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Assessing the impact of Digital Elevation Model resolution on Elevation Gain Estimations in Trail Running

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***Abstract*— This study addresses the challenge of accurately estimating Elevation Gain (EG) in trail running using GPS devices, where resolution of Digital Elevation Models (DEMs) plays a critical role. We propose an algorithmic enhancement to increase the resolution of a 4m DEM to 20cm, aligning it closely with high-resolution LiDAR models. Quantitative analyses reveal that this method significantly improves EG estimations, demonstrating a considerable reduction in error margins compared to conventional EG estimation using raw GPS. Specifically, our findings indicate that the bilinearly interpolated DEM achieves near-LiDAR accuracy at 20cm resolution, with error rates markedly decreasing at this scale. This study underscores the potential of using enhanced-resolution DEMs as a cost-effective alternative to LiDAR, particularly in applications like trail running where precise elevation data is crucial. Our approach not only offers a substantial improvement in the accuracy of physical workload assessments but also enhances the accessibility of high-quality elevation data for broader geographical and environmental applications.**

***Keywords*— DEM, LiDAR, GPS Watches, Sports Technology, Trail Running**

I. Introduction

A key aspect of trail running are the elevation changes encountered, which accumulate over the course of a trail, resulting in Elevation Gain (EG) and Loss, depending on the terrain's slope [1]. Accurately quantifying EG is essential because it significantly affects the assessment of physical workload and performance in these activities [2, 3, 4].

The fractal nature of the geographical space makes measuring elevation and EG inherently challenging. While elevation errors might be minor at single points, when aggregating elevation changes over the course of a trail run, these errors can accumulate leading to significant discrepancies in the total EG [5].

Some studies have investigated the accuracy of sports watches in measuring EG in different conditions, such as flat paths [6], or mountain regions [7], and even on other endurance sports like cycling [8]. They all consistently found discrepancies in EG obtained from wearable raw elevation measurements. It has been suggested that some post processing algorithms may improve the EG calculation, such as smoothing and filtering the elevation signals [7].

Elevation gain can be obtained from a wearable device using different techniques, such as measuring elevation using a barometric altimeter or GPS or measuring position using GPS and extracting elevation for that coordinate from a Digital Elevation Model (DEM). All these methods have limitations. Their effectiveness can be influenced by factors such as sensor resolution, signal reliability, atmospheric factors, sensor placement, and DEM resolution [6].

The accuracy of EG measurements via GPS can be influenced by some controllable factors, such as their placement on the body. Studies have shown that devices positioned on the hip yield more accurate readings than those worn on the wrist, particularly during faster activities like jogging or running [9]. Additionally, the configuration of device settings, such as update frequency, plays a crucial role in the accuracy of measurements [10], suggesting that both placement and device settings are key factors in obtaining reliable EG information [7].

Related Work

Using DEM values to assess EG have been proposed as a method for obtaining consistent measures of EG, because elevation values for any given coordinate are always the same [7]. Some studies have found that GPS devices underestimated EG whereas DEM correction led to overestimation, yet still making a significant improvement over uncorrected GPS data [1]. Although these studies tested different DEM resolutions in EG estimations, these resolutions were coarse, with a minimum pixel size of 4 meters.

For applications such as trail running, where accurate EG measurement is critical, it is desirable to obtain high-definition DEM sources, such as obtained from light detection and ranging (LiDAR), or other equivalent techniques. High-resolution DEMs can also be generated through algorithms that enhance the resolution of existing data. Some techniques like Box car smoothing, Discrete Cosine Transform, Singular Value Decomposition, or simpler methods like bilinear or nearest-neighbour have been employed to refine DEM's. As they perform simple forms of interpolation, they increase the resolution without adding new terrain information [11, 12]. These methods have been tested on publicly available DEMs, but have never been contrasted to LiDAR derived DEMs, and haven't been used for EG estimation.

The ubiquity of GPS watches has opened the door to studying trail running in real-world settings [3]. The rich datasets obtained from wearables devices enables the refinement of statistical models, thereby enhancing the accuracy of predictions. This advancement highlights the potential of utilizing extensive GPS data to improve our understanding and analysis of sports performance, particularly in trail running.

Despite the widespread availability of wearable devices and DEMs, the precision of these methods for measuring EG in trail running remains under scrutiny. Given these challenges, this study specifically focuses on assessing the impact of DEM resolution on the accuracy of EG estimations in trail running activities, as recorded by GPS watches. We aim to delineate how different resolutions of DEMs influence the precision of EG calculations and determine which resolution provides the most reliable data for athletes, coaches, and race organizers in the context of trail running. This determination will significantly contribute to improving the consistency of EG estimations, which is crucial for the effective monitoring and optimization of training and performance in trail running and other mountain sports.

II. Methods

A. Study Area and DEM acquisition

This research was conducted on Cerro Calan, a favoured destination for trail running located in Santiago, Chile. Selected for its convenience and the availability of high-quality elevation data, Cerro Calan serves as an appropriate site for analysing EG estimation in trail running. The study utilized two distinct DEMs of the area: a detailed LiDAR DEM with a 20cm resolution, provided by Fundacion Cerros Isla (Santiago, Chile, 2020), and an openly available DEM from AWS terrain tiles (generated by MapZen) with a 4m resolution [13].

B. DEM resolution manipulation

The LiDAR DEM underwent a systematic aggregation process, where its resolution was sequentially doubled from its raw resolution of 20cm up to 5120cm, generating nine different resolutions. This process utilized the mean criteria for aggregation, averaging the values of pixels to form a pixel of twice the resolution of the original.

Concurrently, the AWS DEM, with a raw resolution of 4 meters, was resampled to match the same resolutions obtained from the LiDAR aggregation process. This process was achieved by employing two different interpolation approaches: bilinear interpolation and nearest-neighbour interpolation. The first model assumes that the behaviour of the terrain is linear in both latitude and longitude, generating new points between original pixels using this criterion, while the second model assumes that each new pixel's value is that of the nearest original pixel, thereby preserving the values of the original data points without averaging or creating transitional values.

This process resulted in three comprehensive sets of processed DEMs, each offering varied resolution levels for subsequent analysis.

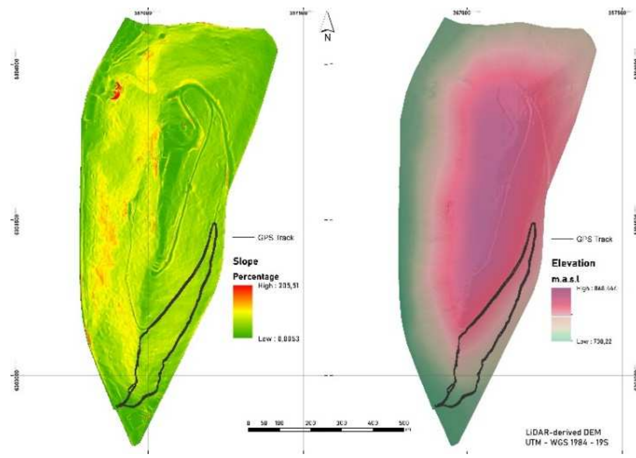

Fig. 1. Topographic visualization of Cerro Calan utilizing high-resolution LiDAR-derived DEM, illustrating the GPS track from the trail running data collection.

C. GPS activities recording

One participant ran six laps on a predefined circuit with a consistent 75m of EG, allowing for direct comparison of DEM resolution impacts on EG estimation. Three Garmin GPS watches were used: the Fenix 5s and Forerunner 745, both with barometric altimeters, and the Forerunner 225, which uses GPS for elevation data. These devices recorded latitude, longitude, and elevation data to provide a comprehensive dataset for analysing the influence of DEM resolution on EG accuracy.

The recorded GPS elevation data was systematically replaced with elevation values extracted from each of the aforementioned DEM. This substitution was conducted for every resolution level of all DEM sets. For each DEM and resolution, the EG for each lap was calculated.

D. EG Error Calculation and Statistical Analysis

After computing EG, the EG error for each lap was calculated. The reference value for EG was 75m and was established through a consensus analysis of the elevation data recorded by the GPS devices. By taking the median values of the maximum and minimum elevations for each segment and considering that the segments are exclusively uphill, reference EG was computed as the difference between the median maximum and minimum elevations. The EG error calculation was performed for the elevation data obtained from each DEM at various resolutions, as well as for the raw elevation data recorded by the GPS devices.

To statistically analyse the differences in EG errors, a Wilcoxon signed-rank test was employed, comparing the elevation data from each DEM at various resolutions to three benchmarks: raw AWS DEM, raw LiDAR DEM, and raw GPS data. This non-parametric test was chosen to compare the median EG errors between the two sets of data without assuming a distribution, providing a robust method to determine if the errors from the DEM-corrected data significantly differ from those of the benchmark.

III. Results

The gathered data is displayed in Figure 1, where topographical visualization of Cerro Calan is presented, utilizing the high-resolution LiDAR-derived DEM. The map illustrates the varied terrain of the study area with a color-coded slope gradient. The solid line delineating the GPS track indicates the running path during the data collection phase. The start and end points of the track show that the loop begins and concludes in the lower elevation region of Cerro Calan.

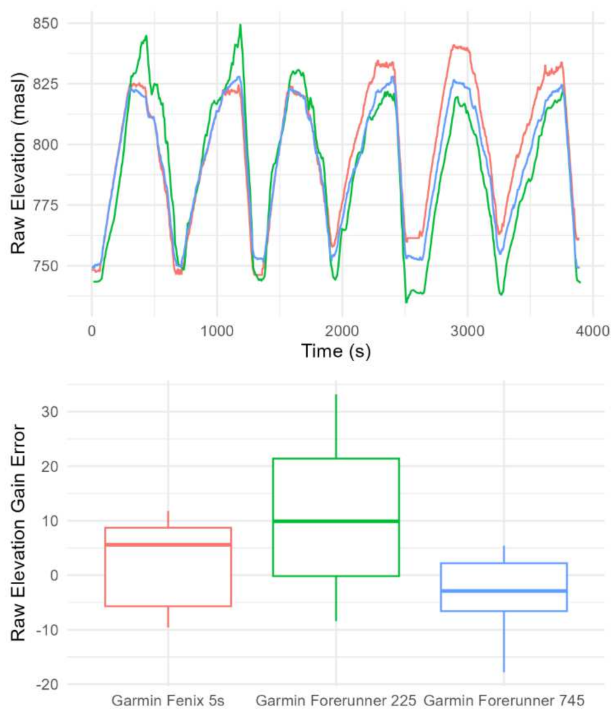

Fig. 2. Analysis of raw EG error from three different GPS watch models over a trail running activity. Top panel showcases the variability in elevation profiles and bottom panel illustrate a boxplot of EG errors.

Raw EG from devices was analysed visually in Figure 2 to explore the consistency of raw EG measures. In the upper graph, the raw elevation profiles recorded by three GPS watch models over time show notable variation at each lap, with the Garmin 745 showing the most consistent elevation profile. The lower graph, a boxplot, quantifies the raw EG error for each device model, measured against the known constant EG of the trail loop. The differences between the watch models are consistent with the upper graph, with the Garmin 745 having the lowest raw EG error. Notably, the Garmin 745 tends to underestimate EG on average, whereas the other two devices tend to overestimate it.

When analysing the EG using different DEM alternatives, we can observe that the resolution has an evident impact on the accuracy of EG calculations. As shown in Figure 3, there is a distinct relationship wherein the EG error escalates with the coarsening of the DEM resolution. The analysis revealed that the AWS DEM, when resampled with bilinear interpolation, tends towards negligible errors, going close to zero at approximately 40cm resolution. However, the nearest-neighbour resampling method does not perform well, especially as it approaches finer resolutions.

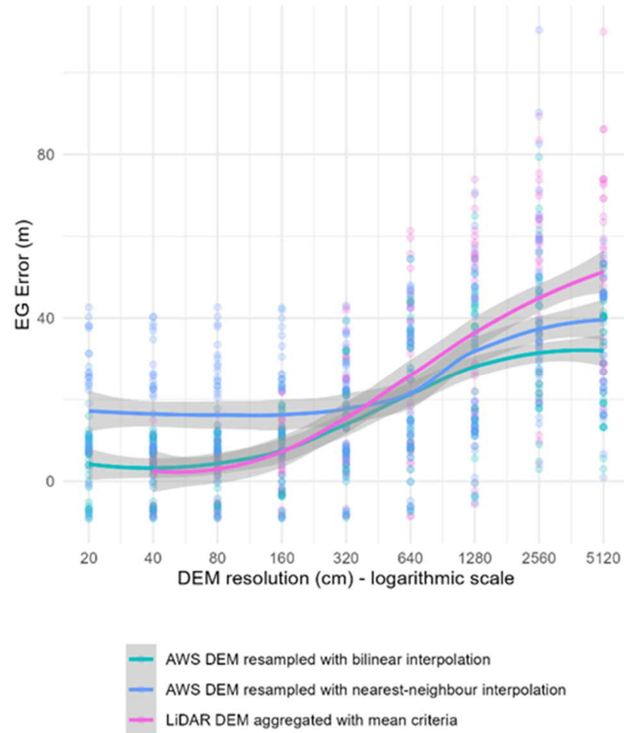

Fig. 3. Comparison of EG errors across different resolutions.

The EG error of each model at varying resolutions was compared with the corresponding raw benchmark EG error, as presented in Table 1. Each entry in the table illustrates the EG error difference between the estimate from the model and the EG error obtained from each benchmark. These evaluations involve models based on aggregated LiDAR DEM and AWS DEMs resampled via bilinear interpolation, with resolutions increasing sequentially from 20cm to 5120cm. Benchmark comparisons were made against Raw Device readings, LiDAR Raw DEM at 20cm resolution, and AWS Raw DEM at 4m resolution. In the table, negative values indicate scenarios where the models yielded lower EG errors than the benchmarks, suggesting superior model performance. Conversely, values near zero indicate that the model's performance is comparable to that of the benchmark. The statistical significance of these differences, determined using the Wilcoxon signed-rank test, is indicated by asterisks: *** signifies $p < 0.01$, ** $p < 0.05$, and * $p < 0.1$. At resolutions finer than 80cm, both models' EG error differences compared to the Raw LiDAR and Raw Device benchmarks were not statistically significant. However, at resolutions of 160cm and coarser, the models begin to exhibit statistically significant increases in EG error, which intensifies as resolution decreases. On the other hand, compared to the raw AWS benchmark, both models demonstrated a statistically significant improvement in EG error at resolutions finer than the AWS's native resolution.

TABLE I. EG ERROR DIFFERENCES AND STATISTICAL SIGNIFICANCE ACROSS VARIOUS DEM RESOLUTIONS WHEN COMPARED AGAINST RAW BENCHMARK DATA.

Model	**Resolution (cm)**	**Benchmark**		
		Raw Device	***AWS Raw 4m***	***LiDAR Raw 20cm***
Aggregated LiDAR	20	0.4	-12.2***	0
	40	0.7	-11.9***	0.3
	80	0.8	-11.8***	0.4
	160	2.6	-10**	2.2**
	320	11***	-1.7	10.5***
	640	24.5***	11.9**	24***
	1280	33.3***	20.7***	32.9***
	2560	42.8***	30.2***	42.4***
	5120	47.5***	34.8***	47***
Resampled AWS	20	3.2	-9.5***	2.7
	40	3.2	-9.4***	2.8
	80	3.7	-9***	3.2**
	160	6**	-6.6**	5.6**
	320	11.2***	-1.5	10.7***
	640	16.5***	3.9	16.1***
	1280	23.9***	11.3**	23.5***
	2560	29.9***	17.3***	29.4***
	5120	31.9***	19.3***	31.4***

IV. DISCUSSION

This study's key finding is that enhancing the resolution of a 4m resolution DEM significantly improve the accuracy of EG estimations from GPS watches when projecting the x/y coordinates onto a DEM. This improvement is achieved without adding new information and shows equivalent accuracy to LiDAR-based models, which are often more costly and less accessible. This low-cost strategy allows improving the quality of EG measurements in trail running and related activities without the need of LiDAR sources.

Building upon the work of [7] who reported positive outcomes using a 4m resolution DEM, our study demonstrates further improvements in EG accuracy when the resolution is enhanced. We found that the precision of EG error estimations is influenced by the resolution of DEMs obtained from LiDAR and AWS Tiles, with higher resolutions providing more accurate outcomes. Our analysis comparing various DEM resolutions indicated that both LiDAR and bilinearly interpolated AWS DEMs have minimal errors at 20cm resolution. However, errors escalate significantly when the resolution degrades, especially beyond 160cm. This finding underlines the necessity of high-resolution DEMs for precise EG calculations in trail running and supports the use of advanced algorithms for DEM resolution enhancement.

Regarding resampling techniques, bilinear interpolation proved superior to nearest-neighbour methods, particularly at finer resolutions. This is expected since bilinear interpolation considers the values of all adjacent pixels, providing a more complete terrain representation than nearest-neighbour methods, which only factors in the closest pixel.

Additionally, we observed variations in performance among different GPS devices, with the Garmin 745 showing notable consistency. This finding is crucial for athletes and coaches in choosing the appropriate devices for training and analysis, as it suggests that device selection can significantly impact the precision of elevation metrics. The underlying reasons for these performance disparities could be attributed to differences in hardware quality, software algorithms, or satellite connectivity among the devices. To provide a more comprehensive understanding, future research could involve a comparative analysis of various watch brands. This would not only broaden our insights into the performance of GPS devices but also aid consumers in making informed decisions based on empirical evidence.

This research broadens the understanding of how DEM resolution affects trail running analysis, offering fresh perspectives on the advantages of higher-resolution DEMs for more accurate elevation tracking in outdoor sports.

This work encounters several limitations that needs further investigation. Primarily, the application of our method is tested predominantly on the terrain around Cerro Calan, which may not represent a wide range of geographical landscapes. This could limit the generalizability of our findings to other types of terrain or environmental conditions. Additionally, while the enhanced resolution of DEMs improves accuracy, it also significantly increases the computational demands and data storage requirements, which could limit the applicability of our methods in settings with fewer resources. Furthermore, our research only incorporated two DEM sources and two interpolation methods.

Future research should focus on expanding the testing framework to include a broader range of DEM sources and interpolation techniques, which is crucial for assessing the robustness and adaptability of our methods across various geographical and environmental contexts. This expansion is necessary to confirm the practical utility and scientific impact of our approach, ensuring its applicability at different scales. Additionally, investigating how our interpolation methods perform across diverse terrains and under varying climatic conditions will be pivotal. This will help validate and possibly enhance the robustness of our techniques. A comparative analysis involving a wider array of GPS devices and diverse resolution scales should also be undertaken. Such comprehensive testing will provide deeper insights into the performance and applicability of our method, aiding in its refinement and customization to meet specific geographic and elevation analysis needs. These efforts will not only broaden the utility of our approach but also deepen the understanding of its limitations and strengths in real-world applications.

V. Conclussion

This study demonstrates that algorithmically enhancing the resolution of 4-meter DEMs to approximately 20 centimetres significantly improves elevation gain (EG) estimations at Cerro Calan, achieving accuracy levels comparable to those provided by traditionally more expensive LiDAR models. These findings not only highlight the feasibility of using enhanced-resolution DEMs as a cost-effective alternative to LiDAR but also underscore their potential to democratize high-quality geographic data analysis. Specifically, in applications like trail running, where precise elevation information is critical, the use of improved DEMs can greatly enhance performance analytics and safety planning. Moreover, this approach opens new possibilities for environmental monitoring, urban planning, and other geographical information systems (GIS) applications, offering a scalable solution that balances cost and accuracy effectively. By broadening access to high-resolution data, our study paves the way for more inclusive and extensive research and operational capabilities in terrain analysis and beyond.

Acknowledgment

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References

[1] A. Schneider, (2019). Calculating elevation gain. GPS Visualizer Tutorials. Accessed online on 2024-03-15 (https://www.gpsvisualizer.com/tutorials/elevation_gain.html)

[2] A. Kay, (2012). Pace and critical gradient for hill runners: an analysis of race records. Journal of Quantitative Analysis in Sports, 8(4).

[3] M.J.Campbell, P.E. Dennison, B.W. Butler, & W.G. Page, (2019). Using crowdsourced fitness tracker data to model the relationship between slope and travel rates. Applied geography, 106, 93-107.

[4] A.E. Minetti, C. Moia, G.S. Roi, D. Susta, & G. Ferretti, (2002). Energy cost of walking and running at extreme uphill and downhill slopes. Journal of applied physiology.

[5] R.E. Johansson, S.T. Adolph, J. Swart, & M.I. Lambert, (2020). Accuracy of GPS sport watches in measuring distance in an ultramarathon running race. International Journal of Sports Science & Coaching, 15(2), 212-219.

[6] R. Ammann, W. Taube, F. Kummer, & T. Wyss, (2016). Accuracy of elevation recording using sport watches while walking and running on hilly and flat terrain. Sports Engineering, 19, 283-287.

[7] R. Sanchez, & M. Villena, (2020). Comparative evaluation of wearable devices for measuring elevation gain in mountain physical activities. Proceedings of the Institution of Mechanical Engineers, Part P: Journal of Sports Engineering and Technology, 234(4), 312-319.

[8] P. Menaspà, E. Haakonssen, A. Sharma, & B. Clark, (2016). Accuracy in measurement of elevation gain in road cycling. Journal of Science and Cycling, 5(1), pp. 10-12.

[9] R. Ammann, W. Taube, M. Neuhaus, & T. Wyss, (2016). The influence of the gait-related arm swing on elevation gain measured by sport watches. Journal of human kinetics, 51(1), 53-60.

[10] M. Beato, G. Devereux, & A. Stiff, (2018). Validity and reliability of global positioning system units (STATSports Viper) for measuring distance and peak speed in sports. The Journal of Strength & Conditioning Research, 32(10), 2831-2837.

[11] A. Martin, G. Gesquiere, W. Puech, &S. Thon, (2006, January). Real-time 3D visualization of DEM combined with a robust DCT-based data-hiding method. In Visualization and Data Analysis 2006 (Vol. 6060, pp. 142-149). SPIE.

[12] E. Rodriguez, C. S. Morris, J. E. Belz, E. C. Chapin, J. M. Martin, W. Daffer, & S. Hensley (2005). An assessment of the SRTM topographic products.

[13] MapZen Terrain Tiles - accessed on 2024-01-14 from https://registry.opendata.aws/terrain-tiles.