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Analyzing Competitive Demands in Mountain Running Races: A Running Power-Based Approach

Juan Rodríguez-Medina, Belén Carballo-Leyenda, Jorge Gutiérrez-Arroyo, Fabio García-Heras, and Jose A. Rodríguez-Marroyo
Department of Physical Education and Sports, Institute of Biomedicine (IBIOMED), Universidad de León, León, Spain

Purpose: This study aimed to analyze the competitive demands of mountain running races of varying lengths. ***Methods:*** Sixty-six male athletes competed in Vertical race (~3 km and ~1000 m of total elevation change), Sky race (~25 km and ~3000 m of total elevation change), and SkyUltra race (~80 km and ~9000 m of total elevation change). Exercise intensity and competition load (TL) were assessed using running power, heart rate, and rating of perceived exertion (RPE). ***Results:*** The highest exercise intensity was observed in Vertical race (3.9 [0.4] $W \cdot kg^{-1}$, 93.6% [2.8%] HR_{max}, and 9.5 [0.7] RPE) compared to Sky race (3.5 [0.5] $W \cdot kg^{-1}$, 89.9% [2.4%] HR_{max}, and 8.5 [1.2] RPE), and SkyUltra (2.7 [0.6] $W \cdot kg^{-1}$, 73.4% [1.1%] HR_{max}, and 8.2 [1.1] RPE). Vertical races had the highest mean maximal power outputs for periods <10 minutes. They also had the highest proportion of time spent >5 $W \cdot kg^{-1}$ and the most time spent above the respiratory compensation threshold. The majority of time in SkyUltra was spent at low intensity. The highest TLs were observed in these races (6200.5 [708.0] kJ, 842.0 [35.7] AU for TL_{HR}, and 4897.3 [940.7] AU for TL_{RPE}). However, when normalized to competition time, the SkyUltra event showed the lowest values compared with the Vertical and Sky races (~11 vs ~14.5 $kJ \cdot min^{-1}$, ~1.5 vs ~2.5 $AU \cdot m^{-1}$ for TL_{HR}). ***Conclusion:*** The results of this study expand knowledge about the effort demands of mountain races and demonstrate how these demands are affected by race duration. Additionally, the study highlights the potential use of running power for quantifying exercise in this sport.

Keywords: exercise intensity, load, heart rate, RPE, trail running

Mountain running races require athletes to navigate established routes in mountainous environments, aiming to achieve the fastest completion time. These races involve steep elevation gains, varied terrains, and unpredictable weather conditions.[1–4] The International Skyrunning Federation classifies these competitions into 3 main disciplines: Vertical races (VR), requiring at least 800 m of ascent with of 20% average gradient; Sky races (SR), covering 20 to 45 km; and SkyUltra races (SUR), spanning 50 to 80 km. Over the past 2 decades, these events have seen a significant rise in popularity, with increased participant numbers[5] and event frequency.[6]

There has been a growing interest in analyzing performance-related aspects in these races. Research on SUR has been extensive, highlighting the significance of the VT in predicting performance.[2] Studies have also explored the role of fatigue in biomechanical gait alterations,[7] and the impact of pacing strategy on competitive outcomes.[8] Similarly, multiple studies have emphasized the importance of variables, such as body composition, VO_2max,[9] and lactate threshold[10] for optimal performance in SR. Conversely, research on VR is more limited, primarily focusing on the influence of the gradient on the metabolic cost of walking or running.[11] Recent findings have also highlighted the importance of VO_2max for mountain runners aiming to excel in this competition type.[12]

Rodríguez-Medina https://orcid.org/0000-0003-1682-0292
Carballo-Leyenda https://orcid.org/0000-0002-2881-5645
Gutiérrez-Arroyo https://orcid.org/0000-0003-3723-6132
García-Heras https://orcid.org/0000-0002-6697-2887
Rodríguez-Marroyo (j.marroyo@unileon.es) is corresponding author, https://orcid.org/0000-0002-9157-1532

While these studies underline key physiological factors, analyzing competition demands can provide valuable insights for designing specific training programs. Currently, there is a paucity of studies examining the effort performed during mountain races.[1–4] Most of these studies have been based on monitoring heart rate (HR) as a marker of exercise intensity. However, in mountain races, factors, such as fatigue, hydration levels, and environmental conditions can significantly affect HR,[13,14] potentially limiting its utility. Recently, some authors have proposed using of running power as a useful and sensitive variable for monitoring performance and fatigue during mountain races.[15] While this variable has been widely used in cycling to quantify competition demands,[16–18] and plan training intensities,[19] its use in mountain races remain limited.[15]

Advances in wearable technology have facilitated the application of running power in various contexts, including mountain running.[15] The Stryd footpod (10 g), equipped with a 6-axis inertial motion sensor (comprising a 3-axis accelerometer and a 3-axis gyroscope), allows for the estimation of various kinetics, kinematics, and spatiotemporal parameters.[20] Studies assessing the Stryd powermeter (Stryd Inc) have demonstrated its validity against theoretical mathematical models[21] and force-based measurements.[21] Additionally, its reliability and consistency in recording this variable during outdoors activities, such as walking, and trail running have been noted (coefficient of variation of 4.2%–4.7% and intraclass correlation of .81–.97).[21] Given the demonstrated relationship between running power measured with this device and the metabolic cost of running, it could be a useful tool for routine use in monitoring training sessions and competitions.[22] Therefore, the aim of this study was to analyze the competitive demands of mountain running races based on running power according to their length.

Methods

Subjects

Sixty-six male athletes participated in this study (mean [SD]; age, 30.7 [6.8] y; body mass, 66.2 [6.2] kg; height, 174.5 [5.4] cm). They were categorized into 3 groups based on their target competition type: VR (n = 19), SR (n = 28), and SUR (n = 19). All subjects were classified as national-level athletes according to the criteria established by Mckay et al,[23] with 4.2 (2.1) years of experience in mountain running and over 5 years of training background. They trained 5.3 (2.1) times per week, dedicating 5 to 15 hours depending on the moment of the season, and typically competed once every 3 weeks during the competitive season. Written informed consent was obtained from all subjects, and the protocol was approved by the local Ethics Committee, adhering to the Declaration of Helsinki.

Procedures

Data acquisition was conducted across 3 different seasons. At the beginning of the competitive period, athletes underwent a graded exercise test on a treadmill (h/p/cosmos pulsar, h/p/cosmos sports & medical GMBH). After a 10-minute self-selected intensity warm-up and 5 minutes of free stretching, the treadmill speed was set at 6 km·h^{-1}, increasing by 1 km·h^{-1} every minute until exhaustion. The treadmill gradient was maintained at 1%. Tests were conducted under similar environmental conditions (22 °C and 30%–40% relative humidity) and at the same time of the day (10:00–14:00 h). Running power (Stryd Summit footpod, Stryd Inc), HR response (Garmin Foreruner 735XT, Garmin International Inc), and breath-by-breath respiratory gas exchange (Medisoft Ergocard Professional, Medisoft Group) were continuously monitored. Maximal running power, HR, and VO_2max were recorded during the last 30-second before exhaustion. Maximal speed was determined as the highest maintained speed for a complete stage plus the interpolated speed from incomplete stages. Ventilatory (VT) and respiratory compensation (RCT) threshold were identified separately by 2 researchers according to Davis.[24] In cases of disagreement, the opinion of a third researcher was sought.

During the competitive period, athletes competed in VR (~5 km and ~1000-m elevation gain), SR (20–45 km and ~2000-m elevation gain), and SUR (>45 km and ~3000-m elevation gain) races. A total of 4 VR, 7 SR, and 4 SUR races were analyzed, all of which were included in regional or national official competition calendars. Each runner participated in at least 2 different races. Athletes wore a GPS device (Garmin Forerunner 735XT and Garmin Heart Rate Monitor Dual Band, Garmin International Inc) linked to the Stryd footpod (Stryd Summit, Stryd Inc), allowing synchronization of HR and running power data at 1-second intervals. The Stryd device was attached to the right foot using a plastic clip through the shoelaces.

Data were analyzed using an open-source software (GoldenCheetah, version 3.5). Three intensity zones were defined based on HR[4] and power output[25] values corresponding to VT and RCT: zone 1 (low intensity, below VT), zone 2 (moderate intensity, between VT and RCT), and zone 3 (high intensity, above RCT). Exercise load (TL) based on HR (TL_{HR}) was calculated by multiplying time spent in each zone by constants 1, 2, and 3, respectively, and summing the results.[26] Additionally, maximal mean running power output (MMP) for various durations (1, 5, 10, and 30 s and 1, 3, 5, 10, 20, 30, 60, 90, 120, 180, and 300 min) and time spent in different relative power bands (<1, 1–2, 2–3, 3–4, 5–6, and >6 W·kg^{-1}) were analyzed.[18,19] Total mechanical energy expenditure (kJ) was calculated from running power.[16] Rating of perceived exertion (RPE) was obtained using a category ratio (0–10) scale, ~30-minute postrace.[26] Competition load based on RPE (TL_{RPE}) was calculated by multiplying RPE by race duration.[26] All subjects were trained and familiarized with the RPE scale during initial laboratory visits and prior training sessions.

Statistical Analyses

The results were expressed as mean (SD). Normality assumption was assessed using the Shapiro–Wilk test, and nonnormal data were log-transformed prior to analysis. One-way analysis of variance was used to detect differences among athletes and races, and to compare exercise intensity and competition load across race types. Two-way analysis of variance examined MMPs, running power bands, and exercise intensity distribution according to ventilatory thresholds among mountain races. When significant F values were found, Bonferroni test was used for post hoc analysis. Effect sizes were calculated using partial eta-squared (η_p^2) for analysis of variance results. Pearson correlation coefficient (r) was used to assess at $P < .05$. Analyses were performed using SPSS (version 26).

Results

The anthropometric and physiological characteristics of the subjects participating in the 3 different competition types were comparable (Table 1). Moreover, the subjects' performance showed similarities among the competitions types, with results situated at the 79.8 (13.0), 76.2 (21.6), and 81.3 (16.8) percentiles for VR, SR, and SUR, respectively.

Table 2 shows the main characteristics of the analyzed races. As expected, longer races had significantly ($P < .001$) longer durations, and greater ($P < .001$) elevation changes, in both positive and negative elevation. Consequently, these changes resulted in an overall decrease in the mean exercise intensity (Table 3).

Table 1 Physiological Characteristics of Subjects

	Mean (SD)
Total test duration, min	13.6 (1.4)
VO_2max, mL·kg^{-1}·min^{-1}	64.1 (6.2)
HR_{max}, beats·min^{-1}	185 (10)
Maximal speed, km·h^{-1}	18.6 (1.3)
Maximal running power, W·kg^{-1}	5.4 (0.4)
VO_2 at RCT, mL·kg^{-1}·min^{-1}	54.4 (5.3)
% VO_2max at RCT	85.1 (5.3)
HR at RCT, beats·min^{-1}	168 (9)
Speed at RCT, km·h^{-1}	15.2 (1.5)
Running power at RCT, W·kg^{-1}	4.4 (0.4)
VO_2 at VT, mL·kg^{-1}·min^{-1}	43.5 (6.8)
% VO_2max at VT	67.9 (8.3)
HR at VT, beats·min^{-1}	147 (10)
Speed at VT, km·h^{-1}	11.9 (1.7)
Running power at VT, W·kg^{-1}	3.4 (0.4)

Abbreviations: HR, heart rate; HR_{max}, maximal HR; RCT, respiratory compensation threshold; %VO_2max, percentage of VO_2max at which RCT and VT occur; VO_2max, maximum oxygen consumption; VT, ventilatory threshold.

Table 2 Descriptive Characteristics of Mountain Races (Mean [SD])

	Vertical races	Sky races	SkyUltra races
Distance, km	2.9 (0.5)*†	24.9 (4.7)†	77.9 (11.0)
Race time, min	41.1 (4.6)*†	143.3 (35.0)†	603.3 (118.8)
Total elevation change, m	970.2 (39.1)*†	2972.2 (969.0)†	8965.2 (162.6)
Positive elevation gain, m	970.2 (39.1)*†	1486.1 (484.5)†	4383.3 (328.4)
Negative elevation loss, m	0.0 (0.0)*†	1486.1 (484.5)†	4581.9 (172.0)
Ratio of positive elevation gain to distance, %	34.8 (5.3)*†	6.2 (1.5)	5.7 (1.3)
Maximum altitude, m	1693.6 (54.8)†	1621.5 (290.7)†	2226.2 (358.8)
Minimum altitude, m	723.4 (87.9)*	957.1 (196.7)†	622.1 (298.7)

*Significant difference with Sky races ($P < .05$). †Significant difference with SkyUltra races ($P < .05$).

Table 3 Mean Exercise Intensity and Competitive Load Based on Running Power, RPE, and HR (Mean [SD])

	Vertical races	Sky races	SkyUltra races
Running power, W·kg^{-1}	3.9 (0.4)*†	3.5 (0.5)†	2.7 (0.6)
% maximal power output	51.0 (7.9)	51.6 (7.2)†	45.9 (10.7)
RPE	9.5 (0.7)*†	8.5 (1.2)	8.2 (1.1)
RPE:PO	2.5 (0.3)†	2.5 (0.5)†	3.3 (0.7)
HR, beats·min^{-1}	175 (9)†	169 (7)†	136 (10)
% maximal rather	93.6 (2.8)*†	89.9 (2.4)†	73.4 (1.1)
%HR$_{max}$:PO	25.5 (2.6)†	27.3 (4.8)†	41.8 (4.4)
Work, kJ	606.2 (66.3)*†	1967.4 (371.7)†	6200.5 (708.0)
Work·min^{-1}, kJ·min^{-1}	14.9 (1.8)†	14.0 (1.7)†	10.8 (2.3)
Work·TEC^{-1}, kJ·m^{-1}	0.60 (0.10)	0.71 (0.20)	0.65 (0.16)
Work·PEG^{-1}, kJ·m^{-1}	0.60 (0.10)*†	1.44 (0.39)	1.36 (0.34)
TL$_{RPE}$, AU	392.3 (58.0)*†	1222.0 (377.1)†	4897.3 (940.7)
TL$_{RPE}$·TEC^{-1}, AU·m^{-1}	0.38 (0.09)†	0.43 (0.12)†	0.55 (0.10)
TL$_{RPE}$·PEG^{-1}, AU·m^{-1}	0.38 (0.09)*†	0.86 (0.23)†	1.12 (0.19)
TL$_{HR}$, AU	108.1 (16.5)*†	333.0 (94.2)†	842.0 (35.7)
TL$_{HR}$·min^{-1}, AU·min^{-1}	2.6 (0.4)†	2.3 (0.5)†	1.4 (0.2)
TL$_{HR}$·TEC^{-1}, AU·m^{-1}	0.11 (0.03)	0.11 (0.05)	0.09 (0.01)
TL$_{HR}$·PEG^{-1}, AU·m^{-1}	0.11 (0.03)*	0.22 (0.09)	0.20 (0.01)

Abbreviations: bpm, beats per minute; HR, heart rate; %HR$_{max}$:PO, ratio of percentage of maximal HR to power; PEG, positive elevation gain; RPE, rating of perceived exertion; RPE:PO, ratio of RPE to power output; TEC, total elevation change; TL$_{HR}$, competition load calculated based on HR; TL$_{RPE}$, competition load calculated based on RPE.
*Significant difference with Sky races ($P < .05$). †Significant difference with SkyUltra races ($P < .05$).

A significant effect of competition type on MMPs ($F = 23.3$, $P = .000$, $\eta^2_p = .37$) and preestablished running power bands ($F = 500.2$, $P = .000$, $\eta^2_p = .93$) was observed. The highest ($P = .043$–.000, adjusted $P = .129$–.000) MMP values were recorded in VR for periods from 5 seconds to 5 minutes (Figure 1). No significant differences were found between VR and SR for the 10- to 30-minute period. MMPs were higher ($P = .032$–.000, adjusted $P = .096$–.000) in SR compared with SUR up to 120 minutes (Figure 1).

Analysis of running power bands revealed that athletes spent most race time between 2 and 5 W·kg^{-1} (Figure 2). VR had the highest ($P = .000$) percentages of time >5 W·kg^{-1}, while SUR had significantly lower ($P = .000$) contribution in the 4 to 5 W·kg^{-1} band and the greatest ($P = .002$–.000, adjusted $P = .006$–.000) percentages of <3 W·kg^{-1}. Time spent <4 W·kg^{-1} was significantly longer ($P = .000$) in SUR, whereas VR had notably higher ($P = .000$) time spent >6 W·kg^{-1} (Figure 2).

A significant effect of competition type on exercise intensity distribution, defined by running power ($F = 15.7$–519.7, $P = .000$, $\eta^2_p = .28$–.93) and HR ($F = 6.8$–535.9, $P = .046$–.000, $\eta^2_p = .13$–.96) was found. Longer races were associated with a decrease in the percentage of effort above the power output ($P = .003$–.000, adjusted $P = .009$–.000) and HR ($P = .013$–.003, adjusted $P = .039$–.009) at RCT (Figure 3), along with an increase ($P = .000$) in time and percentage of total time spent below VT. Similarly, time spent between VT and RCT also increased ($P = .028$–.000, adjusted $P = .084$–.000) with race duration. Although the distribution patterns, based on time spent in the intensity zones, were similar for running power and HR, mean values differed significantly. Using HR, time in zones 2 (98.7 [39.6] vs 48.3 [28.8] min, $P = .019$) and 3 (33.5 [26.6] vs 15.6 [10.7] min, $P = .000$) approximately doubled, while time in zone 1 was reduced by 35% (130.0 [37.7] vs 198.7 [12.9] min, $P = .000$).

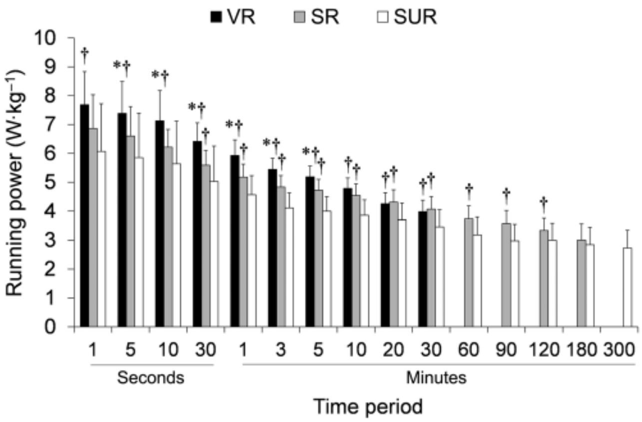

Figure 1 — Maximal mean running power across different time periods. Values are mean (SD). SR indicates Sky races; SUR, SkyUltra races; VR, Vertical races. *Significant difference with SR ($P < .05$). †Significant difference with SUR ($P < .05$).

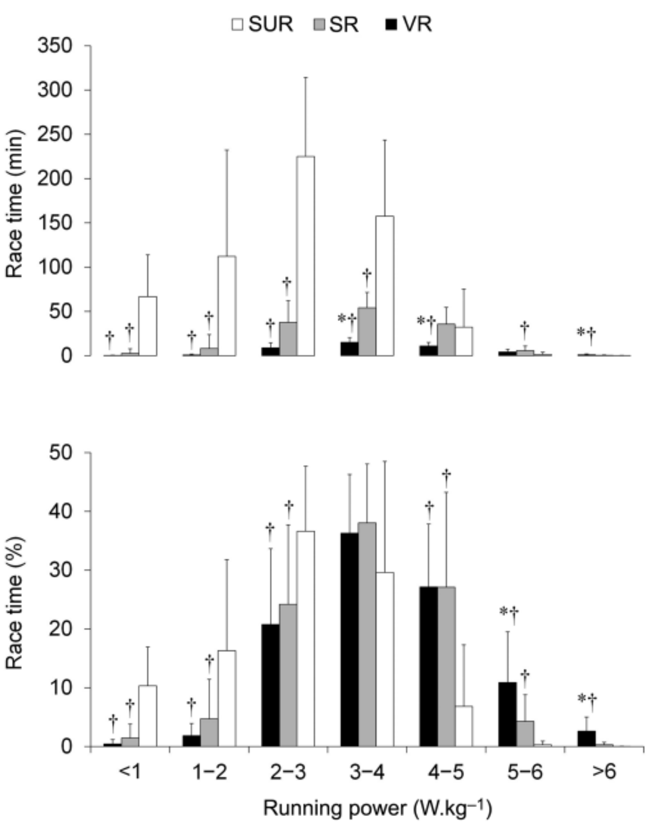

Figure 2 — Distribution of running power in the preestablished bands. Values are mean (SD). SR indicates Sky races; SUR, SkyUltra races; VR, Vertical races. *Significant difference with SR ($P < .05$). †Significant difference with SUR ($P < .05$).

Correlations between time in zones 2 ($r = .49$, $P = .01$) and 3 ($r = .97$, $P = .000$) were found.

The highest ($P = .000$) TL values were observed in SUR, followed by SR and VR, regardless of the quantification method (Table 3). When TL was normalized per minute of effort, SUR exhibited the lowest values ($P = .000$). However, no significant differences were found in external TL or TL_{HR} when normalized by elevation change. The highest ($P = .000$) TL_{RPE} values were obtained in SUR, including when normalized by positive elevation gain. Normalizing external TL and TL_{HR} by positive elevation gain resulted in the lowest ($P = .000$) values for VR, with no significant differences between SR and SUR. Strong correlations were found among all TL quantification methods ($r = .95$, .94, and .93; $P = .000$, for external TL and TL_{HR}, external TL and TL_{RPE}, and TL_{HR} and TL_{RPE}, respectively).

Discussion

Several studies have previously examined exercise intensity during mountain running races, primarily using HR as a marker of exercise intensity and focusing predominantly on SUR and similar race formats.[1–4] However, this study represents the first comprehensive analysis of different-length mountain running races' demands based on running power, providing novel insights into the relationship between race duration and exercise intensity in this context.

The analyzed exercise intensity was closely linked to the duration of the competitions, a phenomenon widely documented in various endurance events,[16,17,27] specifically in mountain running races.[4] Consequently, race intensity decreased significantly with increasing distance (Table 3), resulting in a global reduction of MMP values (Figure 1), the percentage of work in preestablished running power bands > 5 $W{\cdot}kg^{-1}$ (Figure 2) and the percentage of work performed above the RCT in longer races (Figure 3). The accumulated fatigue due to increased race distance may have contributed to this circumstance.[4,27] In fact, the RPE and $\%HR_{max}$ to power output ratios showed a significant rise in SUR (Table 3). Previous studies have documented how race duration can accentuate muscle fatigue[7,28] and affect energy balance[1,3] in mountain runners. Our findings showed that extended race duration led to an increase in negative elevation loss (Table 2), which may have exacerbated exercise-induced muscle damage due to increased eccentric loading in muscles[3,7,28] and consequently influenced exercise intensity. Moreover, it has been reported that the lowest cardiorespiratory demands occur during downhill phases.[7,29,30] Conversely, the highest positive elevation gain in these races might initially imply an increase in physiological strain.[7,15,29,30] However, during uphill sections of these races, runners are advised to adopt more conservative pacing strategies to avoid excessive fatigue and performance decline.[8,28,30] This approach also provides runners with optimal opportunities for energy intake, crucial for maintaining performance levels during endurance events. In races similar to the SUR analyzed in this study, participants have reported negative energy balance,[1,3] which can lead to glycogen depletion and a consequent decrease in exercise intensity.[31] In fact, insufficient carbohydrate intake rates (~0.6 $g{\cdot}min^{-1}$) have been observed in these races, potentially compromising high carbohydrate oxidation rates.[1,3] Adopting an exercise intensity slightly below VT (~10% below HR at VT) could have helped runners conserve carbohydrate reserves and delay glycogen depletion.[2]

The highest exercise intensity was found in VR, irrespective of the variable analyzed (Table 3). These races exhibited the highest MMPs for shorter durations (ie, 5 s to 5 min) (Figure 1) and the greatest percentages of total time >5 $W{\cdot}kg^{-1}$ (Figure 2). Similarly, they achieved the highest percentages of time spent above the RCT (Figure 3). The characteristics of these races, especially their duration and higher elevation-to-distance ratio, influenced these results. During these events, runners had to tackle very long and constant gradients, requiring high muscular activity

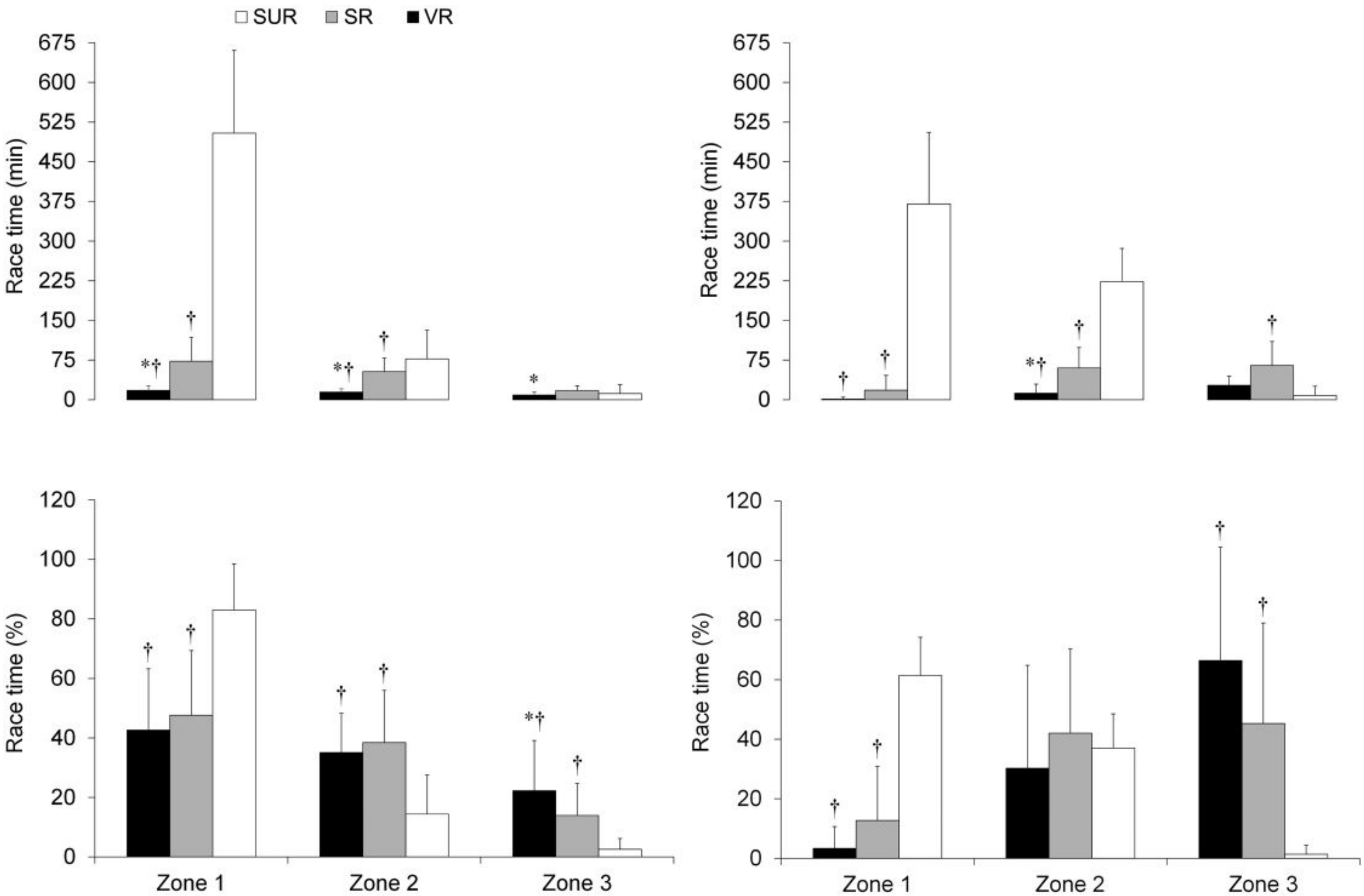

Figure 3 — Distribution of exercise intensity according to the running power (left panels) and heart rate (right panels) at which VTs occur. Values are mean (SD). RCT indicates respiratory compensation threshold; SR, Sky races; SUR, SkyUltra races; VR, Vertical races; VT, ventilatory threshold; Zone 1, exercise intensity below the VT; Zone 2, exercise intensity between VT and RCT; Zone 3, exercise intensity above RCT. *Significant difference with Sky races ($P < .05$). †Significant difference with SkyUltra races ($P < .05$).

to generate more net mechanical work to increase the body's potential energy.[7] Consequently, the metabolic demand[7,15,29,30] and utilization of anaerobic metabolism increased.[7,30] This heightened exercise intensity is in line with previous findings,[4] supporting the notion that maintain high HR levels (>90% of HR_{max}) is crucial for sustaining performance during running events lasting 10 to 60 minutes.[32]

Additionally, the running power obtained in VR was comparable with the estimated power output to overcome gravity required by professional cyclists during mountain climbs lasting 30 to 60 minutes (~4 $W \cdot kg^{-1}$).[33] Using the same methodology, substantially lower running power values (~2.5 $W \cdot kg^{-1}$) were estimated in simulated VR competitions[15] compared with those recorded in our study. Possibly, the simulated nature of the competition, the fact that ~25% of the participants were women, and the ~15% lower elevation-to-distance ratio could explain this difference. The running power values recorded in SR were similar to those achieved by professional cyclists during mountain stages of Grand Tours (3.5 $W \cdot kg^{-1}$)[17] and even comparable to those observed in the hardest and most prestigious single-day road races like Milan-San Remo or Paris-Roubaix (3.2 $W \cdot kg^{-1}$).[16] Similarly, the values analyzed in SUR were in line with those generated by cyclists during flat stages (~2.7 $W \cdot kg^{-1}$).[17,18] Despite these similarities, the exercise intensity based on HR in these events was lower than in SR and SUR. Possibly due to the more stochastic nature of cycling effort.[18]

The consistency of effort performed by mountain runners is evident from the fact that ~30 and ~40% of race time in VR and SR were spent between 3 to 5 and 3 to 4 $W \cdot kg^{-1}$, respectively (Figure 2). Similar percentages were observed in SUR, with efforts concentrated in the 3 to 4 and 2 to 3 $W \cdot kg^{-1}$ range (Figure 2). These power bands corresponded to intensities around the RCT and VT (Table 1) or slightly below them. These findings underline the significance of these physiological markers for performance in these events and support previous research.[2,10] Furthermore, they highlight how increasing race duration shifts runners' intensity selection toward lighter zones (around VT), aiming to balance performance and fatigue for optimal race completion.[2,31,32] Supporting this hypothesis, the MMPs found for durations >30 minutes in SUR were nearly identical (~3 $W \cdot kg^{-1}$), representing around 90% of the running power at VT (Figure 1).

Differences in MMPs were observed over different time durations among the race types. While VR were characterized by higher MMPs over short to moderate durations (<10 min), the increased total elevation gain in SR caused MMPs for longer periods (10–30 min) to become more significant (Figure 1). MMPs analyzed in SR were higher than those in SUR for durations up to

120 minutes, possibly influenced by the pacing strategies adopted in the latter race type. The results obtained are substantially lower compared with those reported for cyclists,[16–19] especially for durations of 5 to 30 seconds, where mountain runners exhibited ~5 to 10 $W \cdot kg^{-1}$ less power. These differences narrowed to ~1 to 2 $W \cdot kg^{-1}$ with longer-duration MMPs (5–180 min). Several factors, such as the variable nature of road cycling,[17,18] subjects' performance level,[16] competition category,[16] and timing within the season[19] may explain these differences.

Overall, all variables used to assess exercise intensity behaved similarly, indicating that increased race distance led to a decrease in effort intensity. However, when RPE was employed, no significant differences were found between SR and SUR. Although RPE is primarily considered a marker of exercise intensity,[26] several factors could have influenced its rating. The greater negative elevation loss observed in SUR could have led to heightened neuromuscular damage and fatigue,[7,28] potentially impacting runners' perception. Additionally, the increased downhill running could have increased the technical difficulty, affecting RPE.[1] On the other hand, RPE's sensitivity to exercise duration[26,34] suggest that the longer duration of SUR, more than 3 times that of SR, could have contributed to the increased RPE, possibly intensified by a reduction in energy substrates.[35] Moreover, the early morning start times for SUR (24:00–07:00 h) could have exposed runners to sleep restriction, affecting RPE.[36]

Another notable finding of this study was the discrepancy observed when analyzing exercise intensity distribution based on running power and HR (Figure 3). Overall, the effort performed by runners at moderate to high intensities was greater when assessed by HR. Conversely, it was greater at low intensities when running power was used. This mismatch between methodologies has been previously reported in early cycling studies.[25] It has been suggested that the slow response of the cardiorespiratory system to rapid changes in power output could overestimate the time spent in moderate intensity zones.[25] Additionally, cardiovascular drift, which could be exacerbated in longer races under hot conditions, might amplify these differences.[13] Increases in HR of up to 15% have been reported following exercise durations of less than 1 hours.[13] Specifically, increases of about 6 beats per minute have been observed in hypohydrated mountain runners for every additional 1% of body mass loss during submaximal runs in the heat.[14] Furthermore, greater afferent feedback from mechanoreceptors due to eccentric contractions in downhill running could increase HR.[29]

Finally, this study highlights the high exercise demands faced by mountain runners. The TL_{HR} values are in agreement with those previously obtained in such events (~150–825 AU).[2,4] The demands of SR were comparable to those of professional cyclists during mass-start races of Grand Tours (~300–360 AU).[17] Furthermore, TLs analyzed in SUR were double those reported for mountain stages (360 AU)[17] and the $TL_{HR} \cdot min^{-1}$ in this study was nearly double that of cyclists (~1.1 $AU \cdot min^{-1}$). Likewise, both external TL and TL_{RPE} were comparable with those of cyclists (~3000–4000 kJ or ~10–13 $kJ \cdot min^{-1}$, ~1500–2500 AU, respectively).[16,17] Additionally, SUR values were similar (~6000 kJ or ~13 $kJ \cdot min^{-1}$) or even higher (~3700 AU for TL_{RPE}) than those found in classic cycling races (~270 km, ~7 h).[16] Despite all methodologies used for TL calculation behaving similarly, RPE appeared to be more sensitive in detecting differences between races when the influence of time or elevation change was eliminated (Table 3). This supports the idea that RPE may provide additional insight into accumulated fatigue not provided by other TL markers.[34]

Despite the findings of the study, certain limitations might have influenced the results. One of the primary issues was the potential interunit reliability associated with the measurement devices used. Although this was partially mitigated by assessing multiple races per athlete and randomly assigning the devices, some variability might still have existed. Another limitation was the use of HR as a marker of exercise intensity, as several uncontrollable factors could have influenced HR responses during the competitions.[13,14] Additionally, the RPE values collected in the study might have been affected by the participants' experience with its use. However, its influence was likely limited, as participants were familiarized with RPE during the graded exercise test and were advised to use it during their training sessions prior to data acquisition. Lastly, the study's sample size limits the ability to generalize the findings to athletes with different competitive levels.

Practical Applications

This study provides valuable data that coaches and practitioners can utilize in designing specific training programs. These reference data can assist in accurately selecting training volumes across different intensity zones, which is crucial for ensuring optimal preparation for runners. Overall, our findings suggest the necessity of conducting high-intensity volume of approximately 15 to 30 minutes, depending on the variable used to monitor training. Additionally, our results establish reference points that can assist in comparing competition performance or pacing strategies across different race types. Specifically, power outputs between 3 and 4 $W \cdot kg^{-1}$, or slightly below the RCT or VT and effort rates between 10 and 15 $kJ \cdot min^{-1}$ or 1.5 and 2.5 $AU \cdot min^{-1}$ when using running power or HR, can serve as useful benchmarks.

Conclusions

In conclusion, this study demonstrates how race characteristics influence the exercise demands placed on athletes. Vertical races exhibited the highest exercise intensities, characterized by prolonged periods of work above the respiratory compensation threshold, the development of running powers >5 $W \cdot kg^{-1}$, and higher maximal mean running power outputs for time periods <10 minutes. Conversely, as race distance increased, exercise intensity decreased, with runners selecting lower power zones and longer duration maximal mean running power outputs becoming more significant. These findings underline the substantial demands placed on runners in this sport and highlight the potential utility of running power as a variable for monitoring exercise intensity in mountain races. Additionally, rating of perceived exertion emerges as a valuable tool for monitoring effort, particularly in longer races where various factors beyond exercise intensity contribute to fatigue and effort severity.

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