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Pacing Strategy and Resulting Performance of Elite Trail Runners: Insights From the 2023 World Mountain and Trail Running Championships

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Purpose: Pacing is crucial in endurance sports such as running, and its importance is also prominent in trail running due to the unique challenges, including high elevation gains and varied terrain. This study aimed to explore the pacing strategies of elite athletes during the 2023 World Mountain and Trail Running Championships for the Trail Short distance. ***Methods:*** The participants included 12 elite trail runners who provided their race data from sport watches for analysis. ***Results:*** The findings indicate a significant decrease in grade-adjusted pace (v_i) as the race progressed, with an average change of −18.7% from the start to the last downhill segment. A linear correlation of −.55 ($P = .031$) was observed between the winning time and the evolution of v_i, suggesting that more consistent pacing led to better performance. The Student t test ($t = 2.628$, numerator degrees of freedom = 10, $P = .013$) confirmed that even pacing is significantly correlated with superior race results at a confidence level above 95%. ***Conclusions:*** A more even pacing strategy is associated with success during elite trail-running races.

Keywords: endurance, pace, performance analysis

Trail running, typically held in natural settings with less than 20% of the paths paved, encompasses a variety of terrains including mountains and deserts. Race distances vary, extending from a few kilometers to over 80 km without a cap on elevation.[1] The 2023 Trail World Championship featured a 45.2-km course with a 3132-m elevation gain.[2] The sport has experienced significant growth, increasing by 2394% over the past 2 decades, with a 231% rise in the last 10 years alone.[3] Since its official recognition by World Athletics in 2015,[4] trail running has seen notable development and professionalization, leading to discussions about its potential inclusion in the Olympics, highlighting its promising future.

Pacing, the method by which an athlete manages work and energy distribution during an exercise task, influences speed during a race.[5] This concept has long been significant in studies of sports like running, where pacing strategies critically affect endurance sport performance,[6,7] and is similarly vital in trail running. Due to the high elevation gains and varying terrain and surfaces in trail running, pacing requires a variable effort analysis, differing significantly from other endurance sports. Research shows that heart rates tend to be lower in uphill mountain races of half-marathon lengths, contrasting with the heart rate drift observed in flat marathons, suggesting increased peripheral demands during uphill movement.[8] In additional, minimizing the heart rate decline in ultramarathon trail races is linked to improved performance.[9] Similarly, 32-km and 50-km trail races with significant elevation gains (2000–3500 m) adversely affect skeletal muscle oxidative metabolism, thereby diminishing exercise capacity and tolerance.[10] Moreover, studies suggest that energy balance in races of comparable length (eg, 54 km) cannot be maintained solely through external nutrition,[11] highlighting the importance of strategic pacing to conserve energy for challenging race segments. Thus, the assessment of grade-adjusted pace (GAP) is commonly used in trail running training and competitions to compare effort, work, and energy distribution among athletes, given the sport's uphill and downhill components.

Various studies have examined successful pacing strategies in trail running across different race distances and terrains. Research indicates that the most successful ultra-distance trail runners maintain consistent pacing, particularly in the latter stages of races.[12–14] This consistent pacing often involves minimizing speed loss on descents toward the race's end, a marker of top-performing runners.[15] A recent review suggests that, although some pacing losses are nearly inevitable, maintaining as even an intensity as possible and mitigating these losses are crucial.[16] It has also been noted that the rate of speed reduction tends to be greater on descents and flat sections than on ascents.[17] However, these trends vary with shorter distances. For instance, in a 7-km simulated trail study, a notable speed loss was observed on the second lap, particularly in uphill sections.[18] Another study on the 56.3-km OCC® race found that high-level runners exhibited more variable pacing, adapting better to the race's profile.[19] These findings underline the importance of managing ascent pacing to optimize descent performance. Moreover, research on a 10.4-km trail with a single ascent and descent suggests that avoiding overly aggressive uphill pacing can enhance performance in subsequent descents.[20] Similarly, strategies like controlling a "fast-start" with a conservative approach have proven effective in improving endurance performance.[21] This approach is especially critical in managing the initial stages of trail races, where maintaining optimal intensity is crucial, particularly in medium or long-duration races such as marathons or ultratrails. This is due in part to the higher energy demands during uphill sections compared with descents.[22]

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Although pacing strategies have already been reported in literature, the description of pacing strategies in a World Championship where worldwide elite trail running athletes are competing against each other is still unknown. Therefore, the main aim of this study was to examine the pacing strategies of elite trail runners during the World Mountain and Trail Running Championships 2023 for the Trail Short distance. Based on the previous literature, we hypothesized that runners that exhibit less variation in pace initially compared with later stages (minimal GAP decrease) and that maintaining a more consistent pacing across the different sections would achieve a better performance.

Methods

For the present study, we analyzed data from athletes who participated in the Trail Short race of the 2023 World Mountain and Trail Running Championships, taking place around Innsbruck, Austria, on June 8, 2023. The official track distance amounted to 45.2 km and exhibited 3132 m of accumulated positive and 2719-m negative elevation changes.[2] The actual race including time-taking began with a neutralized start after the first 0.6 km on flat terrain through the city of Innsbruck, Austria.

Participants

Twelve elite runners (7 men and 5 women, height, mean [SD]: 170 [9] cm; weight, mean [SD]: 56.2 [7.9] kg; age: 31.65 [5.63] y; International Trail Running Association performance index: 813 [79]) volunteered to participate in the study. They provided their height and weight and their race files, as recorded by their sports watches, and gave consent for their data to be analyzed and published as part of this study. The ethics committee of the host university granted approval for the protocol (Certificate 36/2023), adhering to the principles outlined in the Declaration of Helsinki. The athletes recruited ranged from podium placements into the middle of the field for both females and males, with finishing times between 4 hours 21 minutes and 6 hours 00 minutes. The 12 activities were recorded with 8 different sport watch models from 3 different brands (Table 1).

Data Processing

Each of the 12 files was provided in the format of the Flexible and Interoperable Data Transfer protocol (https://developer.garmin.com/fit/protocol/). For data reduction, we first extracted the elapsed time, measured distance, speed, altitude, and cadence of each file and saved it as a *pandas DataFrame*.[23] To ensure that the data of all athletes were comparable, we filtered and checked each of them as follows: First, we removed all recorded information prior to the neutralized start; then, we checked the speed values at the end to ensure that activity was properly stopped at the end of the race, and in case this was missed by the athlete, the exceeding data were removed; and finally, we compared the elapsed time between the beginning and end of the modified data with the official finishing time.

After this prefiltering process, we rescaled the distance information of each activity recording such that the total distance from (neutralized) start to finish equaled 44.6 km. For comparison, the corresponding measured distances before this rescaling averaged 44.4 (0.7) km, indicating decent distance measurements overall. To correct for uneven sampling of the different devices and obtain a coherent evaluation grid, we defined an even spacing of 4 m in distance. All other quantities were then evaluated on this new grid via linear interpolation between the points of the original one. Because some devices are known to incorrectly set the speed to 0 in the case of a low actual speed in combination with a poor satellite signal quality, we recalculated the speed for those cases by using the ratio of the increase of distance and elapsed time with respect to the last grid point. As another measure to enhance the data quality, the altitude information of the recorded activity without barometric altimeter was replaced with the average altitude information of the other 11 recordings.

To analyze the respective pacing evolution, we calculated the grade-adjusted speed v_i following Minetti and colleagues' parametrizations for walking and running.[24] Their parametrizations correspond to best-fitting polynomials of the measured metabolic energy cost as a function of the gradient. At a given grid point, the inclination (i) is determined from the change of altitude over the last 40 m of distance to average out small-scale fluctuations. The grade-adjusted speed, which is the inverse of GAP, for a nominal speed (v) was then calculated as shown by Equation (1) when running ($v_{i,r}$), and Equation (2) when walking ($v_{i,w}$).[24] They correspond to the parametrizations given in the original publication, with each rescaled such that $v_i = v$ for $i = 0$. The discrimination threshold between running and walking is set to a cadence of 120 steps per minute.[25]

$$v_{i,r} = v \cdot (155.4i^5 - 30.4i^4 - 43.3i^3 + 46.3i^2 + 19.5i + 3.6)/3.6, \quad (1)$$

$$v_{i,w} = v \cdot (280.5i^5 - 58.7i^4 - 76.8i^3 + 51.9i^2 + 19.6i + 2.5)/2.5, \quad (2)$$

Table 1 Sport Watches Used by the Athletes During the Competition

n	Brand	Model
3	Coros	Apex 2 Pro
1	Coros	Pace 2
1	Decathlon (by Coros)	GPS 900
2	Garmin	Fenix 6 (S)
2	Garmin	Fenix 7 (S)
1	Garmin	Forerunner 45*
1	Garmin	Forerunner 965
1	Suunto	9

Note: All except 1 athlete (*) wore models with integrated barometric altimeters, which typically provide more accurate altitude data.

Statistical Analysis

For the statistical analysis, the correlation between the overall race time relative to that of the corresponding winner ($\tilde{t}$) and the fitted gradient of v_i over the course of the race (μ) was examined; this gradient corresponds to the best-fit slope of a linear function over the distance d to v_i:

$$\frac{v_i}{\langle v_i \rangle} = \mu \cdot \frac{d}{d_{eval}} + \frac{v_{i,0}}{\langle v_i \rangle} v_{i,r}, \quad (3)$$

where d_{eval} denotes the distance over which the fit was conducted (Equation 3). The grade-adjusted speed was divided by its respective mean $\langle v_i \rangle$, and therefore the fitted slope μ by construction corresponds to the overall relative change of v_i over the fitted range.

To smooth out small-scale fluctuations, the v_i curve corresponds to a rolling average with a window size of 0.5 km. The null hypothesis tested was the absence of any correlation between these variables, with the alternative hypothesis positing a negative correlation. It should be noted that this choice assumes that overpacing, which is starting at a pace faster than the runner can sustain for the entire race, is far more common than underpacing, where the runner begins at a slower pace than their capability would allow. The scenarios were evaluated by comparing 2 groups of athletes, separated by their finishing times, via a Student *t* test. In additional, the linear correlation between the 2 variables for the whole sample via the Pearson correlation coefficient was tested. Confidence intervals are set at 95%. All data analysis was conducted in Python software (Python Software Foundation) using the package *SciPy*[26] with an alpha level of .05 for all statistical tests.

Results

As an example, Figure 1 shows the grade-adjusted speed (v_i) for one runner from our data set together with the altitude profile, both as a function of the covered race distance.

To assess and quantify the pacing evolution over the course of the race, we fit a linear function to the grade-adjusted speed values of each athlete. Because the last section (after $d_{\text{eval}} = 38$ km) corresponded to a long and highly technical downhill, we excluded it from the fit. The fit result of the example runner is also shown in Figure 1, exhibiting a relative change of v_i over the course of the race (μ) of −25% with respect to the mean over this part of the race.

Evolution of Grade-Adjusted Speed

The evolution of the grade-adjusted speed of all runners of our data set is shown in Figure 2, which contains both the average and root mean square of v_i relative to the respective mean. Similar to the exemplary case shown in Figure 1, the average trend for the whole sample exhibits a decline of v_i with increasing race distance where the average fitted changes from the start to the beginning of the last downhill segment amounts to $\bar{\mu} = -18.7\%$. For the 12 athletes, for one of them v_i actually increased over the considered range ($\mu = 4\%$), whereas for all others it decreased by at least 10%.

The results of the linear fits of the relative evolution of v_i for all athletes in our sample are drawn in Figure 3, scaled by $\tilde{t}$.

Correlation Analysis

The fitted evolution of v_i over the evaluated range (μ) is plotted in Figure 4 for all 12 athletes as a function of their achieved race time, relative to that of the respective winner ($\tilde{t}$). To evaluate if a more even pacing strategy correlates with a better finishing time, we analyzed the relation between both variables with 2 different methods. For the given sample, the Pearson correlation coefficient between $\tilde{t}$ and μ states a linear correlation of −.55. The probability of the null hypothesis (no underlying correlation) over the alternative one (negative intrinsic correlation) amounts to $P = .031$. For the second test, we divided the data into 2 classes. As shown in Figure 3, for 5 of the 12 athletes, $\tilde{t} < 1.05$, where there is a noticeable gap from the other 7 (with $\tilde{t} > 1.09$). By comparing the respective means and variances of μ via Student *t* test,[27] we test the compatibility of both classes. Student *t* test resulted in $t = 2.628$ (numerator degrees of freedom = 10, $P = .013$) for the null hypothesis compared with the alternative one that μ is greater for the subsample with $\tilde{t} < 1.05$ than for the one with $\tilde{t} > 1.05$. Both tests thus indicate that a more even pacing strategy correlated with a better race result at a confidence level of greater than 95%.

Discussion

The purpose of the current study was to assess pacing strategies in elite trail runners during the 2023 Trail World Championship. In

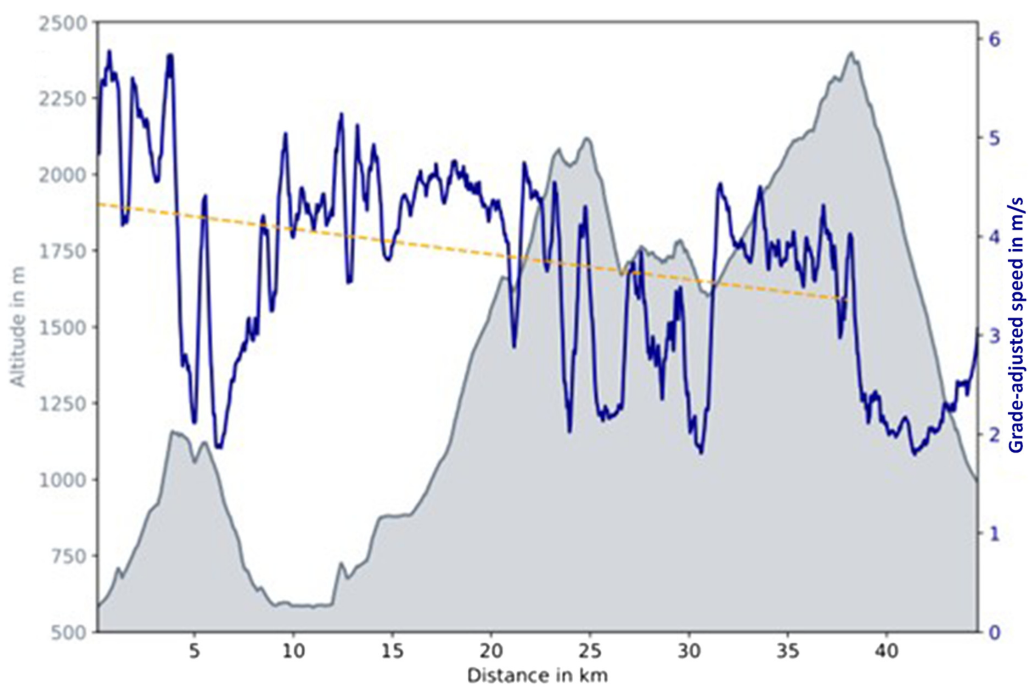

Figure 1 — Altitude profile and grade-adjusted speed (v_i) (rolling average with a window size of 0.5 km) as a function of distance for 1 exemplary athlete (male, height 182 cm, weight 72 kg). The diagonal dashed line corresponds to a linear fit of v_i, excluding the last downhill of the course.

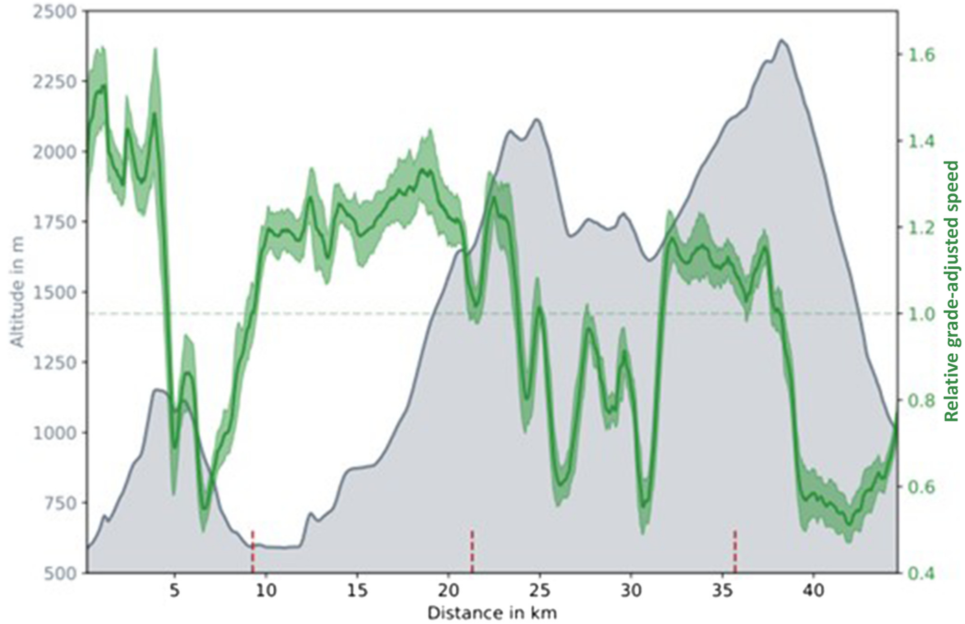

Figure 2 — Evolution of the grade-adjusted speed relative to the respective mean (dashed green line) for the whole sample of athletes, reduced to the average (solid green line) and root mean square (filled green area). In this case, a rolling-average window size of 1.0 km was used. The positions of the 3 aid stations along the race are indicated with short vertical dashed lines extending from the *x* axis. Given that the first aid station came after less than 10 km, apparently most athletes effectively skipped it. Compared with that, a considerable drop is visible at the second aid station, which was located roughly in the middle of the course and thus was important for refilling supplies. The third and last aid station came roughly 10 km before the finish, with only a slight fraction of the total elevation gain remaining. It thus appears reasonable that the average grade-adjusted speed plot only exhibits a smaller drop at its position. See online article for color version of the figure.

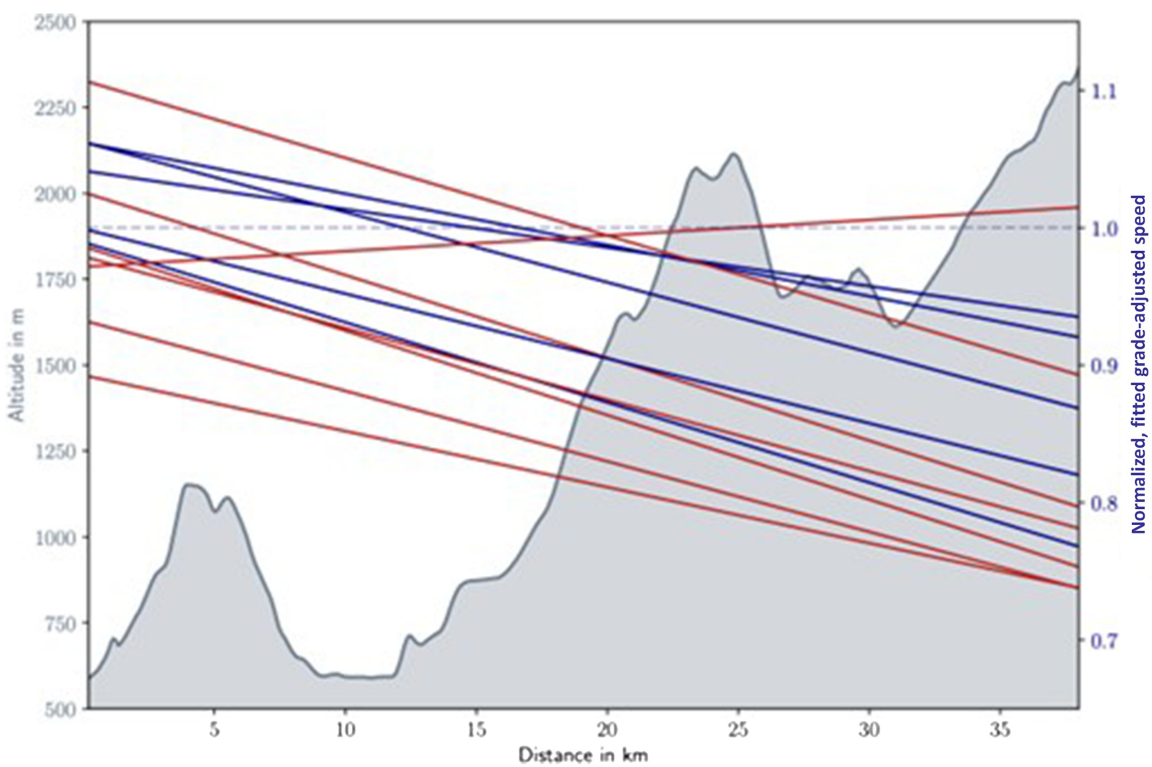

Figure 3 — Results of linear fits to the relative grade-adjusted speed evolution for all runners in our data sample, scaled by 1/(winning time) represented by the horizontal dashed line. Red and blue lines represent female and male athletes, respectively. See online article for color version of the figure.

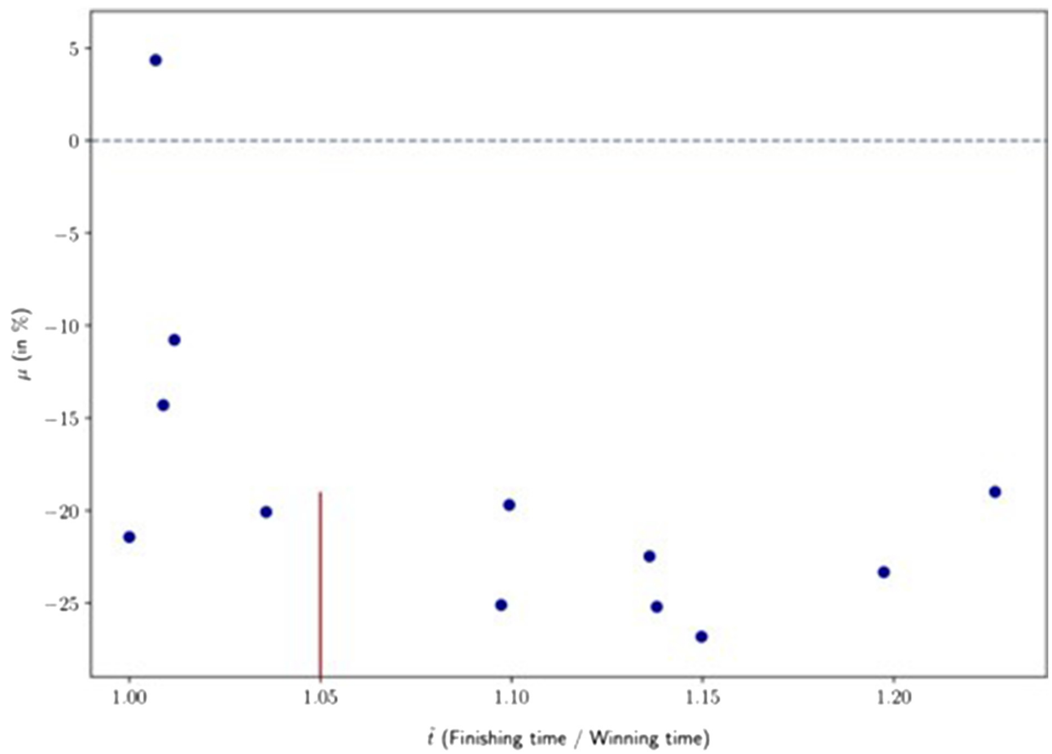

Figure 4 — Fitted change of grade-adjusted speed over the evaluated range (μ, see description in text) for all athletes of our sample, plotted as a function of the achieved race time relative to that of the winner in the respective gender group. The short vertical line extending from the *x* axis indicates the separation between our 2 sub-samples for the Student *t* test, and the dashed horizontal line stands for an even pacing strategy. μ represents the relative change of grade-adjusted speed, and $\tilde{t}$ stands for finishing time relative to the winning time.

line with results from earlier studies in longer competitions,[12–14] the main finding of the present study was that an even pacing strategy during the race correlates with a better race result in elite trail runners during a trail running world championship, therefore supporting our initial hypothesis. Downhill sections typically correlate with a lower grade-adjusted speed (Figures 1 and 2). This is partly because the underlying parametrization is given for even surfaces, not taking into account the unevenness of mountain paths that make up a large fraction of the racecourse. Being especially relevant when running downhill because of the higher overall speed, these technical sections thus have athletes slow down compared with easily runnable paths.

As shown in Figure 4, there is a noticeable correlation between better performance and a smaller decline in GAP during the race. In additional, the unique demands of trail marathon and ultramarathon running, such as eccentric contractions, muscle damage,[28] and tactical challenges, make it difficult to maintain an even pace throughout the competition as displayed in the dramatic variability in change in the grade-adjusted speed among the top 5 performers (Figure 4). Research on pacing strategies in trail running is limited and often not focused on elite runners during world championships. Despite the unique aspects of trail running, it is classified as an endurance sport. Consequently, similar findings regarding pacing behavior have been observed in other endurance sports among elite and high-level athletes. In marathons, high-level runners typically exhibit more consistent pacing compared with amateur runners.[29] Furthermore, data from over 30,000 marathon runners indicate that those who run the first part of the race close to or faster than their critical speed are more likely to slow down by more than 25% in the second half of the marathon.[30] This underscores the importance of pacing, particularly in the early stages of long-distance running events.

An analysis of marathon world records over recent decades suggests that negative pacing or maintaining a consistent pace throughout the race is the most effective strategy, regardless of the race distance.[7] In additional, in longer races, such as 6-hour ultramarathons, starting conservatively does not negatively impact performance. It has been observed in ultra-distance events that faster runners begin at lower relative intensities compared with slower runners in both 100 k[31] and 24-hour races.[32] This suggests that in flat running events, the fastest runners tend to maintain steady speeds with minimal fluctuations. However, this may differ in shorter races, such as 10 k events.[33,34] Nonetheless, an even pacing strategy appears to be superior for longer races and, as reported here, is a favorable approach for elite trail runners performing at a world championship level.

Although an even pacing strategy is generally associated with higher performance, only one of the 12 athletes managed to prevent a decline in GAP. Despite analyzing elite athletes, who are typically highly experienced and adept at optimizing their effort during races, most exhibited a positive pacing strategy. This indicates that, in terms of external intensity, maintaining an even effort in trail running is challenging. First, uphill locomotion demands higher metabolic and energetic expenditure.[35] Second, eccentric contractions, such as those required during downhill sections, are more likely to cause muscle damage.[36] Third, the altitude of the race may add additional stress and internal load to the athletes.[37] Moreover, managing pacing on trails is more challenging due to external factors such as weather conditions.[14] Finally, running too fast in the initial sections of the race, especially due to tactical reasons for elite athletes,[38] and if the section involves ascent,[20] can negatively affect optimal pacing management. In additional, recent research in cycling has shown that the impact of prior efforts on subsequent efforts, manifested as a decrease in power, is greater when these efforts exceed critical power, even if the overall work done is the same.[39] This suggests the importance of managing the initial moments or climbs in trail running races carefully to remain within optimal intensity domains, particularly in medium to long-duration races, such as marathons or ultramarathons, whereas the implications for shorter distances (ie, ≤3–4 h) remain unclear and should be addressed in future studies.

As reported here and in previous studies, a more even pacing strategy might be beneficial for both elite and lower-level trail runners aiming at improving their finish times in marathon trail races. Of note, the optimal pacing strategy varies depending on the goal, such as achieving a personal best time[34] versus competing against other athletes,[32,38] and even on the distance of the race.[33] In additional, individual strengths (ie, excelling in uphill sections) and weaknesses (ie, difficulties on technical terrain), endurance-specific demands (ie, durability), and personal preparation (ie, familiarity with the route or nutritional strategies) should be considered when interpreting the findings reported here. Furthermore, beyond physiological factors, other determinants such as psychological pressure and mental capacities,[40] an initial fast pace to avoid congestion on narrow paths, positioning within the leading group, and the influence of herd behavior[16] are crucial for achieving the best final position when competing with other trail runners. It has been demonstrated that competitors can significantly influence pacing management, particularly in shorter endurance competitions with mass starts involving elite athletes.[41] In such events, securing a good starting position is vital for overall performance. Figure 5 depicts likely scenarios depending on the pacing strategy adopted.

Although this study provides an evaluation of pacing strategies employed by elite trail runners during the 2023 Trail Running World Championship, several limitations must be considered. First, the analysis was based on data from only 12 athletes, though this sample did include a winner, top 5 finishers, and mid-rank male and female athletes. In additional, each runner used their own sport watch, which could potentially affect the comparability of the data given that the level of agreement between these sport watches is unknown. To address this, a rigorous data processing protocol was

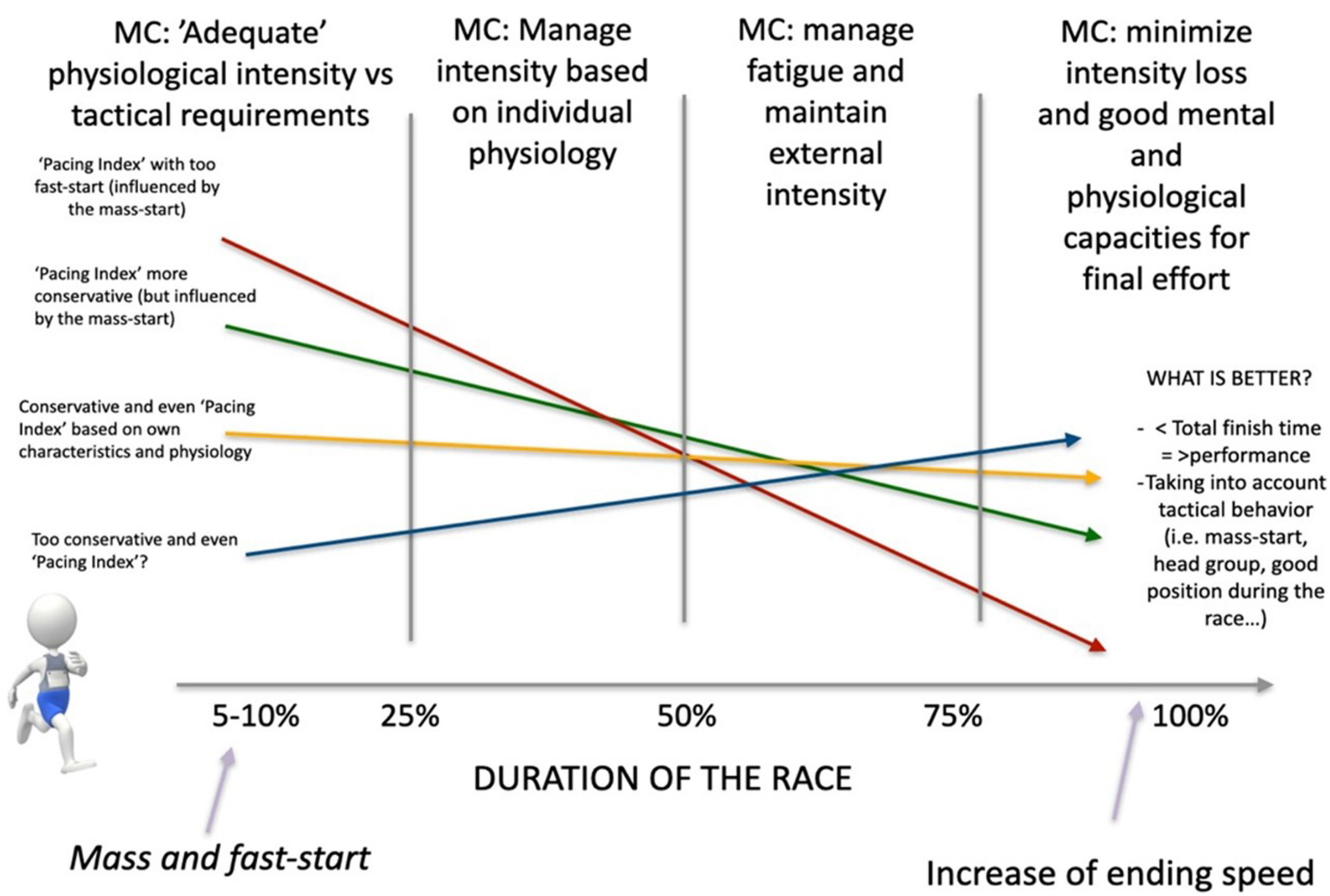

Figure 5 — Various pacing strategies and intensity management techniques are employed throughout a race. The race is divided into 4 segments, each highlighting potential behaviors or MC to address. The red line indicates an overly fast start with a significant decline in grade-adjusted pace as the race progresses. The green line represents a more conservative approach, but with a potentially excessive decrease in grade-adjusted pace. The yellow line illustrates a likely optimal pacing strategy, balancing tactical and physiological demands with individual characteristics. The blue line depicts negative pacing, which might be effective, though its success in achieving top classification in long trail races remains uncertain. MC indicates main challenge. See online article for color version of the figure.

implemented, as detailed in the "Methods" section, to ensure the reliability of the comparisons.

Practical Applications

That a consistent pacing strategy improves performance for elite trail runners has several practical applications. Coaches and athletes can use this to guide race strategies, emphasizing even pacing to avoid early fatigue and maintain steady effort throughout. Training programs can incorporate pacing drills, helping runners develop the discipline to stay within their optimal pace, even on varying terrains. Wearable technology and GPS devices can assist athletes in monitoring their pace in real-time during races. Consistent pacing may also improve fatigue management, reducing the risk of burnout mid-race, and postrace performance analysis can refine future pacing strategies for better outcomes.

Conclusions

The main finding of this study is that employing a consistent pacing strategy throughout a trail marathon race is associated with improved performance outcomes for elite trail runners during a trail running world championship. Despite the limitations described above, the study offers valuable insights into the pacing strategies of elite trail runners. The inclusion of a diverse range of athletes, from winners to mid-rankers, enhances the relevance of the findings across different elite performance levels. Moreover, the meticulous data processing approach strengthens the validity of the results, providing a solid foundation for future research in this area. Overall, this study contributes significantly to the understanding of elite trail running performance and paves the way for further exploration of optimal pacing strategies in competitive trail running.

Acknowledgments

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