ORIGINAL ARTICLE

Morpho-functional characterization of an elite Chilean mountain runner: Insights from a high-performance case study

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ABSTRACT

Trail running (TR) is an endurance sport practised on irregular natural terrain with significant elevation changes. The aim was to analyse cardiorespiratory fitness parameters, bilateral body composition and maximal strength profiles in the lower limbs of elite Chilean trail runners. A 26-year-old Chilean amateur ultra trail runner was studied (body weight: 62.3 kg, height: 1.71 m, BMI: 21.2 kg/m², lean mass: 54 kg (86.6%), muscle mass: 30.3 kg (48.6%), fat mass: 8.3 kg (13.3%) and a skeletal muscle mass index of 7.5 kg/m²). The subject participated in three laboratory sessions: 1) anthropometric and pulmonary measurements, 2) cardiopulmonary exercise testing (CPET) with heart rate variability (HRV) assessment, and 3) isometric and isokinetic lower limb strength assessment. During the CPET, VO_{2max}, ventilatory and HRV thresholds were measured using the DFA a1 algorithm. Quadriceps muscle oxygen saturation (SmO_2) was also recorded. The runner presented a VO_{2max} of 75 ml/kg/min. SmO_2 values during CPET were 67.2% at rest, 38.5% at VT_1, 26.8% at VT_2 and 17.2% at VO_{2max}. The results showed that the first heart rate variability threshold ($HRVT_1$) coincided with the ventilatory thresholds (VT_1 and VT_2). Isometric and isokinetic evaluation revealed a higher eccentric flexion/concentric extension ratio in the right hip compared to the left, with values of 2.58 for the right and 2.25 for the left. Aerobic fitness is essential for trail running performance. Ventilatory thresholds and HRV, together with SmO_2, may be useful tools for monitoring muscle fatigue. The observed muscle strength imbalances between limbs highlight the importance of training for strength symmetry to maximise performance and reduce the risk of injury. Future studies on muscle oxygenation, respiratory function and muscle asymmetries may improve training strategies in TR.
Keywords: Performance analysis, Endurance performance, Off-road running, Mountain running, Elevation gain, Physiology, Cardiorespiratory.

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INTRODUCTION

Trail running (TR) is an endurance sport performed on irregular natural terrain, often characterised by significant variations in altitude (Giovanelli, Ortiz, Henninger, & Kram, 2016). The unique demands of TR, such as uneven surfaces and steep slopes, place substantial physiological stress on the musculoskeletal system (e.g., eccentric impact), as well as on the cardiorespiratory and aerobic energy systems (e.g., sudden shifts in energy requirements), exceeding those typically encountered in road races like marathons (Vernillo et al., 2017). Training in natural environments elevates the metabolic cost of running, thereby fostering greater development of aerobic capacity (Millet, Martin, Lattier, & Ballay, 2011; Scheer, Vieluf, Janssen, & Heitkamp, 2019). In this context, higher levels of maximal oxygen uptake (VO_{2max}) (Balducci, Clémençon, Trama, Blache, & Hautier, 2017; Ehrström, Tartaruga, Easthope, Brisswalter, Morin, & Vercruyssen, 2018) and improved intensity at metabolic thresholds have been linked to better performance in TR athletes (Scheer et al., 2019; Vernillo et al., 2017).

Recent studies highlight the utility of heart rate variability (HRV), derived from nonlinear analyses of electrocardiogram RR intervals, for detecting key metabolic thresholds (both aerobic and anaerobic) (Task Force of the European Society of Cardiology and the North American Society of Pacing and Electrophysiology, 1996). Among the various methods, the alpha-1 detrended fluctuation analysis (DFA a1) algorithm has gained traction due to its reliability in identifying these thresholds (Schaffarczyk et al., 2023).

Compared to road runners, TR training has been shown to significantly enhance lower limb strength (Balducci et al., 2017). This strength gain is attributed to the demands of uphill running, which involves greater concentric muscle activity, and downhill running, which requires heightened eccentric muscle activity, both of which are integral to TR races (Sabater-Pastor, Tomazin, Millet, Verney, Féasson, & Millet, 2023; Drum, Rappelt, Held, & Donath, 2023). Although hip strength adaptations are expected as well, this aspect remains under-documented. Furthermore, not only is maximal strength in key muscle groups crucial for performance, particularly in lower limbs, but so too is balance between agonist and antagonist muscle forces, as well as bilateral symmetry across body segments (Schache, Blanch, Rath, Wrigley, & Bennell, 2001). Muscle imbalances could have a detrimental impact on TR performance (Gabbett, 2016) and maintaining symmetrical muscle mass distribution is essential for minimising the risk of musculoskeletal injury (Zifchock, Davis, & Hamill, 2006).

This study aimed to analyse the cardiorespiratory fitness parameters during a cardiopulmonary exercise test (CPET), bilateral body composition, and maximal strength profiles of the lower limbs in an elite Chilean trail runner. This holistic approach provides valuable insights into the physiological and biomechanical demands placed on elite trail runners, highlighting critical factors such as oxygen uptake, muscle imbalances, and strength asymmetries that could impact performance and injury risk.

By focusing on an elite Chilean trail runner, this case study aims to contribute to understanding how specific physical and metabolic adaptations in high-performance athletes can be optimised for enhanced endurance and performance in trail running. This case-kind type of approach is common in the literature and valuable to understand how high-level ultra runners perform, considering its unique characteristics and a limited number of athletes (Millet, & Jornet, 2019; Garcia de Dionisio, Gómez-Carmona, Bastida-Castillo, Rojas-Valverde, & Pino-Ortega; 2020).

METHODOLOGY

Participant

This study was conducted on a high-performance Chilean male amateur ultra-trail runner with a Ultra Trail Mont-Blanc® (UTMB) index of 828 (highest UTMB index 935) who competes in the categories ultra-trail short (<43 km) and medium (43-69 km) and qualified for UTMB World Series Finals. This level allows him to be considered the best in his category in Chile in 2024. The runner was asked to visit the laboratory three times for morpho functional measurements in May 2024. For the evaluation date, the age of the athlete was 26 years, body weight 62.3 kg, height 1.71m, BMI 21.2 kg/m², lean mass 54 kg (86.6%), muscle mass 30.3 kg (48.6%), fat mass 8.3 kg (13.3%) and a skeletal mass index of 7.5 kg/m² (Table 1). According to his sports planning, the subject has complied with a volume of 15 ± 3 hours of physical training distributed in 15.6% of general physical preparation (place exercises), 35.4% of cycling, 25% of running and 24% of TR runs (characteristics).

The variables of training reported were volume (403 h/year), distance (4107 km/year), distance climbed (58795 m/year), and internal training load according to the TRIMP score (Foster et al., 2001). The procedures that were carried out to obtain the study variables were made known to the athlete before starting the measurements and after signing a written informed consent. All procedures were approved by the Scientific Ethics Committee of the Universidad Viña del Mar (Code R62-19a) and were carried out following the ethical recommendations described in the Declaration of Helsinki.

Table 1. General and anthropometric characteristics.

Parameters	Value
Age (y)	26
Sex	male
Weight (kg)	62.30
Height (m)	1.71
Muscle mass (kg)	30.30
Fat mass (kg)	8.30 (13.30%)
BMI (kg/m^2)	21.30
Lean body mass (kg)	54.00
Skeletal mass index (kg/m^2)	7.50

Procedures

The assessment was performed in the laboratory of the Kinesiology School of the Andres Bello University of Viña del Mar, Chile. The three evaluation days were separated by 24 and 48 hours of rest. All measurements were carried out between 10:00 am and 12:00 am. The distribution of these was as follows: day 1: anthropometric and pulmonary measurements (i.e., spirometry, and respiratory pressures), day 2: 24 hours later CPET (i.e., VO_{2max}, heart rate) with determination of heart rate variability (RR time series), and day 3: 48 hours later isometric and isokinetic lower limbs strength assessments were carried out. Before and during the evaluation period, it was recommended to avoid the consumption of any stimulant or diuretic food or liquid (e.g., coffee or tea) in the hours prior to the evaluation sessions.

Cardiopulmonary exercise testing

CPET was performed with a metabolic cart (Metalyzer 3B, CortexMedical, Germany). Before starting the exercise, 1 minute of rest was recorded. Physical exercise was performed on a treadmill (Runrace, Technogym, Italy) in 1-minute stages (S) with changes in speed and gradient as follows: S1: 5.5 km/h and

0%, S2: 7 km/h and 1%, S3: 7 km/h and 5%, S4: 8 km/h and 5%, S5: 8 km/h and 10%, S6: 9 km/h and 10%, S7: 9 km/h and 15% and S8: 10 km/h and 15%. From stage 9 on, the speed was increased by 1 km/h every minute, maintaining a constant slope of 15% until fatigue.

The VO_{2max} and ventilatory thresholds (VT_1 and VT_2) were obtained from the CPET following previous recommendations (Binder et al., 2008). During CPET, RR time series values were also obtained with a chest strap (H10, Polar, Finland), which were recorded with a heart monitor (V800, Polar, Finland) to calculate heart rate variability (HRV) thresholds through the Kubios program (version 3.1.0, University of Eastern Finland, Kuopio, Finland). In addition, the quadriceps muscle's oxygen saturation (SmO_2) was recorded with near-field infrared spectroscopy equipment (Moxy monitor, Fortiori Design LLC, USA) throughout the test.

Heart Rate Variability Thresholds

RR time series during exercise (i.e., CPET) were downloaded from the heart monitor (V800, Polar, Finland) using the Polar Flow program (version 3.0.0.1337, Polar Finland). Subsequently, data collected with a sampling frequency of 1000 Hz were analysed by the Kubios HRV analysis program (version 3.1.0, University of Eastern Finland, Kuopio, Finland). According to previous recommendations, the DFA a1 algorithm was used to determine HRV thresholds with a time window of 120 seconds (Chen et al., 2002). A DFA a1 just below 0.75 and 0.5 was used to obtain $HRVT_1$ and $HRVT_2$ respectively (Rogers et al. 2021).

Spirometry and inspiratory muscle strength

Lung volumes were measured via forced spirometry with a metabolic cart (Metalyzer 3B, CortexMedical, Germany). Respiratory muscle strength was estimated from the measurement of peak inspiratory/expiratory pressures (PI_{max} [cmH_2O]/PE_{max} [cmH_2O]) with an electronic manovacuometer (MicroRPM, Carefusion, USA). The protocols recommended by the American Thoracic Society and the European Respiratory Society (ATS/ERS 2002) were used for both measurements. Prior to the spirometry measurements, the equipment was calibrated with a 3-liter syringe. Then, FEV_1 (L), FVC (L), and FEV_1/FVC (%) were recorded. Familiarisation of the use of the devices was performed for both evaluations.

For respiratory pressures (strength) only, a warm-up was performed at 40% of the highest inspiratory and expiratory pressure during familiarization (Volianitis, McConnell, & Jones, 2001). The warm-up consisted of two sets of 15 repetitions with a one-minute rest between each set. Both times, respiratory pressures were measured with the subject seated (with a chair fixed to the floor), with the soles of the feet resting on the floor (shoulder-width apart), and with a nose clip.

Isokinetic strength evaluation of the lower limbs

Concentric (Con) and eccentric (Ecc) isokinetic strength of the hip and knee muscles was assessed with a functional electromechanical dynamometer (Health, Dynasystem, Simotech). Hip abduction, adduction, extension and flexion, and knee flexion and extension movements were assessed bilaterally at a speed of 0.5 m/s. Hip positions and movements were adjusted according to (Contreras et al., 2023) Concentric (90° to 180° degrees) and eccentric (180° to 90° degrees) extension and concentric (135° to 90° degrees) and eccentric (90° to 135° degrees) flexion of the knee were performed with the participant in a seated position in an open kinetic chain.

In addition, functional bilateral index of the stronger leg relative to the weaker leg were calculated (eccentric agonist/concentric antagonist). For the warm-up, body positioning, range of motion, and execution were standardised prior to the measurements.

RESULTS

Table 2. Cardiorespiratory and autonomic parameters during cardiopulmonary exercise test.

Parameters	Resting	VT_1 ($HRVT_1$)	VT_2 ($HRVT_2$)	Maximum effort
VO_2 (ml/min/kg)	2.0	41 (30.4)	58 (54.4)	74
$\%VO_{2max}$	2.0	60 (58)	77 (71.4)	100
HR (bpm)	51.0	140 (141)	160 (157)	175
$\%HR_{max}$	29.0	80 (81)	91 (90)	100
VE_{max} (L/min)	7.1	49.8 (55.8)	88.4 (87.1)	152
RER	0.75	0.83 (0.84)	1.01 (1.01)	1.16
Speed (km/h)		9 (9)	10 (10)	13
Grade (%)		10 (10)	15 (15)	15
MAS (km/h)				13 (15%-slope)
Quadriceps SmO_2(%)		38.5 (35.7)	26.8 (31.9)	17.2

Note. HR: heart rate; $HRVT_{1-2}$: heart rate variability thresholds one and two; MAS: maximal aerobic speed; RER: respiratory exchange rate; VT_{1-2}: ventilatory thresholds one and two.

Table 3. Muscle respiratory strength and pulmonary function

Assessment	Value (LLN)
Spirometry	
CVF (L)	5.09 (4.06)
VEF1 (L)	4.44 (3.39)
VEF1/CVF (%)	87
Respiratory muscle pressure	
PI_{max} (cmH_2O)	139
PE_{max} (cmH_2O)	171

Note. FVC: forced vital capacity, FEV_1: forced expiratory volume, LLN: Lower limit of normality.

Table 4. Isokinetic (0.5 m/s) and isometric strength peak and power in lower limbs.

Side	Movement	Isokinetic strength (kg)		Functional ratio
		Concentric	Eccentric	Ecc/Conc
Right Hip				
	Flexion	36.41	58.15	2.58
	Extension	22.50	29.69	
	Abductor	18.29	30.27	1.13
	Adductor	26.71	48.92	
Left Hip				
	Flexion	37.75	54.47	2.25
	Extension	24.20	29.20	
	Abductor	11.16	20.57	0.71
	Adductor	28.93	42.60	
Right knee				
	Flexion	44.71	42.31	0.91
	Extension	46.58	72.70	
Left knee				
	Flexion	41.44	71.42	1.61
	Extension	44.24	91.58	

Note. Conc: Concentric muscle action, Ecc: Eccentric muscle action.

Cardiopulmonary exercise test and Heart Rate Variability Thresholds

During the exercise test, the subject reached the maximum physiological effort parameters, reaching 91% of his predicted maximum heart rate and a respiratory exchange rate of 1.17.In addition to the cardiopulmonary and external load responses in energy thresholds obtained by ventilatory (VT_1 and VT_2) and heart rate variability ($HRVT_1$ and $HRVT_2$) methods, the maximum values for internal (cardiorespiratory) and external (i.e., speed) physiological loads are shown in Table 2.

Spirometry and respiratory pressures

Table 3 shows the normal values obtained from spirometry.

Lower limbs strength

Tables 4 shows the isokinetic hip and knee strength values, strength ratios of antagonistic muscle actions and bilateral muscle symmetry of both joints, respectively.

DISCUSSION

A higher aerobic aptitude is a fundamental factor for endurance athletes' performance in sports. In TR, this is no different; previous studies have shown that runners with better sporting performance have higher VO_{2max} values (Pastor, Besson, Varesco, Parent, Fanget, Koral, & Millet, 2022). In our participant, VO_{2max} was obtained with a maximal exercise test with increasing speed and gradient, reaching maximums of 13 km/h and 15%, respectively. Our participant had VO_{2max} of 74 ml/kg/min in the maximal incremental treadmill test (RER: 1.16), which was higher than those observed in the literature for his category (short and moderate distance ultra-trail) (~60-70 ml/kg/min (Fornasiero, Savoldelli, Fruet, Boccia, Pellegrini, & Schena, 2018). The effort (%VO_{2max}) at threshold VT_1 has been recognised as a strong predictor of performance in TR. Our athlete VT_1 was observed at 60% VO_{2max}, within the range observed in the scientific literature (Doucende et al., 2022). The velocity at VT_1 was lower with concerning to other studies 9 km/h vs 13.3 km/h (Scheer et al.,2019) and 11.2 km/h (Martinez-Navarro et al., 2021), which can be explained by a higher slope reached during the test at that point, i.e., (10% vs 1.0% (Scheer et al.,2019) and 0% (Scheer et al.,2019). It is worth noting that higher slope values (~15-25%) achieved in a maximal effort test have been strongly related to trail running performance in the laboratory and field (Doucende et al., 2022).

Along the same lines, the first threshold of heart rate variability ($HRVT_1$) showed similarity with physiological variables related to the first (VT_1) and second ventilatory threshold (VT_2). Previous studies have shown a high reliability of using HRV to detect metabolic system transition thresholds (Kaufmann et al.,2023). The low complexity and cost of HRV could enhance its use in the control of training in trail running, as has occurred in other endurance sports (Lundstrom et al., 2022). Likewise, SmO_2 also had close values with ventilatory thresholds (ΔSmO_2; VT_1-$HRVT_1$: -2.8% and VT_2-$HRVT_2$: +4.9%). This is very relevant since it would allow studying the oxygen delivery/utilization of the main locomotor muscle during the race, showing the muscle metabolic adjustments due to the duration (time of the race) and the slopes of the course (positive or negative). This will allow, among other things, the adjustment of nutritional supplementation during the race. Currently, in the scientific literature, there is no SmO_2 data on trail runners; however, given the convenience of its use and the reliability of the measurements, it will be necessary to guide studies in the analysis of muscle oxygenation in this sport.

From the onset of the maximal exercise test, the participant was proportionally increasing the oxygen demand (SmO_2) of the primary locomotor muscle (i.e., quadriceps) with decreases in saturation of 67.2%, 38.5%, 26.8% and 17.2% for resting, VT_1, VT_2 and VO_{2max}, respectively. These findings are consistent with results obtained in other endurance sports (Vasquez Bonilla et al., 2023). Therefore, further studies evaluating the use of SmO_2 to monitor muscle fatigue thresholds in real time would be beneficial, allowing more accurate adjustments to training loads (Murias et al., 2013).

The pulmonary function study showed that the participant has higher capacities and volumes than predicted for age, sex and height from the Global Lung Function Initiative. A FVC of 5.09 l (predicted FVC: 4.61 l), FEV_1 of 4.44 l (predicted FEV_1: 3.93 l), and an FEV_1/FVC ratio of 87% (predicted FEV_1/FVC: 85.3%) are indicative of lung function within ranges in mountain ultramarathon runners (Martinez-Navarro et al., 2020). Respiratory muscle pressures have shown a high correlation with performance in endurance athletes (Martinez-Navarro et al., 2020). Our athlete showed slightly higher values in inspiratory pressure (139 cmH_2O) and slightly lower values in expiratory pressure (171 cmH_2O) with respect to predicted for his sex and age against a sample of healthy males (PI_{max}: 136.2 ± 25.1 cmH_2O; PE_{max}: 184 ± 39.5 cmH_2O) (Lista-Paze et al. 2023). Higher basal PI_{max} may have a greater beneficial effect on performance, as it was previously shown that a long-duration ultra-trail run significantly decreased PI_{max} in a sample of competitive male trail runners (PI_{max} pre-run: 115.74 ± 20.92 cmH_2O; PI_{max} post-run: 92.0 ± 20.0 cmH_2O; Δ-26.1%) (Martinez-Navarro et al., 2021). It should be noted that the participant in our study had not specifically trained the respiratory musculature before.

In trail runners, concentric gluteal and quadriceps strength for hip and knee extension, respectively, will be required during ascents on positive slopes and eccentric strength during descents with negative slopes. In the evaluated athlete, we observed that the concentric isokinetic force during hip extension was similar (left: 24.20 kg vs right 22.50 kg). However, the isokinetic concentric extension at the knee was slightly greater on the right (46.58 kg) than on the left (44.24 kg).. The results of the eccentric extension of the hip were similar (right hip: 29.69 kg vs left hip: 29.20 kg). However, for the knee, the difference was significantly greater for left than right strength (91.58 kg vs 72.70 kg, respectively). Another relevant aspect was that the relationship between the abductor and adductor components of the hip, which give stability to this joint during flexion and extension movements, showed significant differences between concentric and eccentric abduction strength in favour of the right hip (Conc: 18.29 vs 11.16 kg; Ecc: 30.27 vs 20.57 kg). Now, it is recognized that prolonged exercise causes a decrease in lower limbs strength (Millet et al., 1985). Decreased knee flexor and extensor torque and functional eccentric/concentric ratios have been observed following fatiguing physical exertion (Oliveira et al., 2008). In our participant, a higher functional eccentric flexion/concentric extension ratio was observed in the right versus left hip (2.58 vs 2.25). However, the eccentric flexion to concentric extension ratio at the knee was higher on the left than on the right (1.61 vs 0.91). For the ratios of eccentric hip abduction and concentric hip adduction, higher values were observed in the right versus the left hip (1.13 vs. 0.71). The strength analysis presented in this article reveals decompensations between muscle groups, even though this sport has balanced bilateral demands. Improving the symmetry of stabilizing and locomotor forces will ensure optimal performance and reduce the risk of injury.

Limitations

This study presents some limitations that should be addressed. First, it focuses on a single high-performance Chilean trail runner, limiting the generalizability of the findings to other athletes or populations. The results may not apply to runners with different experience levels, ages, or competitive environments. Additionally, the environmental conditions typical of trail running, such as altitude and terrain, were not replicated in the lab, potentially affecting the external validity of the results but conserving the results transference. Lastly, important physiological markers such as lactate concentration and neuromuscular fatigue indicators were not measured, which could provide a more comprehensive understanding of endurance performance and fatigue in trail running.

CONCLUSION

In conclusion, high aerobic fitness remains key to excellent performance in trail running. Ventilatory thresholds and heart rate variability align with previous studies, and muscle oxygen saturation showed, in this case, a close relationship to these thresholds, suggesting its potential usefulness for real-time muscle fatigue monitoring. The participant's lung function is within optimal ranges, although differences in locomotor muscle strength between the two sides of the body indicate the need for improved muscle symmetry. To maximise performance and reduce the risk of injury, it is crucial to focus training on force symmetry and consider using SmO_2 as a monitoring tool. These results suggest that future studies on muscle oxygenation, respiratory function and muscle strength symmetries may offer new insights to improve training strategies in trail running.

Practical applications

The findings of this case study provide practical insights for athletes and coaches in trail running. Monitoring ventilatory thresholds and HRV can help assess aerobic and anaerobic capacity, aiding in more targeted training interventions. HRV is a cost-effective, non-invasive tool for evaluating endurance performance and recovery. The study also emphasizes the importance of bilateral muscle symmetry, as strength imbalances between limbs can increase injury risk and reduce performance, especially on challenging terrain. Specific strength training programs are recommended to correct these asymmetries, particularly in the hip and knee. Additionally, muscle oxygen saturation monitoring offers real-time feedback on muscle fatigue, enabling athletes to adjust pacing and nutrition strategies. Incorporating these tools into regular training and competition monitoring could optimize trail running performance.

AUTHOR CONTRIBUTIONS

Study concept and design, drafting the article: Marcelo Tuesta and Claudio Nieto-Jimenez. Its critical revision: Marcelo Tuesta, Claudio Nieto-Jimenez and Rodrigo Yañez-Sepulveda. Data collection: Marcelo Tuesta and Claudio Nieto-Jimenez. Analysis: Marcelo Tuesta, Claudio Nieto-Jimenez and Daniel Rojas-Valverde. Final approval of the version to be published: Marcelo Tuesta, Claudio Nieto-Jimenez, Rodrigo Yañez-Sepulveda, Eduardo Baez-San Martin and Daniel Rojas-Valverde.

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