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Acute Effects of Overload Running on Physiological and Biomechanical Variables in Trained Trail Runners

Antonio Cartón-Llorente [1], Alberto Rubio-Peirotén [1,*], Silvia Cardiel-Sánchez [1], Pablo Díez-Martínez [1], Luis Enrique Roche-Seruendo [1] and Diego Jaén-Carrillo [2]

[1] Universidad San Jorge, 50830 Zaragoza, Spain; acarton@usj.es (A.C.-L.); scardiels@usj.es (S.C.-S.); alu.119408@usj.es (P.D.-M.); leroche@usj.es (L.E.R.-S.)
[2] Department of Sport Science, Universität Innsbruck, 6020 Innsbruck, Austria; diego.jaen@uibk.ac.at
* Correspondence: arubio@usj.es; Tel.: +34-636772225

Featured Application: The additional weight carried in a vest during trail running affects performance and physiological milestones unevenly. Running power appears to be more stable than speed for monitoring training load, particularly at velocities below the second ventilatory threshold.

Abstract: Background: The biomechanical and physiological adaptations to resisted running have been well documented in sprinting; however, their impact at submaximal speeds, such as those typical of long-distance running, remains unclear. This study aimed to evaluate the impact of running with a weighted vest, loaded with 5% and 10% of body mass, on the physiological and mechanical variables of trained trail runners. Methods: Fifteen male trail runners completed an incremental protocol to exhaustion on a treadmill with 0%, 5%, and 10% of their body mass (BM), in random order, with one week of separation between the tests. The maximality of the test was confirmed by measuring lactate concentrations at the end of the test. Oxygen consumption ($\dot{V}O_2$) and respiratory exchange ratio (RER) were recorded using a portable gas analyzer (Cosmed K5), and ventilatory thresholds 1 and 2 (VT1, VT2) were calculated individually. Running power was averaged for each speed stage using the Stryd device. Finally, the peak values and those associated with VT1 and VT2 for speed, power (absolute and normalized by body mass), $\dot{V}O_2$, RER, and the cost of transport (CoT) were included in the analysis. Results: One-way repeated-measures ANOVA revealed a detrimental effect of the extra load on maximum speed and speed at ventilatory thresholds ($p \leq 0.003$), with large effect sizes (0.34–0.62) and a nonlinear trend detected in post hoc analysis. Conclusions: Using running power to control the intensity of effort while carrying extra weight provides a more stable metric than speed, particularly at aerobic intensities. Future research in trail running should investigate the effects of weighted vests across various terrains and slopes.

Keywords: endurance; footpod; weighted vest; wearable resistance training; running power

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1. Introduction

As modern society has become more cosmopolitan and sedentary, many people have sought for means of spending more time outdoors and connecting with nature while exercising. Here, trail running has recently gained momentum as a combination of cross-country and mountain running [1]. Over the last 10 years, the number of participants in this sport has doubled [2]. Trail running races may include a maximum of 20% of asphalt and are classified according to their length, with trails being defined by distances of up to 42 km and ultra-trails those that exceed that distance [3].

Although the performance determinants for trail running slightly diverge from those of road running, a high aerobic capacity and optimized lactate thresholds are still crucial for endurance [4,5]. Furthermore, as in road cycling, higher relative muscle strength and power in relation to low body fat mass are particularly beneficial in terms of positive gradient

due to the weight resistance vector [6]. Additionally, most trail and ultra-trail races require athletes to carry technical equipment and a minimum supply of water and food, adding 3–4 kg of extra load, depending on the distance and climate.

The acute physiological and mechanical effects of running under resisted conditions (e.g., parachutes, sleds, or wearable resistances) have previously been evaluated, showing varying impacts based on the direction, point of application, and magnitude of the load [7–18]. Horizontally resisted running hinders kinematic (e.g., step length and frequency) and physiological variables (e.g., oxygen consumption, running economy) more than running with vertical resistance [12,13]. Distal load placement, especially in the lower body, tends to impair running biomechanics and increases the metabolic cost of transport. In contrast, light loads placed near the runner's center of gravity minimize these changes [7,15,16].

The response to the different magnitudes of extra load has shown contradictory results. Some studies indicate proportional increases in the metabolic cost of running with increased load, similarly to uphill running [16,19], while others report no significant changes or slight improvements in energy expenditure during running at low versus high loads [12,17,18]. From a mechanical perspective, the research suggests an optimal load for maintaining or even improving the storage-restitution of elastic energy. Light loads (around +5% of body mass) result in minimal changes in running mechanics, whereas overloads of $\geq$10% BM negatively affect both the mechanical and physiological aspects of running [9,11,14]. However, it must be acknowledged that most of the studies to date have focused on sprint performance or evaluated the longitudinal responses to training with wearable resistance, whereas the acute effects of a weighted vest on endurance athletes remain unclear.

Maximal oxygen uptake ($\dot{V}O_2$max) and maximal power output (Pmax) reached during ergometric tests are the most commonly used milestones to assess endurance capacity [20]. However, gas exchange methods for determining peak ergometric values are not without limitations, including the requirement for maximal effort, dependence on the motivation or attitude of the participant or researcher, challenges in ensuring accurate measurements during high-intensity exercise, and a lack of sensitivity to minor changes in endurance ability [21]. Therefore, submaximal parameters, such as ventilatory thresholds [3,20], alongside novel external load metrics such as power output [22], emerged to facilitate the assessment of performance and the customization of training regimens in endurance sports. Here, novel wearable sensors have made it possible to reliably monitor mechanical power during running [23,24]. However, the scientific literature has yet to fully address how metabolic zones change during loaded training and why studies reporting running power values associated with $\dot{V}O_2$max and ventilatory thresholds are scarce.

Understanding and determining these metabolic zones, including ventilatory thresholds (VT1 and VT2) and peak oxygen consumption ($\dot{V}O_2$max/$\dot{V}O_2$peak), are essential for effectively setting training intensities and paces. Therefore, the present study aims to evaluate the acute effects of running with an additional load (i.e., 5 and 10% additional body mass) on the physiological and mechanical parameters of trained trail runners. It was hypothesized that running with a 5% body mass weighted vest will not produce significant physiological and mechanical changes during an incremental protocol, whereas running with a 10% body mass vest will alter both metabolic and mechanical power generation at peak values and ventilatory thresholds.

2. Materials and Methods

2.1. Subjects

Fifteen male trained trail runners (age: 37.8 $\pm$ 5.9 years; height: 1.76 $\pm$ 0.05 m; body mass: 72.2 $\pm$ 4.9 kg) voluntarily participated in this study. All participants satisfied the inclusion criteria: (1) males aged over 18 years, (2) possessing a minimum of two years of trail running experience, (3) absence of any injuries in the six months preceding data collection, and (4) no cardiorespiratory or metabolic disorders. Current use of any ergogenic aid that could influence the results of the study was considered an exclusion

criterion. Detailed information about the study's goals and methods was provided to each participant, who then signed an informed consent form in accordance with the ethical guidelines of the World Medical Association's Declaration of Helsinki (2013). Participants were informed that they could withdraw from the study at any time. The research protocol was authorized by the Local Ethics Committee (Universidad San Jorge, Zaragoza, Spain 12/1/21-22).

2.2. Procedures

The research was carried out over four sessions. In the initial session, consent forms were obtained from all participants; additionally, anthropometric data were recorded, and participants were acclimated to the running protocol. On days 2, 3, and 4, the running protocol was executed with incremental additional loads (i.e., 0%, 5%, and 10% of body mass). To minimize bias, the sequence of the additional loads was randomized (Figure 1).

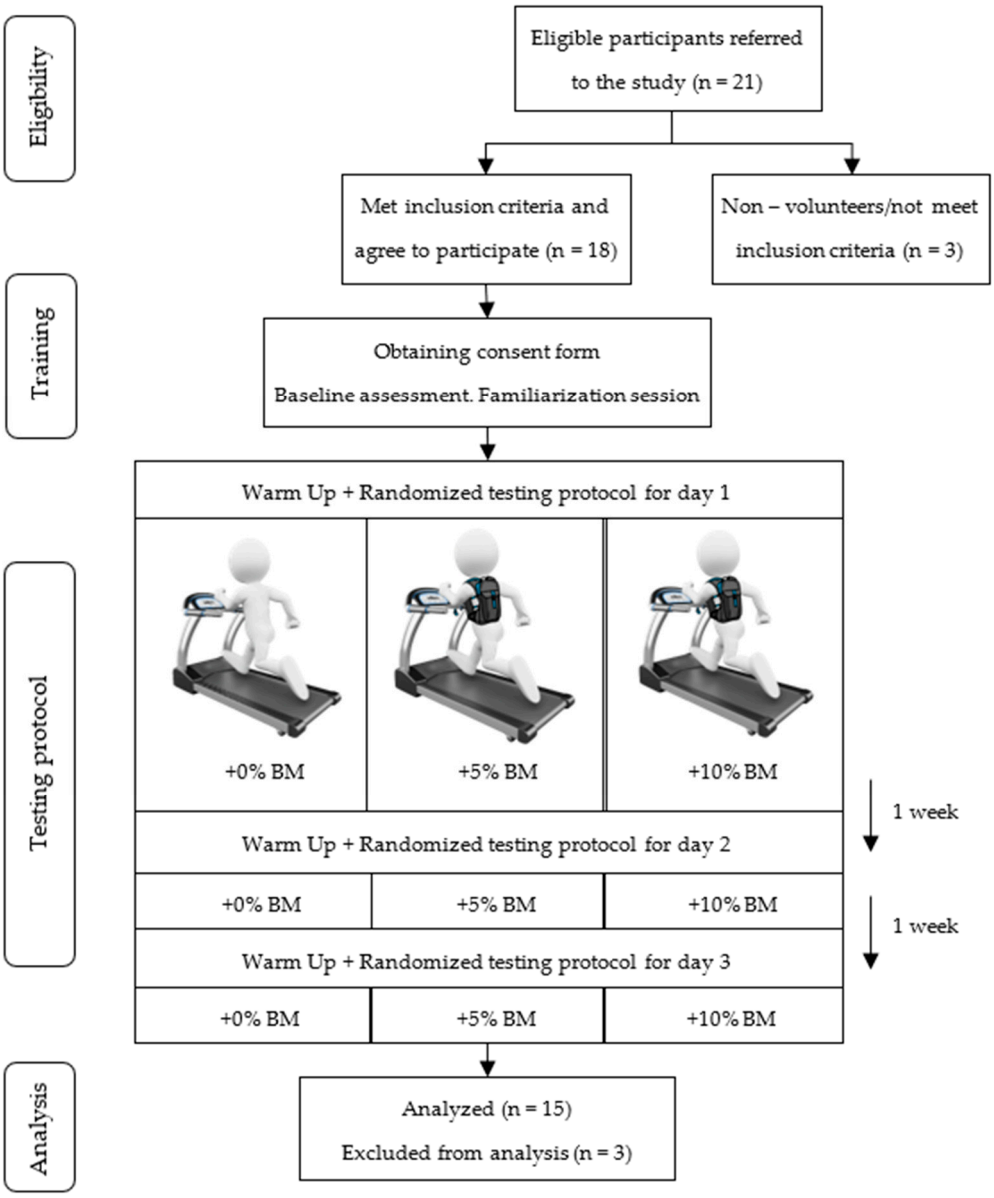


Figure 1. Project design timeline.

All participants were required to abstain from intense physical activities for at least 72 h prior to the tests, and all assessments were conducted no less than three hours post-

meal. The tests were performed with participants wearing their standard training footwear to accurately assess their typical performance levels.

Participants executed an incremental running protocol on a motorized treadmill (HPCosmos 20, HP Cosmos Sports & Medical GmbH, Nussdorf-Traunstein, Germany), initiating with a warm-up phase at a speed of 8 km/h for three minutes. Subsequently, the speed was increased by 1 $km \cdot h^{-1}$ each minute until the participants reached volitional exhaustion. Throughout the protocol, the treadmill incline was set at 1% to mimic the resistance encountered in outdoor running conditions [25]. The additional load (i.e., 5% and 10% of body mass) was added through a weighted vest (Jack, Elksport, Zaragoza, Spain). The weighted vest features multiple pockets on both the front and back, designed to accommodate 300 g bags. This design facilitates precise control over the additional load and ensures an even distribution of extra weight. The same protocols under the corresponding overload conditions were conducted one week apart and at approximately the same time of day.

2.3. Material and Testing

For descriptive purposes, participants' height (cm) and body mass (kg) were determined using a precision stadiometer and a weighing scale (SECA 222 and 634, respectively, SECA Corp., Hamburg, Germany). Additionally, body fat (mm) was also calculated as the sum of 6 specific point skinfolds (i.e., subscapular, triceps, abdominal, supraspinal, iliac crest, and front thigh) using a slim guide skinfold caliper (Harpenden, British Indicators, Burgess Hill, West Sussex, UK). All instruments were adjusted before their use and measurements were taken following the guidelines of the International Society of the Advancement of Kinanthropometry (ISAK) [26]. A description of participants' characteristics is available in Table 1.

Table 1. Descriptive characteristic of the participants (mean ± SD).

Variable	Mean ± SD
Age (years)	37.8 ± 5.9
Height (m)	176.3 ± 4.7
Body mass (kg)	72.2 ± 4.9
Σ 6 skinfolds (a. u.)	65.8 ± 15.0
Training volume ($km \cdot w^{-1}$)	49.7 ± 20.7
Time in 10 km race (min)	40.4 ± 3.0

$\dot{V}O_2$ and $\dot{V}CO_2$ during the trials was recorded using a portable gas analyzer (Cosmed K5, L.L.C. Rome, Italy) in breath-by-breath mode [27]. Before conducting any tests, the K5 was calibrated in line with the manufacturer's guidelines, which are as follows: (1) calibrating with room air, (2) calibrating the flow meter with a 3-L syringe, (3) calibrating the scrubber to zero the CO_2 analyzer, (4) calibrating with a reference gas consisting of 16% oxygen (O_2), 5% carbon dioxide (CO_2), and 79% nitrogen (N_2), and (5) performing a delay calibration specifically for the breath-by-breath mode. Data collection was averaged each 15 s to smooth the graphs and facilitate the detection of inflection zones. Subsequently, $\dot{V}O_2$max and ventilatory thresholds 1 and 2 (VT1 and VT2) were individually determined for each runner according to the V-slope method proposed by Wasserman et al. and described elsewhere [28,29]. All physiological determinations were performed independently by one investigator in a blinded manner (i.e., without knowing to which subject and which overload condition the test corresponded), with two cases of failed detection and the breath-by-breath data from another participant ultimately being removed due to equipment malfunctions during one test. Additionally, the respiratory exchange ratio (RER) was also registered at VT1, VT2, and exhaustion.

Capillary blood samples were taken from the fingertip one minute after the test to measure peak blood lactate concentration (La^-), in $mmol \cdot L^{-1}$, using Lactate Scout+

(EKF Diagnostics, Leipzig, Germany). Maximal exertion was defined by the following criterion [30]: (1) a discernible plateau of $\dot{V}O_2$, (2) [La+] $\geq$ 8 mmol·L^{-1} or (3) RER $\geq$ 1.10.

Absolute mechanical power output (in W) and the mechanical power output normalized to body mass (in W·kg^{-1}) were registered with the Stryd™ powermeter (Stryd powermeter, Stryd Inc., Boulder, CO, USA) attached to the runners' shoelaces. Despite the validity of Stryd not having yet been evaluated against gold standard methods, recent studies position it as the leading wearable sensor available, showing the highest level of agreement with theoretical methods of running mechanical power calculation [31] and measured metabolic power [23]. Data from Stryd™ were extracted from the manufacturers' official website (https://www.stryd.com/eu/es (accessed on 21 March 2024)) into separated .csv files. Then, power was averaged from the middle 30 s of each 1 min speed stage to avoid errors arising from adaptation. Finally, the data were transferred to an Excel® file (2023, Microsoft, Inc., Redmond, WA, USA), and the power outputs associated with the speeds at VO_2max, VT1, and VT2 were obtained based on the recorded data.

In addition, the metabolic cost of transport (CoT), (i.e., the amount of energy required for a runner to move at a specific speed) was also calculated for all speeds associated with the physiological milestones determined in each test, using the following formula (Equation (1)).

$$\text{Cost of Transport (J} \times \text{kg}^{-1} \times \text{m}^{-1}\text{)} = \text{Metabolic power (W/kg)/speed (m} \times \text{s}^{-1}\text{)} \quad (1)$$

Metabolic power (in W·kg^{-1}) was obtained from oxygen consumption data following the conversion proposed by Péronnet and Massicotte [32] assuming zero protein metabolism. Subsequently, it was transformed to J/kg to calculate CoT.

2.4. Statistical Analyses

A preliminary power calculation was conducted using G*POWER 3.1.9.7 (University of Dusseldorf, Dusseldorf, Germany) indicating that a sample of 15 subjects was required to observe an effect size f = 0.35, assuming an alpha level of α = 0.05 and a power of 1-β = 0.8. Although existing research suggests a strong correlation between VO_2max values derived from various maximal exercise protocols (r = 0.78–0.93) [33,34], the present study adopted a more cautious approach by selecting an effect size analogous to η^2p = 0.14.

Descriptive statistics are presented as means ± standard deviations (SD) and 95% confidence intervals (CI) for all variables. The Shapiro–Wilk test was conducted to confirm data distribution normality and Mauchly's test to validate the assumption of sphericity. A one-way repeated-measures ANOVA was used to evaluate the effect of extra load on the variables of interest. Finally, post hoc analyses with Bonferroni's adjustment were also conducted to determine the significant differences between the three conditions studied. Effect sizes (ESs) for all pairwise comparisons were also calculated using partial eta squared (η^2p) and interpreted as follows: small $\geq$ 0.01, medium $\geq$ 0.06, large $\geq$ 0.14). A statistically significant level was defined as 0.05. Data analysis was performed using SPSS (version 29, SPSS Inc., Chicago, IL, USA).

3. Results

Table 2 summarizes the acute physiological and mechanical responses during an incremental running protocol under three different overload conditions. Peak values alongside with the VT1 and VT2 corresponding data are shown for the three evaluated runs (i.e., +0, +5 and +10% of body mass).

The repeated-measures ANOVA revealed a detrimental effect of the additional load on peak velocity (p < 0.001, $F_{2.28}$ = 12.886, η^2p = 0.54), velocity at VT1 (p = 0.003, $F_{2.28}$ = 7.176, η^2p = 0.34), and velocity at VT2 (p < 0.001, $F_{2.28}$ = 22.804, η^2p = 0.62). Additionally, $\dot{V}O_2$ VT2 (p = 0.047, $F_{2.28}$ = 3.421, η^2p = 0.20), power VT2 (p = 0.021, $F_{2.28}$ = 5.309, η^2p = 0.27), normalized power VT2 (p = 0.012, $F_{2.28}$ = 6.750, η^2p = 0.32), and CoT VT2 (p = 0.013, $F_{2.28}$ = 5.117, η^2p = 0.27) also displayed a significant influence of extra load. Furthermore,

no other peak or VT1 values showed a significant effect of extra load. Table 3 shows the main effect of running with a weighted vest on the physiological and mechanical variables of interest. The differences found in the post hoc analysis between the three conditions evaluated are also presented in the table and illustrated in Figure 2.

Table 2. Physiological and mechanical responses (mean ± SD, 95% CI) during an incremental running protocol under three different overload conditions (+0, +5 and +10% of body mass).

Peak Values	+0% BM		+5% BM		+10% BM	
	Mean ± SD	95% CI	Mean ± SD	95% CI	Mean ± SD	95% CI
$\dot{V}O_2$ (mL·min^{-1}·kg^{-1})	59.4 ± 6.7	55.7–63.1	59.1 ± 5.7	56.0–62.3	57.0 ± 5.5	54.0–60.1
Power (W)	338 ± 27	323–353	337 ± 32	320–355	346 ± 35	327–366
nPower (W·kg^{-1})	4.6 ± 0.4	4.4–4.9	4.7 ± 0.3	4.5–4.9	4.8 ± 0.4	4.6–5.0
Speed (km·h^{-1})	17.1 ± 1.2	16.4–17.7	16.5 ± 1.0	15.9–17.0	15.9 ± 1.0	15.3–16.4
RER	1.09 ± 0.08	1.04–1.14	1.08 ± 0.06	1.04–1.12	1.07 ± 0.09	1.02–1.12
Lactate (mmol/L)	11.4 ± 4.1	9.1–13.6	11.0 ± 3.4	9.1–12.8	12.6 ± 4.6	10.1–15.1
CoT (J·kg^{-1}·m^{-1})	4.2 ± 0.6	3.9–4.6	4.3 ± 0.5	4.1–4.6	4.4 ± 0.4	4.1–4.6
VT1						
$\dot{V}O_2$ (mL·min^{-1}·kg^{-1})	35.1 ± 3.9	33.2–37.4	34.3 ± 3.4	32.5–36.6	34.2 ± 3.9	31.8–36.0
r$\dot{V}O_2$ (%)	59.4 ± 0.3	57.7–61.1	58.9 ± 0.3	57.5–60.4	60.0 ± 0.3	58.1–61.0
Power (W)	200 ± 23	187–213	204 ± 16	195–212	208 ± 23	195–220
nPower (W·kg^{-1})	2.7 ± 0.4	2.5–2.9	2.8 ± 0.2	2.7–2.9	2.9 ± 0.3	2.7–3.0
Speed (km·h^{-1})	9.5 ± 0.9	9.0–10.0	9.2 ± 0.6	8.9–9.5	8.9 ± 0.8	8.4–9.3
RER	0.82 ± 0.04	0.80–0.84	0.82 ± 0.06	0.78–0.85	0.81 ± 0. 06	0.77–0.84
CoT (J·kg^{-1}·m^{-1})	4.5 ± 0.6	4.2–4.9	4.5 ± 0.4	4.3–4.8	4.7 ± 0.6	4.3–5.0
VT2						
$\dot{V}O_2$ (mL·min^{-1}·kg^{-1})	49.6 ± 5.1	46.8–52.4	49.0 ± 4.0	46.8–51.2	47.9 ± 4.6	45.3–50.4
r$\dot{V}O_2$ (%)	83.6 ± 0.3	81.9–85.3	83.7 ± 0.3	81.9–85.6	83.3 ± 0.3	81.5–85.2
Power (W)	277 ± 27	263–292	278 ± 20	268–289	291 ± 17	282–300
nPower (W·kg^{-1})	3.8 ± 0.4	3.6–4.0	3.8 ± 0.2	3.7–4.0	4.0 ± 0.3	3.9–4.2
Speed (km·h^{-1})	14.0 ± 1.1	13.4–14.6	13.1 ± 0.7	12.7–13.5	12.7 ± 1.0	12.1–13.2
RER	0.94 ± 0.03	0.93–0.96	0.93 ± 0.05	0.90–0.96	0.96 ± 0. 07	0.91–0.99
CoT (J·kg^{-1}·m^{-1})	4.3 ± 0.5	4.0–4.6	4.4 ± 0.3	4.1–4.7	4.6 ± 0.5	4.3–4.9

+0% BM: body mass running; +5% BM: running with a 5% of body mass weighted vest; +10% BM: running with a 10% of body mass weighted vest; $\dot{V}O_2$: rate of oxygen consumption; r$\dot{V}O_2$: rate of oxygen consumption relative to peak value; nPower: power normalized to kg; RER: respiratory exchange ratio; CoT: cost of transport.

Table 3. Repeated-measures ANOVA results for physiological and mechanical variables of interest. Effect of extra load and pairwise comparisons (with Bonferroni correction) between the +0, +5, and 10% of body mass, along with calculated effect sizes (η^2p).

Peak Values	Extra load *p*-Value (ES)	+0 vs. +5%BM *p*-Value (ES)	+5 vs. +10%BM *p*-Value (ES)	+0 vs. +10%BM *p*-Value (ES)
$\dot{V}O_2$ (mL·min^{-1}·kg^{-1})	0.008 * (0.29)	1.000 (0.01)	0.076 (0.31)	0.025 * (0.40)
Power (W)	0.243 (0.10)	1.000 (0.00)	0.326 (0.17)	0.679 (0.10)
nPower (W·kg^{-1})	0.268 (0.20)	1.000 (0.01)	0.204 (0.22)	0.140 (0.25)
Speed (km·h^{-1})	<0.001 ** (0.54)	0.069 (0.32)	0.008 * (0.49)	<0.001 ** (0.67)
RER	0.476 (0.05)	1.000 (0.02)	1.000 (0.03)	0.675 (0.10)
Lactate (mmol/L)	0.207 (0.11)	1.000 (0.02)	0.340 (0.17)	0.749 (0.09)
CoT (J·kg^{-1}·m^{-1})	0.185 (0.11)	0.390 (0.16)	1.000 (0.01)	0.539 (0.12)
VT1				
$\dot{V}O_2$ (mL·min^{-1}·kg^{-1})	0.198 (0.11)	0.492 (0.13)	1.000 (0.01)	0.436 (0.15)
r$\dot{V}O_2$ (%)	0.170 (0.12)	0.798 (0.09)	0.131 (0.26)	1.000 (0.02)
Power (W)	0.248 (0.09)	1.000 (0.06)	0.941 (0.07)	0.537 (0.13)
nPower (W·kg^{-1})	0.102 (0.16)	0.546 (0.12)	0.636 (0.11)	0.251 (0.20)
Speed (km·h^{-1})	0.003 * (0.34)	0.311 (0.18)	0.058 (0.33)	0.021 * (0.42)
RER	0.333 (0.12)	1.000 (0.01)	0.829 (0.09)	0.440 (0.10)
CoT (J·kg^{-1}·m^{-1})	0.604 (0.07)	1.000 (0.00)	0.379 (0.07)	0.883 (0.04)

Table 3. *Cont.*

Peak Values	Extra load *p*-Value (ES)	+0 vs. +5%BM *p*-Value (ES)	+5 vs. +10%BM *p*-Value (ES)	+0 vs. +10%BM *p*-Value (ES)
VT2				
$\dot{V}O_2$ (mL·min^{-1}·kg^{-1})	0.047 * (0.20)	1.000 (0.06)	0.445 (0.14)	0.050 (0.34)
r$\dot{V}O_2$ (%)	0.618 (0.03)	1.000 (0.00)	1.000 (0.05)	1.000 (0.04)
Power (W)	0.021 * (0.27)	1.000 (0.00)	0.108 (0.28)	0.019 * (0.42)
nPower (W·kg^{-1})	0.012 * (0.32)	1.000 (0.03)	0.058 (0.33)	0.006 * (0.51)
Speed (km·h^{-1})	<0.001 ** (0.62)	0.084 (0.30)	0.001 * (0.59)	<0.001 ** (0.70)
RER	0.499 (0.05)	1.000 (0.04)	0.880 (0.08)	1.000 (0.02)
CoT (J·kg^{-1}·m^{-1})	0.013 * (0.27)	1.000 (0.02)	0.070 (0.32)	0.042 * (0.36)

* $p < 0.05$; ** $p < 0.001$; ES: effect size; +0% BM: body mass running; +5% BM: running with 5% of body mass weighted vest; +10% BM: running with a 10% of body mass weighted vest; $\dot{V}O_2$: rate of oxygen consumption; r$\dot{V}O_2$: rate of oxygen consumption relative to peak value; nPower: power normalized to kg; RER: respiratory exchange ratio; CoT: cost of transport.

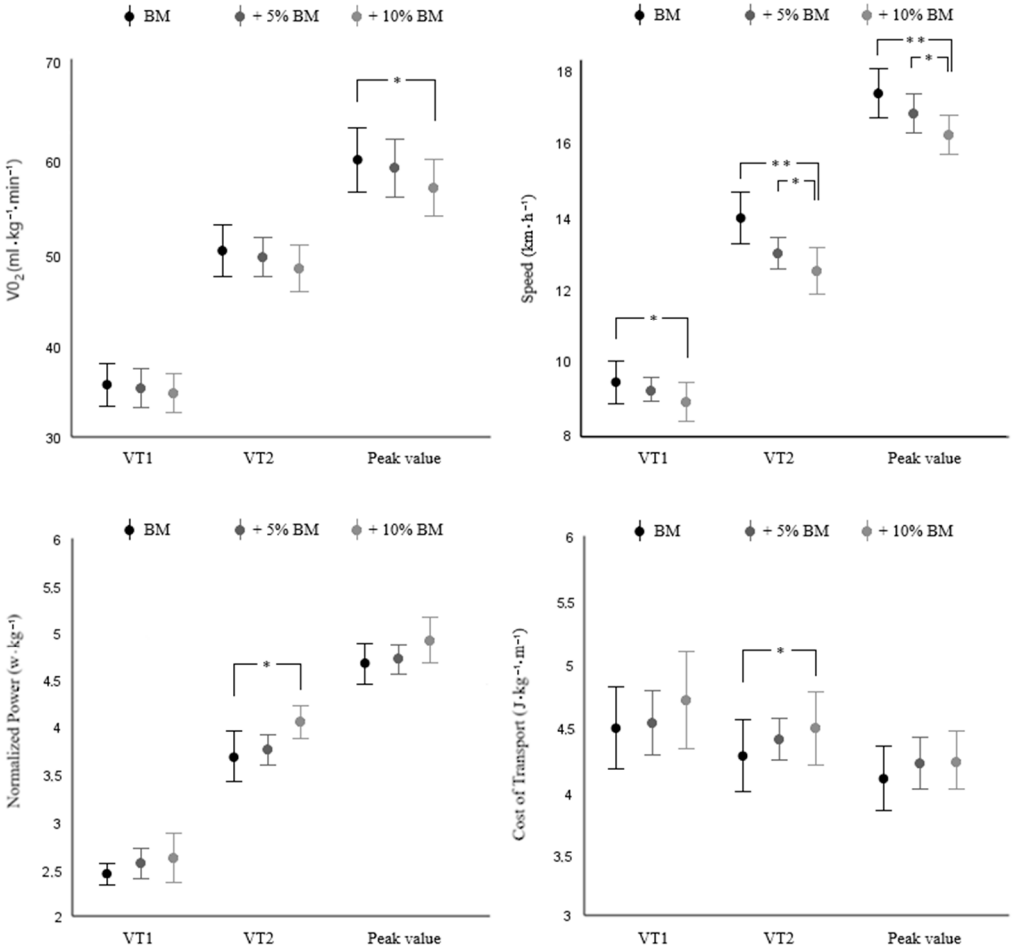


Figure 2. Comparison of the acute physiological and mechanical responses of experienced trail runners during an incremental running protocol under three different overload conditions (+0%, +5%, and +10% BM). Peak values and values at ventilatory threshold intensities 1 and 2 are presented for the main variables of interest. * $p < 0.05$; ** $p < 0.001$.

4. Discussion

The aim of the present work was to evaluate the effects of running with an additional load on peak physiological values and ventilatory threshold during a maximal incremental test in trained trail runners. In addition, the running power and cost of transport associated

with $\dot{V}O_2$ peak and ventilatory thresholds 1 and 2 were also compared between three overloaded conditions (i.e., +0, +5, and +10% BM).

The main findings of this work were as follows: (i) the maximum speed and speed at ventilatory thresholds were significantly affected by the excess in the vest's load ($p \leq 0.003$), with large effect sizes (0.34–0.62); (ii) the increase in wearable resistance had a moderate effect on $\dot{V}O_2$ peak, although the r$\dot{V}O_2$ values (in %) at VT1 and VT2 were not affected; (iii) power was not significantly influenced by the overload of the vest at peak and VT1 values, but it showed a detrimental effect at VT2 (ES $\approx$ 0.30).

4.1. Physiological Effects

The maximality of the trials was controlled by $\dot{V}O_2$ levelling-off (i.e., three consecutive points with an increase <100 mL/min), blood lactate at the end of every trial (13.2 $\pm$ 4.2 $mmol^{-1}$), and peak RER (1.08 $\pm$ 0.08). Despite the fact peak blood lactate and RER showed no significant differences between the three studied conditions, it must be acknowledged that ~60% of participants failed to achieve all three maximality criterion (i.e., $\dot{V}O_2$ plateau, [La+] $\geq$ 8 $mMol \cdot L^{-1}$ or RER $\geq$ 1.10) and a test was taken as valid if volitional exhaustion was reached under the other two conditions. Endurance training has been linked to a reduction in the RER at a given running speed, indicating an increased reliance on lipids as the energy source for the exercise [35]. Therefore, the somewhat low RER values reported here could be partially explained as an adaptation to endurance training.

Strikingly, the $\dot{V}O_2$ peak was significantly lower as the additional load increased (p = 0.008; ES = 0.29), particularly in the +10% BM condition. In this regard, Poole and Jones [36] raised the question about $\dot{V}O_2$max determination and its consideration as a gold standard measurement of cardiopulmonary-muscle oxidative function. Their main concern was about the arbitrarily selected cut-off values to confirm the maximality of the tests. Thus, many researchers opted for incorporating confirmatory tests and assumed the higher $\dot{V}O_2$max as the true maximal value [36]. Interestingly, these authors confirmed previous evidence pointing that shorter duration tests tend to underestimate $\dot{V}O_2$max calculation [37]. A possible explanation for this finding could be that the increase in workload produces an elevation in the RER for the same $\dot{V}O_2$ level. In fact, when the work rate increases, the HCO_3—buffering of H+ ions derived from lactic acid will become faster. This means that the rate of CO_2 output may be greater, because it tracks the rate of H+ buffering, without a necessary increase in $\dot{V}O_2$ [37]. Another explanation would be a shift towards peripheral fatigue due to overloading [38], although volitional aspects related to vest discomfort could be a confounding factor.

Of note, RER and r$\dot{V}O_2$ (%) at VT1 and VT2 did not change significatively throughout the trials, whereas CoT experimented a slight increase at VT2 due to extra load (p = 0.013; ES = 0.27). Again, the increase in CoT was particularly observable in the +10% BM condition, and arguably it may be due to the lower peak $\dot{V}O_2$ values reported under this condition. Previous evidence on the running CoT is inconsistent [35,39,40]. On the one hand, it is known that fatigue induces a degradation of CoT [40], while other authors argue for the existence of a quadratic trend with increasing speed [39], such that an optimal CoT is reached at intermediate speeds. Regarding overloaded running, a previous study [11] also found that running with light loads (i.e., +5% BM) increased leg stiffness, while moderate loads (i.e., +10% BM) prevented the optimization of elastic energy reutilization. In this context, greater leg stiffness has been shown to correlate highly with a lower CoT and improved performance [41].

4.2. Mechanical Effects

This maximal speed during the test and speed at the physiological boundaries here reported were lower as the load increased ($p \leq 0.003$; ES: 0.34–0.62). Moreover, based on a previous work [11], it was hypothesized that the mechanical effects of submaximal running

with an extra load would be load-specific. Indeed, the response to excess load does not seem to be linear, with moderate effects observed between +0 and +5% BM (ES: 0.18–0.32) and very large effects between +5 and +10% BM conditions (ES: 0.33–0.59).

Of note, absolute and normalized (to BM) power revealed no significant changes at VT1 and exhaustion regardless of the increase in vest load, whereas moderate-to-large effects were observed at VT2 (ES: 0.27–0.51). Pairwise comparisons revealed negligible effects (ES: 0.00–0.03) between +0 and +5% BM, while large effects were found between +5 and +10% conditions (ES: 0.42–0.51). On the one hand, current knowledge about novel running power sensors indicates that their reliability increases at aerobic paces, whereas the reported variability spikes at high intensities [23,42]. On the other hand, the environment around the second ventilatory threshold (VT2) is characterized by the onset of metabolic instability, which could also jeopardize their running technique and affect the variables involved in the estimation of power data, such as step frequency. Despite these considerations, running power seems to be a more stable metric than speed for working at aerobic paces, regardless of the vest weight.

Despite the findings presented herein, some limitations must be acknowledged. First, the sample size (n = 15) was adequate but may need to be increased in future studies to validate the obtained results. Additional populations of trail runners (elite, females, recreational) should be tested to identify the potential differences between groups. Another limitation identified in this study is the discomfort caused by the weighted vest. Although it allowed for the extra load to be evenly distributed, the recommendation for future trials is to use appropriate trail running vests to minimize discomfort and ensure maximum specificity. Notwithstanding these limitations, the present study provides valuable insights into the acute biomechanical and physiological responses to running with an additional load. To gain a more comprehensive understanding of trail running conditions, future research should consider both positive and negative slopes, as well as in-field protocols to explore potential interactions with an additional load.

5. Conclusions

Running with a weighted vest impacts one's performance in trail running. The current work indicates that the magnitude of the carried load affects the speed at which key physiological milestones occur in a nonlinear manner, with a greater and disproportionate deterioration for loads of +10% BM compared to +5% BM, than for +5% BM compared to running without a load. Trail runners and coaches should consider their running power given its greater stability in comparison with speed for prescribing training load in weighted running conditions, particularly at aerobic intensities, which is usual in competitions for longer distances (i.e., $\geq$42 km).

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