptation and optimize performance in high-level athletes.

In particular, the inclusion of physiological markers (e.g., $VO_2$max, lactate, heart rate) and neuromuscular assessments (e.g., strength, fatigue indices) would provide a more comprehensive understanding of the mechanisms underlying performance differences. Combining these data with kinematic analysis could help clarify how physiological capacity and neuromuscular control contribute to uphill and downhill running efficiency.

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## Credit authorship contribution statement

Conceptualization: S.B., L.B., C.Z.; Methodology: S.B., L.B., B.P., C.Z.; Data collection; S.B., G.V., B.P., C.Z.; Formal analysis: S.B., A.F., C.Z.; Writing - original draft preparation: S.B. and C.Z.; Writing - review and editing: S.B., L.B., B.P., A.F., G.V., C.Z., F.S.; Resources: B.P., F.S.;

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## Ethical considerations

The permission to record videos was obtained from the organizing committee, as the participants had previously granted their consent to the committee, which extended this permission to third parties. This study was conducted in accordance with the ethical principles of the Declaration of Helsinki. Given that the data collection was observational and did not interfere with the athletes' performance or well-being, no additional ethical approval was required.

## Consent to participate

The permission to record videos was obtained from the organizing committee, as the participants had previously granted their consent to the committee, which extended this permission to third parties.

## Data availability

The data that support the findings of this study are available from the corresponding author, SB, upon reasonable request.

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