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How fractal complexity distorts distance and elevation gain in trail and mountain running: The case for course measurement standardization

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Abstract

This study investigates how fractal complexity affects Trail and mountain running (TMR) race course measurements at varying GPS resolutions and emphasizes the need for standardized course measurement protocols. GPX files from 34 UTMB World Series race courses, including final events in Chamonix, were analyzed. Horizontal distance, elevation gain, km-effort, and fractal complexity were computed at varying GPS spatial resolutions (0.2–100 m). Elevation data were refined using a 20-cm resolution Digital Elevation Model (DEM) to ensure consistency across the dataset. The courses were systematically resampled and compared to assess the effects of spatial resolution on race measurements and classifications. The findings reveal that a decrease in GPS spatial resolution significantly reduces measured distances and elevation gains. Discrepancies in kilometer-effort reached up to 14% (mean = 7.0%, SD = 3.8%), horizontal distance up to 6.3% (mean = 2.9%, SD = 1.5%), and elevation gain up to 32% (mean = 14.0%, SD = 9.5%). Adopting a 1-m resolution, chosen for its practical balance between capturing terrain complexity at a human scale and computational efficiency, would enhance the reliability of distance, elevation gain, and km-effort calculations, ensuring fairer race classifications and improved comparability across events.

Keywords

Course measurement, trail running, mountain running, race classification, GPS accuracy

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Introduction

The rising popularity of Trail and Mountain Running (TMR), along with other running disciplines in natural terrain, such as sky, fell, ultra, or cross-country running, has inspired thousands to connect with natural environments, fostering efforts to further develop and organize the sport.

TMR courses, often set in diverse and rugged topographies, vary widely in distance, cumulative elevation gain, technical difficulty, and complexity. This variability introduces a unique challenge: the irregular and self-similar (fractal) structure of mountain geography impacts the accuracy of distance measurements, both horizontally and vertically.[1]

The fractal nature of geographic features is well-documented in scientific literature.[2,3] However, explicit studies quantifying fractal effects specifically in trail and mountain running contexts are currently lacking. A renowned study by Mandelbrot[4] demonstrated how attempts to measure the coastline of Great Britain yielded varying distances depending on the spatial resolution of the measurement. This concept applies to TMR courses, where intricate and repeating patterns in the terrain make distance and elevation measurements sensitive to the spatial resolution of course data, typically obtained from global positioning system (GPS) devices[5] or Geographical Information Systems (GIS).

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Even minor changes in resolution can result in substantial differences in reported distances and elevation gains, as reported by Skinner,[1] where the total distance of the Appalachian Trail decreases as the spatial resolution increases.

Two consecutive points on a TMR course, recorded with a spatial resolution of 10 m, imply that the athlete's trajectory between them is a straight line. However, the irregularity of natural terrain often makes this assumption inaccurate. If the segment were measured at a finer, human-scale resolution (e.g. 1 m), the recorded distance would increase, capturing the fractal complexity of the terrain.

In road running, established standards for measuring distance and altitude ensure consistency and comparability across events.[6,7] Tools like the Jones Counter, which measures distances by rolling a standardized wheel along the course, account for both horizontal and vertical displacement, providing accurate three-dimensional measurements for official races. While these mature and widely adopted methods ensure precision in road running, they cannot be used effectively in natural environments with irregular and uneven terrain.

In contrast, GPS devices commonly used in TMR calculate distance based on a two-dimensional model, treating the vertical components of rugged terrain as a separate measure, referred to as elevation gain. This distinction can lead to discrepancies between official distances recorded for road races and those measured by commercially available GPS devices, particularly on hilly courses.

Research indicates that GPS devices tend to overestimate road distances by 0.04%–0.28%.[8] While this level of accuracy aligns with the minimum uncertainty requirements set by World Athletics, GPS is recommended only for validation purposes in road race measurements rather than as a primary tool.[7] In natural terrain, the importance of GPS resolution becomes more pronounced for accurately measuring distances[5] and elevation gain.[9] Campbell et al.[10] observe that high-frequency GPS points may introduce noise, while low-frequency points fail to capture terrain-travel rate relationships. Rampinini et al.[11] further highlight the impact of sampling frequency on GPS accuracy, noting that only devices with a 10 Hz frequency provide sufficient precision for quantifying distances in team sports, particularly as accuracy diminishes with increased speed. Similarly, Gløersen et al.[12] demonstrate that speed influences positional deviations in ski data, with higher sampling frequencies improving accuracy.

To enhance data quality and accuracy, some studies have implemented latitude-longitude corrections to improve distance estimation in pedestrian locomotion.[10] Others have explored the use of Digital Elevation Models (DEM) for obtaining and inputting elevation data.[13–15] However, in TMR, there is currently no consensus on best practices for measuring either distance or elevation gain.

Derived from Naismith's Rule,[16] the kilometer-effort formula—widely adopted by the International Trail Running Association (ITRA)—adds 1 km of effort (km-effort) for every 100 m of elevation gain to approximate the physical demands of a course. Using this metric, ITRA classifies races into standardized categories, such as S for Short (45–74 km-effort), M for Medium (75–114 km-effort), L for Long (115–154 km-effort), XL for Extra Long (155–209 km-effort), and XXL for Ultra Long (210 km-effort or more). To refine these estimations, more advanced hiking formulas have been proposed, incorporating factors like elevation loss, a nonlinear relationship between slope and speed, or the impact of altitude on route difficulty.[13,17–19] Nevertheless, these methods rely heavily on the consistent and accurate measurement of both distance and elevation gain.

Given this context, the aim of this paper is to assess how spatial resolution influences the measurement and classification of trail and mountain running courses, with a focus on its implications for distance, elevation gain, and race categorization.

The specific objectives are:

1. To characterize the current variation in spatial resolution, distance, and elevation gain across UTMB World Circuit, one of the major global TMR event series.
2. To examine how race distances, elevation gains, and kilometer-effort values change across a wide range of spatial resolutions, comparing these to values derived using a human-scale 1-m spatial resolution standard.
3. To assess the impact of adopting a 1-m spatial resolution standard on race classification systems, particularly concerning ITRA's race categories.

This paper addresses a critical gap in the literature regarding the standardization of spatial resolution for TMR course measurement by exploring how fractal complexity impacts TMR course measurements. To our knowledge, this study is the first to explore TMR course measurements using this approach. The absence of consistent standards complicates event comparison and course classification, limiting the sport's formal development. A standardized framework would enable fair comparisons and provide sports scientists with reliable tools to study athletes in real-world environments, enhancing our understanding of athletes' performance.

Methods

Assessing variation in spatial resolution across the UTMB circuit

The dataset consists of GPX files published online by races within the Ultra-Trail du Mont-Blanc (UTMB) World circuit,[20] which is the most established trail and mountain running series worldwide. For each race event, the longest available distance was selected, resulting in a total of 34 GPX files from different UTMB circuit races available as of November 2024. All distances from the final event, which start and/or finish in Chamonix, France (TDS, CCC, UTMB, OCC, and MCC) were also included.

The GPX files analyzed in this study were collected from publicly available sources provided by race organizers. Importantly, these files were recorded under diverse conditions, including different GPS devices, varying sampling intervals, and non-uniform data collection protocols. This variability reflects the current absence of standardization in TMR course measurement practices, an issue explicitly addressed and quantified in this research.

For each GPX file, the distance between two consecutive points was calculated using the cosine-haversine formula,[21] which provides the horizontal distance without accounting for vertical displacement. For simplicity, we will refer to horizontal displacement as distance. Vertical displacement between consecutive points was calculated separately, which can result in elevation gain or elevation loss.

To characterize each TMR course, a range of spatial and statistical metrics was computed. Total distance, cumulative elevation gain, and cumulative elevation loss were calculated for the entire course. Spatial resolution was defined as the average horizontal distance between consecutive GPS points, while kilometer-effort was determined using Naismith's formula, incorporating both distance and elevation gain. Data quality was assessed by calculating the percentage of measurements with no horizontal displacement between consecutive points (% idle time), and elevation changes during these idle periods were examined to identify spurious gains caused by sensor errors or recalibration. The geometric complexity of each course was quantified using fractal analysis via the periodogram estimator. Lastly, descriptive statistics—including global means, standard deviations, quartiles, and medians—were reported for all variables to summarize overall trends and variability across courses.

Comparing kilometer-effort, distance, and elevation gain across spatial resolutions

To compare courses at different spatial resolutions, we first resampled all GPX files to the highest resolution of 0.2 m using linear interpolation. Linear interpolation was chosen primarily due to its simplicity, ease of implementation, computational efficiency, and to avoid introducing additional assumptions or biases associated with more complex model-based interpolation methods. Alternative interpolation techniques were not explored, as the primary objective of this study was to examine the general effect of varying spatial resolutions rather than comparing interpolation methods. Once all courses were resampled to a 0.2-m resolution, they were systematically down-sampled to resolutions ranging from 0.2 to 100 m, resulting in 500 versions of each course across the resolution spectrum.

To minimize inconsistencies in elevation data, elevation values for each course at each resolution were derived from a Digital Elevation Model (DEM), following the methodology outlined in previous studies.[14,22] The DEM used in this study was sourced from the Shuttle Radar Topography Mission (SRTM),[23] which is globally available and offered at multiple spatial resolutions. To obtain a 20-cm resolution DEM, bilinear interpolation was applied to downscale the SRTM data, as this resolution has been shown to reduce elevation gain measurement errors.[15] For each course and resolution, we then computed horizontal distance, elevation gain, elevation loss, km-effort, and fractal complexity using the criteria explained in the previous section.

To explore the impact of course resolution on km-effort, distance, and elevation gain, we performed a graphical analysis. This analysis contrasts, for each course, the relationship between course spatial resolution and km-effort, distance, and elevation gain, each measure presented in separate subplots. Rather than displaying total km-effort (or distance or elevation gain), the graphical analysis shows the relative measure compared to the 1-m standard. At each resolution, the relative measure then reflects the proportion of the 1-m standard captured at that resolution. To make the results more accessible, only the five races from the final UTMB event, which start and/or finish in Chamonix, France, will be highlighted in the charts for improved readability and clarity.

Evaluating the impact of 1-m spatial resolution on ITRA's race categorization system

To evaluate the effect of 1-m spatial resolution on ITRA's race categorization system, each course's km-effort scores and classification, calculated using both raw course data and the 1-m standard, were compared through graphical analysis.

Results

Variation in spatial resolution across the UTMB circuit

Table 1 presents descriptive statistics for the 34 UTMB circuit courses included in this study, providing the mean, standard deviation, minimum, first quartile ($q1$), median ($q2$), third quartile ($q3$), and maximum values for the following variables: distance, elevation gain, elevation loss, km-effort, course resolution, fractal complexity, idle time, elevation gain during idle time, and elevation loss during idle time.

The average course resolution is 14.9 m, with the variability across events ranging from 1.9 to 39.7 m. As a result, the fractal complexity, which measures

Table 1. Descriptive statistics for all 34 GPX files, including mean, standard deviation (±); minimum, first quartile ($q1$), median ($q2$), third quartile ($q3$), maximum) values for distance, elevation gain, elevation loss, km-effort, course resolution, fractal complexity, idle time, elevation gain during idle time, and elevation loss during idle time.

Variable	Descriptive statistics
Distance (km)	129 ± 45 [38, 100, 123, 161, 258]
Elevation gain (m)	6879 ± 2883 [2436, 5058, 6312, 8692, 15,652]
Elevation loss (m)	6981 ± 2972 [1894, 5041, 6667, 9236, 15,655]
Km-effort	198 ± 69 [62, 158, 184, 237, 414]
GPS resolution (m)	14.9 ± 9.4 [1.9, 8.2, 14.2, 21.1, 39.7]
Fractal complexity	1.18 ± 0.13 [0.68, 1.15, 1.19, 1.24, 1.38]
Idle time (%)	2.3 ± 4.91 [0, 0.02, 0.16, 2.49, 24.85]
Elevation gain during idle time (m)	32 ± 122 [0, 0, 0, 1, 688]
Elevation loss during idle time (m)	-5 ± 13 [-66, -1, 0, 0, 0]

geometric complexity, has a mean value of 1.18, with a range between 0.68 and 1.38. Most races exceed 100 km in distance, with an average race distance of 129 km. Elevation gain and loss are approximately symmetric, with average values around 6900 m, as indicated by the similar distributions across all quantiles.

In terms of data quality and course measuring protocols, 25% of the courses show that the average time spent stationary (idle time), when the person measuring the track was not moving, exceeds 2.5%, with one extreme case reaching 24%. During these idle periods, elevation gain is typically minimal, with the third quartile ($q3$) value being just 1 m. However, an extreme case recorded 688 m of elevation gain during GPS inactivity, likely due to measurement pauses and sensor recalibration, underscoring the potential for inaccuracies in such conditions.

Differences in kilometer-effort, distance, and elevation gain across spatial resolutions

Figure 1 shows the first 5 km of the UTMB 170-km course in Chamonix, France, the main event of the circuit. In this example, the horizontal frequency of GPS measurements was resampled to various resolution values, using the minimum, first quartile ($q1$), median ($q2$), third quartile ($q3$), and maximum values observed in the previous section, rounded to the nearest meter, as well as a 1-m standard. As a result, the measured distance decreased from 4998 m, when using the 1-m standard, to 4867 m, representing a shortening of the measured running distance by 2.62%. Additionally, as resolution decreased, both the distance and the number of vertices decreased, and the fractal complexity, which reflects the geometrical complexity of the course, was also reduced. This pattern aligns with the changes in resolution observed in the descriptive statistics.

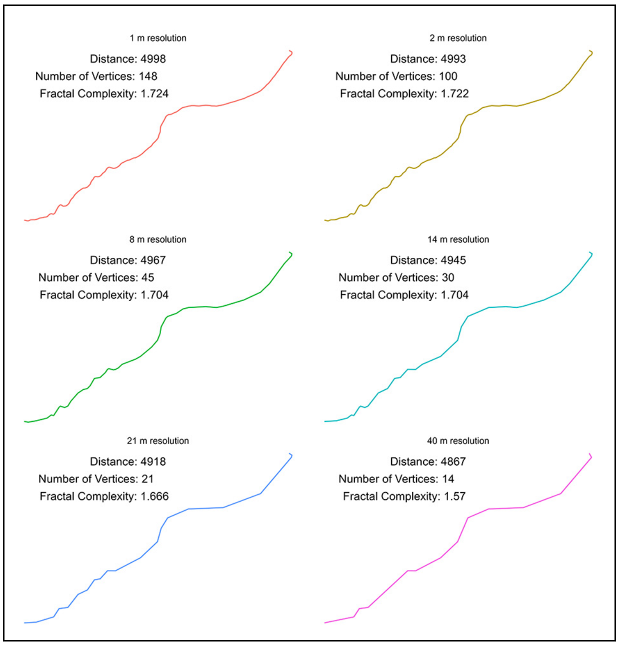

Figure 1. Stylized map illustrating the first 5 km of the UTMB final event in Chamonix, France, used here as a representative example of an alpine trail running course. The figure shows how total course length progressively decreases as the spatial resolution of the course data becomes coarser. This example illustrates the expected impact of spatial resolution on distance estimation and serves as a practical reference for other races held in similar mountain terrains.

Figure 2 shows three panels illustrating the relationship between horizontal resolution and km-effort, distance, and elevation gain for all 34 courses in the UTMB World circuit, across a range of resolutions from 0.2 to 100 m. The continuous lines represent the computed values obtained by systematically resampling each course across this resolution spectrum. The dots correspond to the original resolution values extracted from the GPX files provided by the race organizers, serving as a reference for the resolutions typically used in practice. Down-sampling these courses leads to significant reductions in km-effort, distance, and elevation gain across all races. The most notable loss occurs in elevation gain, with certain courses losing up to 30% compared to a standard model with 1-m resolution. The reduction in elevation gain ranges from 5% to 20% across most races. Reductions in measured

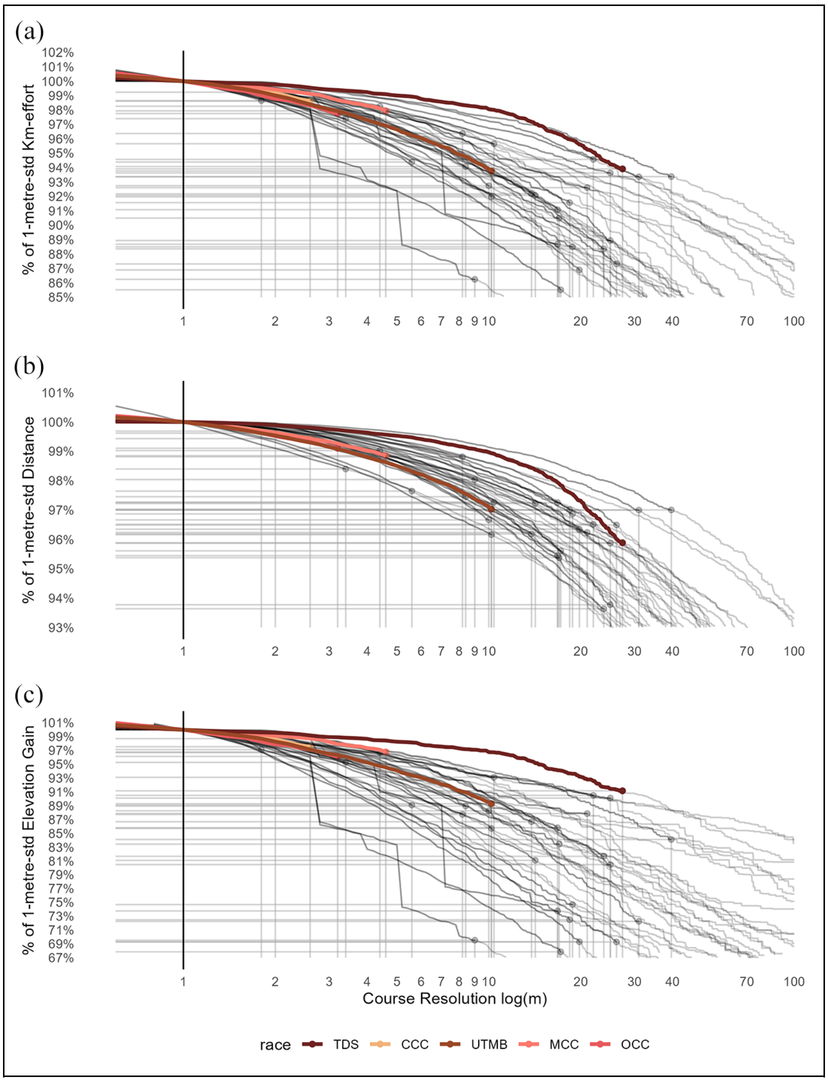

Figure 2. Relationship between course resolution and (a) km-effort, (b) distance, and (c) elevation gain, expressed as percentages relative to the 1-m standard. Continuous lines represent the values obtained by systematically resampling all 34 courses across the resolution spectrum (0.2 to 100 m). Dots indicate the original resolution values extracted from the GPX files published by race organizers. A vertical black line at 1-m resolution marks the recommended standard, where all curves intersect the 100% reference. Races from the main UTMB final event are labeled and highlighted in color, while the rest of the UTMB World Series races are shown in grey.

horizontal distance are less dramatic than those in elevation gain but still significant. Races like TDS and UTMB show reductions of 3%–4%, while other courses can lose up to 6.5% of their length. Most of the courses presented here experience a reduction in km-effort of more than 5% when compared to the standard 1-m measurement. When the resolution is below 1-m km-effort, distance and elevation gain continue to increase, but the growth rate is much slower than above 1 m.

Impact of 1-m spatial resolution on ITRA's race categorization system

Figure 3 compares race classification and km-effort across all races using two protocols: raw original data and data processed at a 1-m resolution. The results demonstrate the impact of resolution standardization on race categorization. While most races remain in their original categories, some shift to a different category when recalculated at the 1-m standard, emphasizing the significance of standardization. None of the five UTMB final event races—highlighted in this figure and the previous one—change categories, though subtle variations in their km-effort are evident. Races measured at higher resolutions typically show minimal changes in km-effort, indicated by horizontal lines between the protocols.

Discussion

The findings of this study reveal the profound impact of spatial resolution on the accuracy of trail and mountain running (TMR) course measurements, carrying significant implications for the sport's ranking systems, race classification systems, performance comparisons, and overall development. By addressing the influence of resolution on key metrics such as distance, elevation gain, and km-effort, this study provides a critical foundation for standardizing measurement practices in events held on natural terrain courses.

The variability inherent in natural terrains, characterized by fractal complexity, exacerbates the challenges of accurate measurement. Coarse GPS resolutions, such as the average 14.9 m observed in this study, fail to capture the human-scale details of rugged terrains, leading to significant underestimations of both distance and elevation gain. These inaccuracies, in turn, distort km-effort values, which are crucial for race classification and athlete benchmarking. For example, races measured at coarser resolutions experienced reductions in km-effort exceeding 5%, with some courses losing up to 30% of their elevation gain. Such discrepancies highlight the limitations of current measurement practices and the urgent need for a standardized approach.

Our results indicate that GPS measurements significantly underestimate distance and elevation gain at coarse resolutions in TMR events. Interestingly, previous studies have shown that GPS typically slightly overestimates distances in road running.[8] This apparent contradiction arises not from fundamental differences between road and trail running environments but from different underlying GPS error mechanisms. Positional inaccuracies cause recorded GPS points to scatter randomly around the true trajectory, artificially lengthening the measured distance. Conversely, the substantial underestimation observed in this study occurs due to excessively coarse spatial resolutions, where large gaps between recorded GPS points oversimplify and thus shorten the actual complex paths on fractal terrains. Similarly, elevation measurements at coarse resolutions fail to capture detailed terrain variations, resulting in significant underestimations of cumulative elevation gain.

The adoption of a 1-m spatial resolution as a standard emerges as a practical solution.[5] This resolution aligns with the level of detail required to represent natural terrain courses at a human scale accurately, mitigating distortions introduced by the fractal nature of the landscape. Resampling data to this resolution enhances the precision of key metrics and ensures consistency across events, enabling meaningful comparisons between races and athlete performances. For example, recalculating km-effort at a 1-m resolution revealed shifts in race rankings and classifications, illustrating how inconsistencies in measurement practices can distort the perceived difficulty of events and affect competitive benchmarks. Achieving a uniform spatial resolution directly from GPS devices, however, is not straightforward, as GPS data are typically recorded at fixed time intervals rather than at fixed distances. Therefore, obtaining a consistent spatial resolution requires algorithmic resampling. Because course data are already post-processed by organizers to produce official maps, elevation profiles, and course descriptions, integrating a standardized resampling step, such as adopting a 1-m resolution, is technically feasible and does not require additional field measurements or hardware modifications.

For race organizers, these results highlight the necessity of collecting and using racecourse data at a minimum spatial resolution of 1 m. Given that measurement precision significantly affects the estimated distance, elevation gain, and km-effort, these discrepancies can impact race classifications (e.g. ITRA scores) and, consequently, athlete rankings and public perceptions. For a race to be perceived as professional and trustworthy, it is essential to measure and calculate course distances according to standardized requirements, to be consolidated and enforced by a regulatory body. Superficial aspects such as media coverage, scenic settings, or

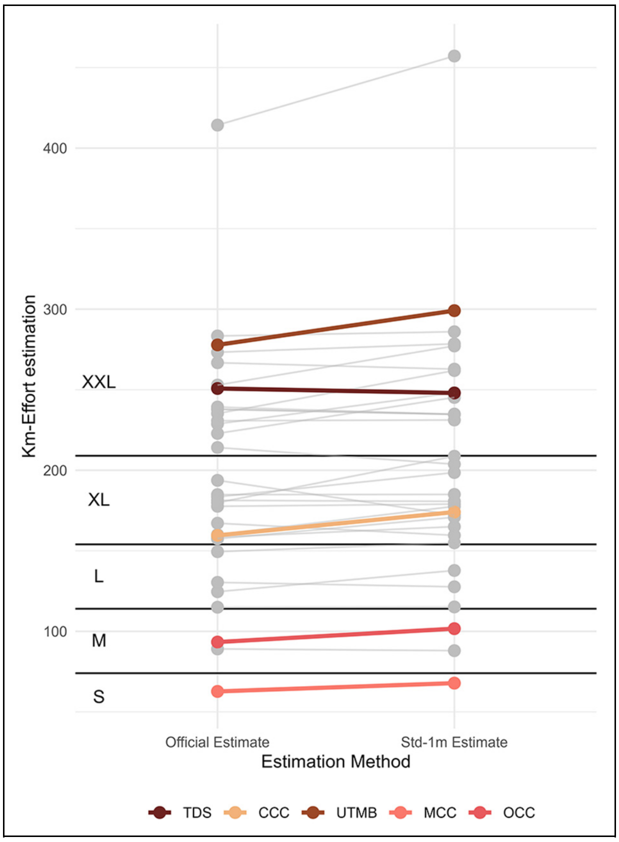

Figure 3. Comparison of km-effort scores between the original course data and standardized 1-m resolution data, highlighting shifts in race classifications. The horizontal lines represent the thresholds for category changes, based on km-effort. Races of the main UTMB event are labeled and highlighted in color, while other races in the UTMB World Series are depicted as grey lines.

advertising are irrelevant if course measurement standards are not respected.

For athletes, standardized measurements enable accurate evaluation of their performance, directly affecting training, racing strategies, and career development. Measurement inconsistencies complicate fair comparisons between international events, particularly when different subsets of athletes compete across diverse races and continents. These discrepancies make it challenging to calibrate performance indices such as ITRA or UTMB scores, ultimately affecting athletes' visibility, rankings, and even sponsorship negotiations. Establishing standardized measurement protocols would provide athletes with reliable data to support performance analysis and professional progression.

Regulatory bodies can leverage these results to develop and implement a formal measurement standard for TMR events. While this study proposes a 1-m spatial resolution as a practical and technically feasible option, regulatory entities could apply the methodology presented here to larger datasets, refining or confirming the proposed standard. Ultimately, the adoption of a formalized, science-based protocol would enhance accuracy, consistency, and fairness across events.

For elite runners, where performances are often separated by narrow margins, the measurement errors associated with inconsistent resolutions could influence rankings and performance indices such as the ITRA index. For instance, the performances of the first and fifth runners at UTMB 2024 lie less than 5% apart in terms of time.[20] If km-effort translates linearly into time spent running, this 5% difference means that when comparing efforts performed on two courses with theoretically equal distances but different GPS measurement intervals, the performance difference between these athletes could potentially lie within the margin of error introduced by disparate measurement standards. This issue becomes particularly relevant when comparing performance indices across different races, landscapes, and even different editions of the same race, especially as TMR events often feature minor course modifications every year.

Unexpected findings, such as elevation gain discrepancies during idle time, further illuminate the inconsistencies in current GPX data recording protocols. Several plausible causes may explain these discrepancies, including barometric altimeter recalibration during stationary periods driven by atmospheric pressure changes, sensor drift, temporary signal interference or loss, and changes in satellite geometry during idle periods, which may result in spurious elevation variations once the signal is reacquired. These variations highlight the need for standardized criteria in GPX files to ensure data cleanliness and reliability. Additionally, while some courses exhibited minimal changes when recalculated at a 1-m resolution, others showed substantial shifts, pointing to the influence of both terrain complexity and device accuracy on measurement outcomes.

Elevation-gain variability is a multifactorial problem in trail and mountain running. It is influenced by the fractal nature of terrain, the spatial resolution of the recorded track, the point precision of the GPS device, and the specific method used to compute cumulative elevation gain. In this study, we focused exclusively on the role of spatial resolution, demonstrating how coarse resolution underestimates elevation gain by oversimplifying the terrain. However, other factors — including GPS point dispersion, driven by device accuracy, and the algorithm used to estimate elevation gain — also contribute significantly to the variability of this metric, as extensively studied in previous works.[14,15,22] While this broader discussion is beyond the scope of the present work, our findings highlight the critical role of adopting an adequate spatial resolution to mitigate one of the key sources of variability. In any scenario involving elevation gain analysis, addressing the fractal complexity through appropriate spatial resolution is an indispensable step.

Despite its contributions, this study has several limitations. First, our analysis relied on publicly available GPX files recorded under diverse conditions, including differences in GPS devices, sampling frequencies, and data collection protocols, which introduced inherent variability in data quality. While rigorous interpolation methods were applied to standardize spatial resolutions, these cannot fully replicate the accuracy achievable with real-time, high-resolution GPS measurements. Nevertheless, this variability highlights the central issue our study addresses: the critical need for standardized GPS measurement methods in trail and mountain running. Additionally, although our focus on UTMB races provides valuable insights into measurement variability within a prominent global event, it may limit the generalizability of our findings to other contexts. Future research should therefore include a broader variety of events, diverse terrain types, and field-based validations to further enhance GPS and elevation measurement methodologies. Athlete-specific factors, such as stride variability, running style, or movement irregularities on technical terrain, may also influence GPS positional accuracy. Although not directly addressed in this study, these factors represent an additional source of variability that should be considered in future research.

Although technically feasible, the widespread implementation of a 1-m resolution standard requires consensus among organizers, federations, and certifying bodies. The main challenge is organizational rather than technological. Following the example of road running, the discipline would benefit from the establishment of an independent validation body and the adoption of transparent certification protocols. Once in place, such a framework would ensure consistent and fair course measurements without necessitating changes to existing GPS devices or consumer technologies.

The implications of this study extend beyond trail and mountain running. The standardization of distance and elevation gain measurements is equally applicable to other locomotion sports, such as cycling, hiking, skiing, and rowing, among others.[24] These disciplines encounter similar challenges related to GPS variability, barometric recalibration, and the lack of standardized measurement protocols. Implementing approaches like those proposed in this study could significantly improve measurement accuracy and ensure comparability across events in a wide range of sports.

Future research should investigate how fractal complexity affects measurement accuracy across a broader range of TMR terrains. While this study focused on mountainous courses, other environments such as rolling hills, coastal paths, or forest tracks may exhibit lower fractal complexity and different sensitivity to spatial resolution. Understanding these terrain-specific patterns could help develop flexible measurement standards tailored to diverse race contexts. Future work should also assess the practical implementation of the 1-m resolution, including feasibility, computational demands, and the influence of athlete-specific factors on GPS accuracy.

Conclusion

The adoption of a 1-m resolution standard for measuring distance and elevation gain in trail and mountain running would significantly improve the reliability and accuracy of course measurements, enabling consistent race classification and facilitating scientific research on athlete performance in natural environments. These advances are crucial for the formal development of trail and mountain running as a globally recognized sport, supported by robust benchmarks and reliable metrics. Notably, elevation gain is particularly prone to measurement errors due to the inherently lower vertical accuracy of GPS devices, the variability introduced by different elevation estimation methods (e.g. barometric vs GPS-based), and the absence of standardized data processing protocols. This variability makes the standardization of elevation measurement especially critical for achieving reliable and comparable course classifications.

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