

## Training &amp; Testing

# Uphill Walking Economy and Maximal Oxygen Consumption in Trail Runners: Relationship with Ultra-Trail Performance

Ignacio Martínez-Navarro<sup>1</sup> , Juan Vicente-Mampel<sup>2</sup>, Raul López-Grueso<sup>3</sup>, Eladio Collado-Boira<sup>4</sup>, Carlos Hernando<sup>3,5</sup>

Affiliation addresses are listed at the end of the article.

## ABSTRACT

The aim of this study was two-fold. Firstly, to assess whether uphill walking economy was related with step and ventilatory kinematics. Secondly, to examine whether uphill walking economy represented an independent performance factor in ultra-trail races. Thirty-six athletes (25 men and 11 women) completed an uphill peak exercise test and an uphill walking economy test 4–8 weeks before a 106-km ultra-trail race. Ventilatory and gait parameters were recorded during uphill walking. Body composition, jumping, and isometric and inspiratory strength were also measured. Step length and tidal volume were associated ( $r = 0.72$ ;  $p < 0.001$ ) and they correlated with uphill walking economy ( $r$  between 0.47 and 0.58;  $p < 0.01$ ). Peak speed and running power and speed and running power linked to ventilatory thresholds all correlated with race time ( $r$  between 0.51 and 0.80;  $p < 0.01$ ). Uphill walking economy, when expressed as a percentage of peak oxygen uptake, explained 58 % of performance variation; however, multiple regression analysis revealed that the best model comprised peak oxygen uptake alone, predicting 79 % of performance. In conclusion, longer step length and greater tidal volume align with lower energy expenditure during uphill walking. Uphill walking economy is not an independent performance factor in ultra-trail races. Uphill-obtained peak oxygen uptake predicts a large percentage of performance variation in ultra-trail races.

**Keywords** maximal oxygen uptake, ventilatory thresholds, vertical speed, running power, step length, tidal volume

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**Correspondence** Dr. Ignacio Martínez-Navarro, Physical Education and Sports, Universitat de Valencia, Valencia, Spain, Email: marnaig@uv.es

## Introduction

Trail running (TR) was recognized by World Athletics as a new running discipline in 2015.<sup>1</sup> Since then, research to identify the physiological determinants of TR performance has greatly increased. This ongoing effort aims to improve training strategies and competition results. However, identifying these factors in TR is challenging<sup>2,3</sup> and fatigue in ultra-trail (UT) races appears multi-factorial.<sup>4</sup> Establishing a relationship between endurance variables and UT performance becomes harder as race distance increases.<sup>5–7</sup>

One feature that distinguishes TR from flat races, such as road marathons, is the alternation between level, uphill, and downhill sections. It has been shown that while level and shallow (i.e., below 20 % slope) uphill running economy is correlated, steep uphill running economy does not correlate with level running economy.<sup>8</sup> In addition, when an incremental test is performed with a 25 % gradient versus level or a 15 % gradient, TR athletes are able to reach a higher maximal oxygen uptake ( $\text{VO}_{2\text{max}}$ ).<sup>9</sup> Thus, it seems more appropriate in moderate to highly-trained TR to assess physiological variables of performance using steep slopes and enable them to express their cardiovascular potential to the fullest.<sup>10</sup> However, the two previous studies assessing performance factors in  $\approx 100$ -km UT races used either a level or a shallow (12 % slope) uphill running protocol.<sup>7,11</sup> Interestingly, one of those studies found no relationship between running economy and race time.<sup>7</sup> Meanwhile,

the speed at first and second ventilatory thresholds, peak speed and  $\text{VO}_{2\text{max}}$  were consistently correlated with performance in both studies.<sup>7,11</sup>

Although there is a wide variation in the distance, the cumulative elevation gain-to-distance ratio and terrain of UT races, another of their specific traits, compared to flat ultramarathons, is the interplay of two different locomotor patterns (i.e., walking and running). The work rate in UT races is approximately 50–70 % of  $\text{VO}_{2\text{max}}$ ,<sup>4</sup> and even in well-trained runners, walking is the locomotion mode when displacing uphill at a 15 % slope and 60 %  $\text{VO}_{2\text{max}}$ .<sup>12</sup> Thereby, walking predominates in uphill sections of UT races, especially among less proficient athletes. Additionally, uphill walking economy has been demonstrated to be uncorrelated with either downhill running or level running economy in TR.<sup>12</sup> This fact reinforces the notion that the assessment of uphill walking economy could improve coaches' knowledge about TR's physical conditions. However, no study has yet explored if uphill walking economy constitutes a performance factor in UT races. Similarly, although lower limb and inspiratory muscle strength have been linked to UT performance,<sup>7,13,14</sup> it remains unknown whether these factors may influence uphill walking economy.

Therefore, this study aimed to (i) assess uphill walking economy in trained trail runners and examine if step and ventilatory kinematics associate with lower limb and inspiratory muscle strength;

(ii) identify possible links between uphill walking economy and uphill peak exercise test (UPET)-derived variables: peak oxygen uptake ( $\dot{V}O_{2\text{peak}}$ ), peak vertical velocity and power and vertical velocities and powers corresponding to first and second ventilatory thresholds; and (iii) determine whether including uphill walking economy enhances the predictive value of body composition and UPET-derived variables for UT performance. We hypothesized that (1) inspiratory and lower limb strength align with step and ventilatory kinematics during uphill walking, and these four variables also correlate with uphill walking economy; (2) uphill walking economy, however, does not correlate with UPET-derived variables and constitutes an independent performance factor in UT races.

## Materials and methods

### Participants

Thirty-six experienced trail runners (25 men and 11 women) were recruited to participate in the study. This research was developed at the Penyalgosa Trails CSP race in 2025. The race distance was 106.1 km, starting at an altitude of 40 m and finishing at 1,280 m above the sea level, with a total positive and negative elevations of 5,584 and 4,369 m, respectively. The temperature at the start was 14 °C, and it ranged between 18.9 and 7.4 °C at mid-race (km 66), and between 16.2 and 0.5 °C at the finish line. All subjects were fully informed of the procedure and gave their written consent to participate. They were also allowed to withdraw from the study at will. Demographic, training, and competition history were collected using a questionnaire. The investigation was conducted in accordance with the Declaration of Helsinki, it obtained approval from the Research Ethics Committee of an institution affiliated with one of the authors, and it met the ethical standards of the International Journal of Sports Medicine.<sup>15</sup> This study was enrolled in the ClinicalTrials.gov database.

### Experimental overview

Participants attended the laboratory on two occasions, separated by 2 weeks. The body composition was measured at the start of both days. During the first visit, which was 6–8 weeks before the race, jump tests and UPETs were performed. In the second visit, 4–6 weeks before the race, isometric strength tests and the uphill walking economy test were conducted. Maximal inspiratory pressure (MIP) was measured the day before the race.

Participants were asked to attend both visits in a fasted state (>6 h) and maintain their habitual mixed macronutrient diet the day before the test. Resistance training, downhill running, and vigorous running were not allowed for 48 hours before. No training was permitted for 24 hours before. All these pre-trial standardisation measures were verbally checked with each participant at their arrival to the laboratory.

Finishing times were obtained from the official timer of the race (LiveTrail, LiveTrail SARL, France). Moreover, at the end of the race, participants were asked about their competitive intention during the race: being finisher no matter the time taken or doing the race accompanying a slower runner versus performing the race as fast as possible.<sup>16</sup>

### Body composition

The body mass index (BMI), percentage of fat mass (%FM), and percentage of lean body mass (%LBM) were evaluated using a bioelectrical impedance weight scale (Tanita BC-780MA, Tanita Corp., Tokyo, Japan). Measurements were performed with minimal clothing (i.e., running shorts and t-shirts), following the manufacturer's guidelines. The skin and the electrodes were cleaned and dried before testing.

### Uphill peak exercise test

UPETs were performed on a treadmill (BH Fitness SK7990) with a 20% constant slope. After a 3-minute warm-up at  $2.5 \text{ km} \cdot \text{h}^{-1}$ , corresponding to a vertical velocity of  $500 \text{ m} \cdot \text{h}^{-1}$ , the speed was increased  $0.5 \text{ km} \cdot \text{h}^{-1}$  every minute (equivalent to a vertical velocity of  $100 \text{ m} \cdot \text{h}^{-1}$ ) until volitional exhaustion.<sup>10</sup> We opted for a lower gradient than suggested in the original protocol (25%), which was tested in highly-trained men because our sample was composed of men and women with a greater heterogeneity in fitness levels, and we wanted to avoid a premature muscle fatigue that could preclude in turn the attainment of  $\dot{V}O_{2\text{max}}$ . Participants were free to walk or run as they preferred. Walk-to-run transition occurred at  $5.1 \pm 0.6 \text{ km} \cdot \text{h}^{-1}$ . All participants finished the test running. Expired gases and heart rates were collected continuously using an indirect calorimeter (Quark CPET, COSMED, Rome, Italy) and a chest-strap heart rate monitor (H10, Polar Electro Oy, Kempele, Finland). The gas-analysis system was calibrated (including replacing the sample line and turbine) before each test to improve the stability and sensitivity of the instrumentation.<sup>17</sup>  $\dot{V}O_{2\text{max}}$  values were accepted when a plateau (an increase of  $<2 \text{ mL kg}^{-1} \text{ min}^{-1}$ ) or a decline in  $\dot{V}O_2$  was reached despite increasing workloads. If these criteria were not met, a  $\dot{V}O_{2\text{peak}}$  value was taken, defined as the highest  $\dot{V}O_2$  measured over a 30-seconds period. First and second ventilatory thresholds ( $VT_1$  and  $VT_2$ ) were determined using the guidelines of Skinner and McLellan<sup>18</sup> by two independent researchers. The peak vertical velocity ( $V_{\text{vertpeak}}$ ) and vertical velocities corresponding to  $VT_1$  and  $VT_2$  ( $V_{\text{vert}VT_1}$  and  $V_{\text{vert}VT_2}$ ) were calculated as the speed of the last complete stage added to the multiplication of the speed increment by the completed fraction of the incomplete stage.<sup>19</sup> Running power was estimated using a Stryd powermeter (Stryd Inc., Boulder, CO, USA) affixed to the runner's left shoe.<sup>20,21</sup> The iPhone Stryd mobile application was used to collect running power during the testing sessions. For each runner, a unique Stryd user profile was created that included their respective height and body mass. Data were sampled at 1 Hz and relativized to body mass. Peak power ( $W_{\text{peak}}$ ) was defined as the highest power measured over a 5-seconds period. Powers corresponding to  $VT_1$  and  $VT_2$  ( $W_{VT_1}$  and  $W_{VT_2}$ ) were obtained averaging the 5-second period around the time at which  $VT_1$  and  $VT_2$  were located.

### Uphill walking economy test

The uphill walking economy test consisted of a 5-minute uphill walking with the same slope used in the UPET (20%) at the speed corresponding to  $VT_1$  ( $4.27 \pm 0.49 \text{ km} \cdot \text{h}^{-1}$ ). The walk-to-run transition during the UPET was above  $V_{\text{vert}VT_1}$  in all of the participants, so walking was their preferred locomotor pattern at that intensity.<sup>22,23</sup> The final 3 minutes were used to calculate the respiration frequency ( $F_R$ ), the tidal volume ( $V_T$ ), the vertical oxygen cost of

transport ( $OC_{\text{vert}}$ ,  $\text{ml} \cdot \text{kg}^{-1} \cdot \text{km}^{-1}$ ), and the vertical energy cost of transport ( $EC_{\text{vert}}$ ,  $\text{J} \cdot \text{kg}^{-1} \cdot \text{m}^{-1}$ ). Additionally, we calculated the 'relative' vertical oxygen cost of transport ( $\%OC_{\text{vert}}$ ; i.e., what percentage of  $\dot{V}O_{2\text{peak}}$  is required to overcome a given positive elevation) as follows:  $\%OC_{\text{vert}} = \dot{V}O_2 (\dot{V}O_{2\text{peak}} V_{\text{vert}} VT_1)^{-1}$ . Energy expenditure was obtained using the equation proposed by Jeukendrup and Wallis:<sup>24</sup>

$$\text{Energy expenditure (Kcal} \cdot \text{min}^{-1}) = 0.550 \cdot VCO_2 + 4.471 \cdot \dot{V}O_2$$

$$\text{Energy expenditure (Kcal} \cdot \text{min}^{-1}) \times 4184 = \text{Energy expenditure (J} \cdot \text{min}^{-1})$$

Step kinematics (i.e., step length [SL] and step frequency [SF]) were measured using a Stryd powermeter (Stryd Inc., Boulder, CO, USA).<sup>25</sup>

### Strength tests

Subjects were familiarized with procedures concerning strength assessment during an informative session prior to the investigation. The following tests were carried out: (1) a squat jump (SJ) test; (2) an ankle rebound test; (3) two isometric maximal voluntary contraction tests: squat (SQ) and ankle plantar flexion (PF); and (4) a MIP test. Each test was performed twice (with the exception of MIP measurement), with 1-minute of rest between attempts, and the best performance in each test was retained for statistical analysis.

In the SJ, participants were asked to jump as high as possible from a starting position with hips and knees flexed at 80 degrees and hands stabilized on their hips to avoid arm swing. The jump height was estimated by the flight time measured with a contact platform (Chronojump, Barcelona, Spain). In the ankle rebound test, participants were asked to perform 10 consecutive maximal jumps with minimal ground contact time and no knee flexion. The ratio between flight and contact times ( $\text{Leg } Q_{\text{index}}$ ), measured using a contact platform (Chronojump, Barcelona, Spain), was considered for analysis.

Isometric maximal voluntary contraction was measured with a force sensor (Chronojump, Barcelona, Spain) held onto a bar using a custom-adapted Smith machine (i.e., the bar was firmly anchored to impede any movement). The bar height for each participant and test was individually set. For the PF assessment, participants stood upright with their hips and knees fully extended and their ankles in 0-degree PF; for the SQ assessment, they adopted a knee angle of 140° in the ready position.<sup>26</sup> For each contraction, participants were instructed to drive upwards against the bar, mimicking the movement pattern of a half-squat and a calf extension, respectively. Each contraction was initiated following a verbal prompt from the researcher, and consistent verbal encouragement was provided throughout. The maximum force produced was modeled using the inverse monoexponential function that better fitted the raw data.<sup>13</sup> This fitting was made by adjusting the maximum force to the speed at which the maximum force was reached. This method was used to more accurately estimate MVC, accounting for variations in the rate of force development and potential signal noise.

The MIP was measured to assess volitional maximal inspiratory strength using a handheld electronic device (Powerbreathe K5,

HaB International Ltd, UK). This instrument was shown to be reliable.<sup>27</sup> Each participant performed three attempts, and the best result that did not differ by more than 5% was considered for analysis.<sup>28</sup>

### Statistical analysis

Statistical analyses were carried out using the Statistical Package for the Social Sciences software (IBM SPSS Statistics for Windows, version 30; IBM Corp., Armonk, NY). Normality was checked using the Shapiro–Wilk test, and all variables met normality assumptions.

Pearson product–moment correlations were computed to explore possible relationships between uphill walking economy ( $EC_{\text{vert}}$  and  $OC_{\text{vert}}$ ), step and ventilatory kinematics (SL, SF,  $F_R$ , and  $V_T$ ), lower limb and inspiratory strength (SJ, Leg  $Q_{\text{index}}$ , PF, SQ, and MIP). A second Pearson product–moment correlation analysis was conducted to assess possible relationships between uphill walking economy and UPET-derived variables ( $\dot{V}O_{2\text{peak}}$ ,  $V_{\text{vertpeak}}$ ,  $W_{\text{peak}}$ ,  $V_{\text{vert}} VT_1$ ,  $W_{VT1}$ ,  $V_{\text{vert}} VT_2$ , and  $W_{VT2}$ ). Lastly, a third Pearson product–moment correlation analysis was computed within the sample set of race finishers to assess whether the primary outcome, finishing time, was associated with body composition variables (BMI, %FM, and %LBM), uphill walking economy, including  $\%OC_{\text{vert}}$ , and UPET-derived variables. The following criteria were adopted to interpret the magnitude of the correlations:  $r \leq 0.1$ , trivial;  $0.1 < r \leq 0.3$ , small;  $0.3 < r \leq 0.5$ , moderate;  $0.5 < r \leq 0.7$ , large;  $0.7 < r \leq 0.9$ , very large; and  $r > 0.9$ , almost perfect.<sup>29</sup>

Afterwards, the body composition, uphill walking economy, and UPET-derived variables were entered as independent variables into a stepwise multiple regression analysis with race time as the dependent variable. Additionally, using the percentage of winning time as a splitting variable, we divided the sample into faster and slower runners (i.e., below and above the median value for our sample) and we conducted the aforementioned analysis on these sample sets. Assumptions of linearity, normality, independence (Durbin–Watson statistic values were between 1.5 and 2.5), homoscedasticity, and the absence of collinearity (VIF values are equal to 1) were checked in all the multiple regression analyses performed. The significance level was set at  $p < 0.05$ , and data are presented as means and standard deviations ( $\pm$  SD).

### Results

Participant characteristics, including demographic information, training and competition history, and data from the UPET, are presented in **Table 1**. From the initial sample (36 athletes), 1 participant did not start the race due to injury, and 27 athletes (21 men and 8 women) successfully completed the race. The finishers/starters ratio for the subjects of the present study (77.1%) was similar to the ratio when all race participants were considered (79.8%). Five finishers (two men and three women) were not considered for analysis as their competitive intention was not to perform the race as fast as possible; accordingly, the final finishers set was composed of 22 athletes (19 men and 5 women). The male athletes' average finish time was 18 hours 17 minutes  $\pm$  2 hours 38 minutes, 166% of winning time (11 h 01 min), while the female athletes' average finish time was 19 hours 53 minutes  $\pm$  58 minutes, 142% of winning

**Table 1** Sample main characteristics (mean  $\pm$  SD)

|                                                                     | All participants<br>(n = 36) | Males<br>(n = 25)  | Females<br>(n = 11) |
|---------------------------------------------------------------------|------------------------------|--------------------|---------------------|
| Age (y)                                                             | 45 $\pm$ 8                   | 44 $\pm$ 6         | 49 $\pm$ 9          |
| Number of years running                                             | 15 $\pm$ 8                   | 14 $\pm$ 7         | 15 $\pm$ 8          |
| Number of races > 100 km                                            | 3 $\pm$ 4                    | 4 $\pm$ 5          | 2 $\pm$ 2           |
| Weekly training days                                                | 5 $\pm$ 1                    | 5 $\pm$ 1          | 5 $\pm$ 1           |
| Weekly running volume (km)                                          | 71 $\pm$ 22                  | 70 $\pm$ 22        | 74 $\pm$ 23         |
| Weekly cumulative positive/negative elevation (m)                   | 2,514 $\pm$ 1,132            | 2,651 $\pm$ 1,233  | 2,172 $\pm$ 780     |
| Weekly training hours                                               | 13 $\pm$ 6                   | 13 $\pm$ 7         | 12 $\pm$ 4          |
| BMI (kg/m <sup>2</sup> )                                            | 23 $\pm$ 2.4                 | 23.7 $\pm$ 2.2     | 21.5 $\pm$ 2.2      |
| Weight (kg)                                                         | 67.9 $\pm$ 11                | 73.9 $\pm$ 6.8     | 55.3 $\pm$ 6.4      |
| FM (%)                                                              | 18.5 $\pm$ 6.4               | 17.1 $\pm$ 6       | 21.8 $\pm$ 6.6      |
| LBM (%)                                                             | 78.3 $\pm$ 6                 | 80 $\pm$ 5.5       | 74.3 $\pm$ 5.5      |
| V <sub>vert</sub> VT <sub>1</sub> (m h <sup>-1</sup> )              | 820.8 $\pm$ 97.6             | 853.2 $\pm$ 87     | 746.9 $\pm$ 80.9    |
| W <sub>VT1</sub> (w.kg <sup>-1</sup> )                              | 2.61 $\pm$ 0.29              | 2.68 $\pm$ 0.28    | 2.49 $\pm$ 0.27     |
| %VT <sub>1</sub> (% VO <sub>2</sub> peak)                           | 65.2 $\pm$ 5.7               | 63.8 $\pm$ 5.5     | 68.5 $\pm$ 5.1      |
| V <sub>vert</sub> VT <sub>2</sub> (m h <sup>-1</sup> )              | 1086.9 $\pm$ 140.4           | 1135.7 $\pm$ 134.8 | 976 $\pm$ 76.6      |
| W <sub>VT2</sub> (w.kg <sup>-1</sup> )                              | 3.57 $\pm$ 0.57              | 3.73 $\pm$ 0.59    | 3.23 $\pm$ 0.37     |
| %VT <sub>2</sub> (% VO <sub>2</sub> peak)                           | 82.8 $\pm$ 7.1               | 82.2 $\pm$ 7       | 84.2 $\pm$ 7.7      |
| VO <sub>2</sub> peak (ml O <sub>2</sub> .kg.<br>min <sup>-1</sup> ) | 57 $\pm$ 8                   | 59 $\pm$ 7.9       | 52.4 $\pm$ 6.6      |
| V <sub>vert</sub> peak (m h <sup>-1</sup> )                         | 1442.9 $\pm$ 182.2           | 1514.6 $\pm$ 159.7 | 1279.9 $\pm$ 113.7  |
| W <sub>peak</sub> (w/kg)                                            | 4.86 $\pm$ 0.60              | 5.16 $\pm$ 0.47    | 4.31 $\pm$ 0.32     |

Abbreviations: BMI, body mass index; FM, fat mass; LBM, lean body mass; V<sub>vert</sub>VT<sub>1</sub>, speed at the first ventilatory threshold; SD, standard deviation; %VT<sub>1</sub>, percentage of the VO<sub>2</sub>peak at the first ventilatory threshold; V<sub>vert</sub>tV<sub>T2</sub>, speed at the second ventilatory threshold; %VT<sub>2</sub>, percentage of the VO<sub>2</sub>peak at the second ventilatory threshold; VO<sub>2</sub>peak, peak oxygen uptake; V<sub>vert</sub>peak, peak speed reached during the uphill peak exercise test; W<sub>VT1</sub>, running power at the first ventilatory threshold; W<sub>VT2</sub>, running power at the second ventilatory threshold; W<sub>peak</sub>, peak running power reached during the uphill peak exercise test.

time (14 h 03 min). All levels of performance were represented in our sample, as shown by their rank ranging from 15<sup>th</sup> to 343<sup>rd</sup> place (of 379 finishers) in the male category, and from 11<sup>th</sup> to 21<sup>st</sup> place (of 35 finishers) in the female category.

Data from strength tests and the uphill walking test, including ventilatory and step kinematics, are presented in **Table 2**. **Table 3** depicts the relationships between uphill walking economy, step and ventilatory kinematics, lower limb and inspiratory strength. EC<sub>vert</sub> appeared significantly and moderately to largely correlated with F<sub>R</sub>, V<sub>T</sub>, SL, SF, and MIP, while OC<sub>vert</sub> displayed significant and moderate to large correlations with V<sub>T</sub>, SL, SF, and MIP. V<sub>T</sub> was significantly and moderately to very largely associated with SL, SJ, PF, SQ, and MIP, while SL was significantly and moderately to large-

**Table 2** Strength and uphill walking test parameters (mean  $\pm$  SD)

|                                                                | All participants<br>(n = 36) | Males<br>(n = 25) | Females<br>(n = 11) |
|----------------------------------------------------------------|------------------------------|-------------------|---------------------|
| Strength tests                                                 |                              |                   |                     |
| Leg Q <sub>Index</sub>                                         | 1.74 $\pm$ 0.32              | 1.84 $\pm$ 0.27   | 1.54 $\pm$ 0.33     |
| SJ (cm)                                                        | 26 $\pm$ 5                   | 28 $\pm$ 4        | 22 $\pm$ 4          |
| PF (N)                                                         | 291.8 $\pm$ 86.1             | 332.2 $\pm$ 62.8  | 199.9 $\pm$ 55.7    |
| SQ (N)                                                         | 264.7 $\pm$ 103.3            | 311.1 $\pm$ 71.3  | 159.4 $\pm$ 86.9    |
| MIP (cm H <sub>2</sub> O)                                      | 102 $\pm$ 26                 | 115 $\pm$ 19      | 74 $\pm$ 17         |
| Uphill walking test                                            |                              |                   |                     |
| OC <sub>vert</sub> (ml · kg <sup>-1</sup> · km <sup>-1</sup> ) | 2,751 $\pm$ 204              | 2,693 $\pm$ 164   | 2,883 $\pm$ 231     |
| %OC <sub>vert</sub> (%VO <sub>2</sub> max · km <sup>-1</sup> ) | 81.9 $\pm$ 11.9              | 77.3 $\pm$ 10     | 92.5 $\pm$ 8.9      |
| EC <sub>vert</sub> (J · kg <sup>-1</sup> · m <sup>-1</sup> )   | 56.8 $\pm$ 4.1               | 55.7 $\pm$ 3.3    | 59.4 $\pm$ 4.8      |
| V <sub>T</sub> (L · breath <sup>-1</sup> )                     | 2.3 $\pm$ 0.58               | 2.59 $\pm$ 0.43   | 1.65 $\pm$ 0.27     |
| F <sub>R</sub> (L · breath <sup>-1</sup> )                     | 28 $\pm$ 5                   | 27 $\pm$ 5        | 30 $\pm$ 5          |
| SF (steps · min <sup>-1</sup> )                                | 114 $\pm$ 10                 | 112 $\pm$ 8       | 119 $\pm$ 12        |
| SL (m · step <sup>-1</sup> )                                   | 0.62 $\pm$ 0.08              | 0.66 $\pm$ 0.05   | 0.53 $\pm$ 0.06     |

Abbreviations: EC<sub>vert</sub>, vertical energy cost of transport; F<sub>R</sub>, respiration frequency; Leg Q<sub>Index</sub>, ratio between flight and contact times in the ankle rebound test; MIP, maximal inspiratory pressure; OC<sub>vert</sub>, vertical oxygen cost of transport; %OC<sub>vert</sub>, percentage of the VO<sub>2</sub>peak to overcome 1 km of positive gradient; PF, ankle plantar flexion isometric strength; SD, standard deviation; SF, step frequency; SJ, squat jump height; SL, step length; SQ, half-squat isometric strength; V<sub>T</sub>, tidal volume.

ly associated with SJ, PF, SQ, and MIP. Besides, F<sub>R</sub> and SF were also significantly and largely correlated. Correlational analysis results regarding uphill walking economy and UPET-derived variables are depicted in **Table 4**. OC<sub>vert</sub> was significantly and moderately correlated only with V<sub>vert</sub>VT<sub>1</sub> and V<sub>vert</sub>VT<sub>2</sub>. EC<sub>vert</sub> showed no relationship with UPET-derived variables. **Table 5** depicts the relationship between the finishing time and uphill walking economy, body composition and UPET-derived variables. The race time showed a large to very large correlation with all UPET-derived variables:  $\dot{V}$ O<sub>2</sub>peak (**Fig. 1**), V<sub>vert</sub>peak, W<sub>peak</sub>, V<sub>vert</sub>VT<sub>1</sub>, W<sub>VT1</sub>, V<sub>vert</sub>VT<sub>2</sub> and W<sub>VT2</sub>. The race time was also very largely associated with %OC<sub>vert</sub> (**Fig. 2**). Conversely, body composition variables, EC<sub>vert</sub> and OC<sub>vert</sub> were uncorrelated with finishing time.

Results from multiple regression analysis are reported in **Table 6**. For the three sets analysed (all competitive finishers, faster finishers and slower finishers), the  $\dot{V}$ O<sub>2</sub>peak was the only statistically significant variable explaining 79 % (adj R<sup>2</sup> = 0.789; F<sub>1,19</sub> = 75.85; p < 0.001), 80 % (adj R<sup>2</sup> = 0.797; F<sub>1,9</sub> = 36.35; p < 0.001) and 74 % (adj R<sup>2</sup> = 0.736; F<sub>1,9</sub> = 28.87; p < 0.001) of the variation observed in race time, respectively.

## Discussion

The results of this study showed that uphill walking economy does not constitute an independent performance factor in UT races, although %OC<sub>vert</sub>, calculated as the percentage of the  $\dot{V}$ O<sub>2</sub>peak required to overcome a given positive elevation, was very largely cor-

**Table 3** Relationships between uphill walking economy, step and ventilatory kinematics, lower limb and inspiratory strength ( $r/p$ )

|                        | OC <sub>vert</sub> | EC <sub>vert</sub> | V <sub>T</sub> | F <sub>R</sub> | SF           | SL           | Leg Q <sub>index</sub> | SJ           | PF           | SQ           | MIP          |
|------------------------|--------------------|--------------------|----------------|----------------|--------------|--------------|------------------------|--------------|--------------|--------------|--------------|
| OC <sub>vert</sub>     | –                  | 0.997/<0.001       | –0.487/0.003   | 0.324/0.054    | 0.388/0.023  | –0.58/<0.001 | 0.013/0.941            | –0.277/0.102 | –0.256/0.132 | –0.327/0.051 | –0.468/0.005 |
| EC <sub>vert</sub>     | 0.997/<0.001       | –                  | –0.467/0.004   | 0.333/0.047    | 0.412/0.016  | –0.561/0.001 | 0.019/0.915            | –0.272/0.109 | –0.251/0.14  | –0.321/0.056 | –0.452/0.006 |
| V <sub>T</sub>         | –0.487/0.003       | –0.467/0.004       | –              | –0.505/0.002   | –0.302/0.083 | 0.718/<0.001 | 0.14/0.416             | 0.461/0.005  | 0.519/0.001  | 0.601/<0.001 | 0.626/<0.001 |
| F <sub>R</sub>         | 0.324/0.054        | 0.333/0.047        | –0.505/0.002   | –              | 0.543/0.001  | –0.26/0.137  | 0.142/0.409            | –0.17/0.322  | –0.292/0.084 | –0.183/0.286 | –0.244/0.158 |
| SF                     | 0.388/0.023        | 0.412/0.016        | –0.302/0.083   | 0.543/0.001    | –            | –0.312/0.072 | –0.084/0.638           | –0.192/0.275 | –0.32/0.065  | –0.283/0.105 | –0.195/0.278 |
| SL                     | –0.58/<0.001       | –0.561/0.001       | 0.718/<0.001   | –0.26/0.137    | –0.312/0.072 | –            | 0.208/0.239            | 0.622/<0.001 | 0.449/0.008  | 0.515/0.002  | 0.641/<0.001 |
| Leg Q <sub>index</sub> | 0.013/0.941        | 0.019/0.915        | 0.14/0.416     | 0.142/0.409    | –0.084/0.638 | 0.208/0.239  | –                      | 0.589/<0.001 | 0.484/0.003  | 0.54/0.001   | 0.313/0.067  |
| SJ                     | –0.277/0.102       | –0.272/0.109       | 0.461/0.005    | –0.17/0.322    | –0.192/0.275 | 0.622/<0.001 | 0.589/<0.001           | –            | 0.532/0.001  | 0.597/<0.001 | 0.574/<0.001 |
| PF                     | –0.256/0.132       | –0.251/0.14        | 0.519/0.001    | –0.292/0.084   | –0.32/0.065  | 0.449/0.008  | 0.484/0.003            | 0.532/0.001  | –            | 0.766/<0.001 | 0.556/0.001  |
| SQ                     | –0.327/0.051       | –0.321/0.056       | 0.601/<0.001   | –0.183/0.286   | –0.283/0.105 | 0.515/0.002  | 0.54/0.001             | 0.597/<0.001 | 0.766/<0.001 | –            | 0.519/0.001  |
| MIP                    | –0.468/0.005       | –0.452/0.006       | 0.626/<0.001   | –0.244/0.158   | –0.195/0.278 | 0.641/<0.001 | 0.313/0.067            | 0.574/<0.001 | 0.556/0.001  | 0.519/0.001  | –            |

Abbreviations: EC<sub>vert</sub>, vertical energy cost of transport; F<sub>R</sub>, respiration frequency; Leg Q<sub>index</sub>, ratio between flight and contact times in ankle rebound test; MIP, maximal inspiratory pressure; OC<sub>vert</sub>, vertical oxygen cost of transport; PF, ankle plantar flexion isometric strength; SF, step frequency; SJ, squat jump height; SL, step length; SQ, half-squat isometric strength; V<sub>T</sub>, tidal volume.  
Note: in bold,  $p < 0.05$ .

**Table 4** Relationship between uphill walking economy and CPET-derived variables ( $r/p$ )

|                    | V <sub>vert</sub> VT <sub>1</sub> | W <sub>VT1</sub> | V <sub>vert</sub> VT <sub>2</sub> | W <sub>VT2</sub> | VO <sub>2</sub> peak | V <sub>vert</sub> peak | W <sub>peak</sub> |
|--------------------|-----------------------------------|------------------|-----------------------------------|------------------|----------------------|------------------------|-------------------|
| OC <sub>vert</sub> | –0.358/<br>0.032                  | –0.188/<br>0.278 | –0.347/<br>0.038                  | –0.213/<br>0.219 | 0.139/<br>0.418      | –0.15/<br>0.383        | –0.247/<br>0.153  |
| EC <sub>vert</sub> | –0.33/<br>0.05                    | –0.15/<br>0.389  | –0.325/<br>0.053                  | –0.192/<br>0.269 | 0.153/<br>0.372      | –0.131/<br>0.446       | –0.229/<br>0.186  |

Abbreviations: EC<sub>vert</sub>, vertical energy cost of transport; OC<sub>vert</sub>, vertical oxygen cost of transport; VO<sub>2</sub>peak, peak oxygen uptake; V<sub>vert</sub>peak, peak speed reached at the uphill peak exercise test; V<sub>vert</sub>VT<sub>1</sub>, speed at the first ventilatory threshold; V<sub>vert</sub>VT<sub>2</sub>, speed at the second ventilatory threshold; W<sub>peak</sub>, peak running power reached at the uphill peak exercise test; W<sub>VT1</sub>, running power at the first ventilatory threshold; W<sub>VT2</sub>, running power at the second ventilatory threshold.

Note: In bold,  $p < 0.05$ .

related with race time. Submaximal (i.e., associated with VT<sub>1</sub> and VT<sub>2</sub>) and peak power, alongside submaximal and peak vertical speed, were also largely to very largely associated with race time. However, multiple regression analysis indicated that the best predictive model was composed of the  $\dot{V}O_{2\text{peak}}$  alone and explained between 74 and 80 % of the variation observed in race time (when considering all finishers, faster finishers, and slower finishers). Lastly, inspiratory strength, ventilatory and step kinematics were moderately to largely linked to uphill walking economy.

The  $\dot{V}O_{2\text{peak}}$  has been thoroughly associated with TR performance in distances from 27 km to 166 km.<sup>7, 11, 30–34</sup> Notwithstanding, it has been claimed that its importance diminishes as race distance increases,<sup>2, 5, 34</sup> and it has been suggested that other factors different from the  $\dot{V}O_{2\text{peak}}$  may have a predominating influence on UT performance.<sup>4</sup> We thought that one of these factors could be the efficiency of uphill walking gait. The results of the present study do not confirm our hypothesis; however, a lower VO<sub>2</sub>, relative to the  $\dot{V}O_{2\text{peak}}$ , required to overcome a given positive gradient was very largely correlated with a faster race time ( $r^2 = 0.58$ ). This relationship suggests that the ability to use a smaller fraction of  $\dot{V}O_{2\text{peak}}$  during uphill walking might connote a performance-enhancing trait for UT races.

In a previous study from our group in the same race, the  $\dot{V}O_{2\text{peak}}$  reached under level conditions predicted 45 % of variation in performance.<sup>11</sup> Another study carried out in a similar race (101 km and 6,100 m of cumulative elevation gain) obtained a stronger relationship ( $r^2 = 0.85$ ) between the race time and the  $\dot{V}O_{2\text{peak}}$  obtained under uphill conditions (12 % slope),<sup>7</sup> similar to the results of the current study ( $r^2 = 0.79$ ). Therefore, on the one hand, UPETs performed under uphill conditions, as previously suggested,<sup>9, 10, 35</sup> seem more suitable to test TR athletes. Moreover, the vertical velocity and running power associated with the first and the second ventilatory thresholds obtained in this way can be easily translated into uphill workouts. On the other hand, the greater the race's positive elevation gain-to-distance ratio, the more important it seems to have a high VO<sub>2max</sub>.<sup>36</sup>

**Table 5** Relationship between finishing time and uphill walking economy, body composition and CPET-derived variables (*r/p*)

|           | $V_{\text{vert}}VT_1$ | $W_{VT1}$    | $V_{\text{vert}}VT_2$ | $W_{VT2}$    | $VO_{2\text{peak}}$ | $V_{\text{vert}}\text{peak}$ | $W_{\text{peak}}$ | $OC_{\text{vert}}$ | $EC_{\text{vert}}$ | $\%OC_{\text{vert}}$ | BMI         | %FM         | %LBM        |
|-----------|-----------------------|--------------|-----------------------|--------------|---------------------|------------------------------|-------------------|--------------------|--------------------|----------------------|-------------|-------------|-------------|
| Race time | -0.569/0.006          | -0.515/0.017 | -0.755/0.001          | -0.665/0.001 | -0.855/0.001        | -0.798/0.001                 | -0.735/0.001      | -0.194/0.387       | -0.223/0.319       | 0.763/0.001          | 0.065/0.773 | 0.311/0.159 | -0.333/0.13 |

Abbreviations: BMI, body mass index;  $EC_{\text{vert}}$ , vertical energy cost of transport; FM, fat mass; LBM, lean body mass;  $OC_{\text{vert}}$ , vertical oxygen cost of transport;  $\%OC_{\text{vert}}$ , percentage of the  $VO_{2\text{peak}}$  to overcome 1 km of the positive gradient;  $VO_{2\text{peak}}$ , peak oxygen uptake;  $V_{\text{vert}}\text{peak}$ , peak speed reached at the uphill peak exercise test;  $V_{\text{vert}}VT_1$ , speed at the first ventilatory threshold;  $V_{\text{vert}}VT_2$ , speed at the second ventilatory threshold;  $W_{\text{peak}}$ , peak running power reached at the uphill peak exercise test;  $W_{VT1}$ , running power at the first ventilatory threshold;  $W_{VT2}$ , running power at the second ventilatory threshold.  
Note: In bold,  $p < 0.05$ .

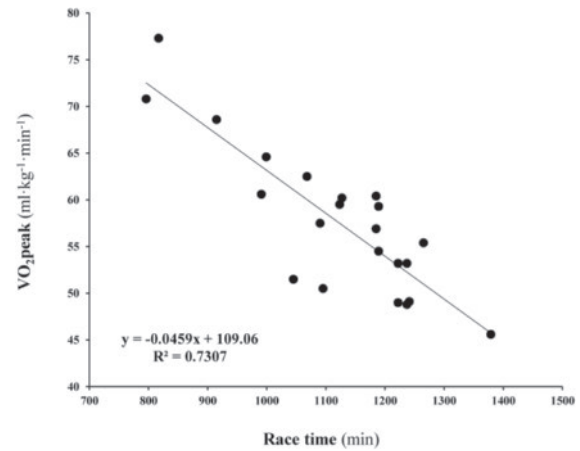


**Fig. 1** Relationship between the  $VO_{2\text{peak}}$  and race time.  $\%OC_{\text{vert}}$ , percentage of the  $VO_{2\text{peak}}$  to overcome 1 km of the positive gradient.  $VO_{2\text{peak}}$ , peak oxygen uptake.

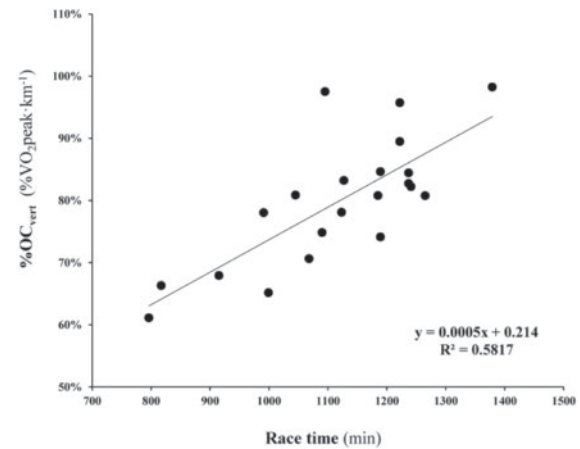


**Fig. 2** Relationship between  $\%OC_{\text{vert}}$  and the race time.  $VO_{2\text{peak}}$ , peak oxygen uptake.

The results of the present study also showed a tight relationship between SL and  $V_T$  during uphill walking. Additionally, both variables showed an inverse association with  $EC_{\text{vert}}$  and  $OC_{\text{vert}}$ . Accordingly, despite the exploratory nature of the study, it appears that a longer stride cycle may enable the use of a deeper breathing pattern (i.e., increased  $V_T$ ) and contribute to lower energy expenditure during uphill walking. Previous studies showed that more economical runners exhibited a higher SL during uphill running<sup>37</sup> and that fatigue-related reduction in vertical speed during an UT race was mainly related to a SL shortening.<sup>38</sup> Conversely, despite an increasing scientific interest around ventilatory parameters during exercise,<sup>39–41</sup> we are unaware of prior evidence of a relationship between  $V_T$  and uphill running/walking efficiency. Given

**Table 6** Race time prediction models in all participants, faster and slower runners sample sets**Analysis 1: All participants (n = 22)**

|   | Model               | Coefficients B | 95 % CI for B |          | Standardized coefficient | p-value | Partial R | R <sup>2</sup> | R <sup>2</sup> change |
|---|---------------------|----------------|---------------|----------|--------------------------|---------|-----------|----------------|-----------------------|
|   |                     |                | Lower         | Upper    |                          |         |           |                |                       |
| 1 | (Constant)          | 2096.639       | 1860.456      | 2332.823 |                          | <0.001  |           | 0.789          |                       |
|   | VO <sub>2peak</sub> | -16.803        | -20.841       | -12.765  | -0.894                   | <0.001  | 0.894     |                |                       |

**Analysis 2: Faster runners sample set (n = 11)**

|   | Model               | Coefficients B | 95 % CI for B |          | Standardized coefficient | p-value | Partial R | R <sup>2</sup> | R <sup>2</sup> change |
|---|---------------------|----------------|---------------|----------|--------------------------|---------|-----------|----------------|-----------------------|
|   |                     |                | Lower         | Upper    |                          |         |           |                |                       |
| 1 | (Constant)          | 1983.237       | 1621.311      | 2345.163 |                          | <0.001  |           | 0.797          |                       |
|   | VO <sub>2peak</sub> | -15.477        | -21.396       | -9.557   | -0.905                   | <0.001  | 0.905     |                |                       |

**Analysis 3: Slower runners sample set (n = 11)**

|   | Model               | Coefficients B | 95 % CI for B |          | Standardized coefficient | p-value | Partial R | R <sup>2</sup> | R <sup>2</sup> change |
|---|---------------------|----------------|---------------|----------|--------------------------|---------|-----------|----------------|-----------------------|
|   |                     |                | Lower         | Upper    |                          |         |           |                |                       |
| 1 | (Constant)          | 2046.051       | 1684.245      | 2407.857 |                          | <0.001  |           | 0.736          |                       |
|   | VO <sub>2peak</sub> | -15.353        | -21.817       | -8.889   | -0.873                   | <0.001  | 0.873     |                |                       |

Abbreviations: VO<sub>2peak</sub>, peak oxygen uptake.

that EC<sub>vert</sub> and OC<sub>vert</sub> were also correlated to MIP, and one of the putative mechanisms through which respiratory training could influence exercise performance is the improvement of ventilatory efficiency,<sup>42</sup> our results should encourage coaches to add respiratory training tasks in the training programs of their UT athletes. Indeed, MIP (relativized by body weight) was largely correlated with race time ( $r = -0.689$ ;  $p < 0.001$ ; data not shown).

In contrast to our expectations, neither jump-derived variables (SJ and Leg Q<sub>index</sub>) nor isometric strength variables (PF and SQ) correlated with uphill walking economy. However, SJ nearly approached the statistical significance threshold ( $p = 0.051$  with OC<sub>vert</sub> and  $p = 0.056$  with EC<sub>vert</sub>), and both PF and SQ were largely associated with SL. Lower limb strength improvement is a well-established pathway to improve running economy, both in 'fresh' and 'fatigued' states.<sup>43–45</sup> Besides, greater lower limb strength has appeared correlated with a better TR performance in several studies<sup>7,13,14</sup> and it is a distinguishing feature of more proficient TR athletes.<sup>46</sup> Therefore, although the role of lower limb strength in uphill walking economy might not be as straightforward as with running economy, strength training is definitely advocated for TR athletes.

There are some limitations in our study that should be acknowledged. The sample was not equally composed of men and women, and the study lacked the power to determine possible sex differences. Unfortunately, women participation in UT races is rather

low (i.e., 8 % in the race that hosted this research project). The protocol we employed to determine the ventilatory thresholds and the associated external load variables, although it was very similar to others previously used to this aim,<sup>10,47</sup> does not allow the attainment of steady-state conditions within each intensity stage. Testing in a fasted state may entail a limitation to the study design as UT races are performed in a fed state. Correlational analyses were done without correction for multiple tests and this could have increased the likelihood of false positives (type I errors).

## Conclusions

Uphill walking economy does not constitute an independent performance factor in UT races. Multiple regression analysis showed that the best predictive model comprised the  $\dot{V}O_{2peak}$  alone, which explained 79 % of the variation observed in race time. Nevertheless, the vertical oxygen cost of uphill walking, when expressed as a percentage of the  $\dot{V}O_{2peak}$ , was able to explain 58 % of performance variation. On the other hand, SL and V<sub>T</sub> during uphill walking were closely correlated and both were also associated with uphill walking economy, thus suggesting that a longer stride cycle may allow the use of a deeper breathing pattern and contribute to lower energy expenditure during uphill walking. Lastly, MIP was correlated to SL, V<sub>T</sub>, and uphill walking economy, thereby

pointing to a relevant role of inspiratory muscle strength in uphill walking economy and gait kinematics.

Therefore, current results should prompt coaches to incorporate uphill locomotion tasks into the training programs of UT runners to optimize step and ventilatory parameters that govern this performance. Inspiratory training is also recommended for UT athletes in view of our results. Meanwhile, both coaches and clinicians are encouraged to assess UT runners using uphill protocols to obtain more reliable and applicable data. Further research is needed to validate whether the application of the aforementioned training strategies improve athletes' performance in UT races.

### Author Affiliations

- 1 Physical Education and Sports, Universitat de Valencia, Valencia, Spain
- 2 Department of Physiotherapy, Catholic University of Valencia San Carlos Borromeo Campus, Valencia, Spain
- 3 Department of Education and Specific Didactics, Universitat Jaume I, Castellón de la Plana, Spain
- 4 Faculty of Health Sciences, Universitat Jaume I, Castellón de la Plana, Spain
- 5 Sport Service, Universitat Jaume I, Castellón de la Plana, Spain

### Statements and Additional Information

**Conflict of Interest** The authors declare that they have no conflict of interest.

**Contributors' Statement** Ignacio Martinez-Navarro: conceptualization, data curation, formal analysis, investigation, methodology, resources, software, supervision, validation, visualization, writing—original draft, and writing—review and editing. Juan Vicente-Mampel: conceptualization, data curation, investigation, methodology, validation, visualization, and writing—review and editing. Raul López-Grueso: conceptualization, data curation, investigation, methodology, validation, visualization, and writing—review and editing. Eladio Collado: conceptualization, data curation, funding acquisition, investigation, methodology, resources, supervision, validation, visualization, and writing—review and editing. Carlos Hernando: conceptualization, data curation, funding acquisition, investigation, methodology, project administration, resources, supervision, validation, visualization, and writing—review and editing.

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