The Energetics during the World’s Most Challenging Mountain Ultra-Marathon—A Case Study at the Tor des Geants®

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Purpose: To provide insights into the energy requirements as well as the physiological adaptations of an experienced 50-year-old ultra-marathon male athlete during the world’s most challenging mountain ultra-marathon (MUM).

Methods: The international race supporting the study was the Tor des Geants®, characterized by 330 km with +24,000 m D+ to be covered within 150 h. Before the MUM, we assessed the peak oxygen uptake (\(\dot{V}O_{2}\text{peak}\)) by means of an incremental graded running test. During the MUM we monitored six ascents (once per race day) with a portable gas analyzer, a GPS and a finger pulse oximeter. We then calculated the net metabolic cost per unit of distance (C), the vertical metabolic cost (C_{vert}) and the mechanical efficiency of locomotion (Eff_{mech}) throughout the six uphills monitored. We further monitored the distance covered, speed, altimetry and D+ from the GPS data as well as the pulse oxygen saturation with the finger pulse oximeter.

Results: Subject’s \(\dot{V}O_{2}\text{peak}\) was 48.1 mL·kg\(^{-1}\)·min\(^{-1}\). Throughout the six uphills investigated the mean exercise intensity was 57.3 ± 6.0% \(\dot{V}O_{2}\text{peak}\) and 68.0 ± 8.7% HR_{peak}. C, C_{vert} and Eff_{mech} were 11.4 ± 1.9 J·kg\(^{-1}\)·m\(^{-1}\), 57.9 ± 15.2 J·kg\(^{-1}\)·m\(^{-1}\)_{vert}, and 17.7 ± 4.8%, respectively. The exercise intensity, as well as C, C_{vert}, and Eff_{mech} did not consistently increase during the MUM.

Conclusions: For the first time, we described the feasibility of assessing the energy requirements as well as the physiological adaptations of a MUM in ecologically valid environment settings. The present case study shows that, despite the distance performed during the MUM, our participant did not experience a metabolic fatigue state. This is likely due to improvements in locomotor efficiency as the race progressed.

Keywords: energy expenditure, locomotion, metabolic cost, mountain ultra-marathon, MUM, ultra endurance, ultra trail, uphill

OPEN ACCESS

Edited by:
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Specialty section:
This article was submitted to Exercise Physiology, a section of the journal Frontiers in Physiology

Received: 20 September 2017
Accepted: 20 November 2017
Published: 05 December 2017

Citation:
Savoldelli A, Fornasiero A, Trabucchi P, Limonta E, La Torre A, Degache F, Pellegrini B, Millet GP, Vernillo G and Schena F (2017) The Energetics during the World’s Most Challenging Mountain Ultra-Marathon—A Case Study at the Tor des Geants®, Front. Physiol. 8:1003. doi: 10.3389/fphys.2017.01003
INTRODUCTION

Ultra-marathon events generally refer to any foot race involving distances longer than the classic marathon length of 42.195 km (Millet and Millet, 2012). During these events, the energy demand is likely to be at the extremes of human tolerance (Millet and Millet, 2012) and the knowledge of this aspect is still scarce (Hill and Davies, 2001; Ardigò and Capelli, 2012). This is likely due to the fact that to date there are no methods available to directly measure the energy demand over long periods of time without placing major (or minor) restrictions on the athletes’ activity. However, the knowledge of the energy demand is important for ultra-marathons in general and, particularly, for extreme mountain ultra-marathon (MUM), where the ultra-long distance is coupled to run and/or walk on mountain trails with considerable positive and negative elevation changes and in a harsh mountainous environment (Vernillo et al., 2014, 2015). This information is essential to increase our understanding of the control of human locomotion resulting from the ability to appropriately regulate locomotor behavior in response to change in grade (Vernillo et al., 2016a).

Recently, a growing body of literature on the physiological and biomechanical changes associated with MUM has been published (for example, Millet et al., 2011; Morin et al., 2011; Saugy et al., 2013; Vernillo et al., 2014, 2015; Degache et al., 2015). For instance, our group (Vernillo et al., 2014) showed that after the world’s most challenging MUM the energy cost of uphill running decreased by ~14%, due to changes in the uphill-running step mechanics that likely lead to a more economical running style. This improvement in the energy cost of uphill running has been confirmed by another study (Vernillo et al., 2016c). However, these studies investigated only pre-to-post changes. This aspect does not allow the understanding of the evolution of the energy demand during a MUM. Further, for this kind of competition most of the athletes tend to walk for longer sections of the race (Millet et al., 2011; Saugy et al., 2013; Vernillo et al., 2014; Degache et al., 2015). Thus, no physiological data set that provides insight on the influence of slope on the energy cost of walking measured during a MUM is available. Moreover, due to the difficulty to measure the energetics during the competitions (Vernillo et al., 2016c), research has been restricted to laboratory or non-mountainous outdoor settings. Thus, there are no data examining the effect of MUM in ecologically valid environments, thereby limiting our understanding on the physiological changes associated with MUM.

Accordingly, we report for the first time the case of an experienced MUM athlete who participated in the world’s most challenging MUM (Saugy et al., 2013; Vernillo et al., 2014; Degache et al., 2015), with the aim to provide preliminary insights into the energy requirements as well as the physiological adaptations during the race.

MATERIALS AND METHODS

Participant

Our participant was an experienced 50-years-old MUM male athlete (69.0 kg body mass, 1.73 m body height, BMI of 22.3 kg·m⁻²). Before the race, a questionnaire was administered to collect data about his training experience (Vernillo et al., 2016b). Our participant had 15 years of training in running and 8 years of ultra-marathons experience. Pre-race, weekly training consisted of 3-5 sessions comprising 12.1 ± 3.5 h and 70 ± 19 km with a cumulative elevation change between 5,000 and 10,000 m. Our participant had also a broad experience of MUM races, for example having finished three of the four editions of the present MUM at the time of data collection (2013 edition). Our participant raced this MUM with the aim to finish it in the fastest time possible. Written informed consent was obtained from him. Further, the study was approved by the institutional ethics committee of the Department of Neurosciences, Biomedicine and Movement Sciences of the University of Verona and it was performed according to the ethical standards laid out in the 2013 revision of the Helsinki Declaration for experimentation on human subjects.

The Event

The international race supporting the study was the Tor des Geants®, characterized by 330 km with a cumulative elevation gain (D+) of +24,000 m that must be completed within 150 h. The altitude along the course ranges between 322 and 3,300 meters above sea level, with 20 mountain passes over 2,000 m (Figure 1).

Methodology

Peak oxygen uptake (VO₂peak) was assessed by means of an incremental graded running test performed on a motorized treadmill in a custom-recreated laboratory in Courmayeur (Italy, 1,234 m asl). Breath-by-breath gas exchanges were measured throughout the test by means of a portable metabolimeter (K4b2, Cosmed, Rome, Italy) that was also able to collect the heart rate (HR) data. After apparatus calibration, gas exchanges were measured at rest with the participant standing in an upright position for 5-min. Then, the test started at 6 km·h⁻¹ at a constant slope of +10% for 3-min, with speed increments of 0.5 km·h⁻¹ every 0.5 min until exhaustion. VO₂peak was considered as the highest 30-s VO₂ average during the incremental tests.

During the race we monitored six ascents (Figure 1), once per race day, in which the participant was equipped with the same portable metabolimeter used for the incremental test, a GPS (Forerunner 310XT, Garmin, Olathe, USA) and a finger pulse oximeter (Wristox 3100TM with 8000SM-WO Sensor, Nonin, Plymouth, MN). The setting was complicated because at least 2 researchers were involved on each uphill in order to carry the material required for the data collection and, also, to provide the adequate assistance to the participant. Distance covered, speed (s), altitude and D+ were obtained from the GPS data. Vertical speed (svert) was calculated as the ratio between D+ and the time to complete each ascent. Percentage of slope gradient was determined from the ratio between D+ and the projection of distance covered on each single ascent. The net metabolic cost per unit of distance (C) was calculated from the ratio between the difference in VO₂ at steady state minus VO₂ at rest and the speed maintained...
during each ascent. This value was expressed in J·kg\(^{-1}\)·m\(^{-1}\) by converting the net \(\dot{V}O_2\) to the corresponding metabolic energy output using an energy equivalent of O\(_2\) ranging from 21.13 to 19.62 kJ·L\(^{-1}\), depending on the RER. The vertical metabolic cost \((C_{\text{vert}})\) and the mechanical efficiency of locomotion \((\text{Eff}_{\text{mech}})\) were further calculated (Minetti et al., 2002).

### Statistical Analysis
Data are presented as mean ± standard deviation. Given the nature of the study, only a qualitative analysis was performed. To describe the participant’s exercise intensity, \(\dot{V}O_2\) and HR recordings were expressed relative to the participant’s peak values (%\(\dot{V}O_{2\text{peak}}\) and %HR\(\text{peak}\), respectively) observed during the incremental test. Due to the time it takes to reach a physiological steady-state condition and for the portable metabolimeter to reflect actual C, the first 5-min of each ascent were discarded in the analysis and the remaining sets were averaged. Pulse oxygen saturation (SpO\(_2\)) was presented as absolute value (i.e., the first and last 5-min blocks).

### RESULTS
There were 705 starters and 383 finishers (54.3%) in the 2013 race. The current record is 67 h 52 min 15 s (set in 2017 edition) and our participant completed the race in 125 h 12 min 19 s (139th place), sleeping for 11 h 40 min (9.3% of the total time). On average, the participant run/walked for 15 h and 40 min without sleeping (range, 2 to 23.5 h). Table 1 summarizes the changes in measurements retrieved during the six uphills. Length, gradient, altitude gain, \(s_{\text{vert}}\) and duration of each ascent, as well as sleeping behavior, are represented in Figure 1.

C and \(C_{\text{vert}}\) as a function of the gradient are presented in Figure 2. Participant’s \(\dot{V}O_{2\text{peak}}\) and HR\(\text{peak}\) were 48.1 mL·kg\(^{-1}\)·min\(^{-1}\) and 169 beats·min\(^{-1}\) respectively. Throughout the uphills, the mean exercise intensity was 57.3 ± 6.0% of \(\dot{V}O_{2\text{peak}}\) and 68.0 ± 8.7% of HR\(\text{peak}\). Further, mean C and \(C_{\text{vert}}\) were 11.4 ± 1.9 J·kg\(^{-1}\)·m\(^{-1}\) and 57.9 ± 15.2 J·kg\(^{-1}\)·m\(^{-1}\), respectively (Table 1).

### DISCUSSION
To the best of our knowledge, this is the first time that the energy cost of an official finisher of an extreme MUM has been described throughout the race. C and \(C_{\text{vert}}\) values are in line with the literature, being directly proportional to the slope in the range of gradients here investigated (Minetti et al., 2002; Giovanelli et al., 2015) (Figures 2A,B, respectively). Intuitively, one would assume that the greater distance performed during the MUM, coupled with a fatigue

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**TABLE 1** | Mean oxygen uptake (\(\dot{V}O_{2\text{mean}}\)) and heart rate (HR\(\text{mean}\)) with respect to the peak values (%\(\dot{V}O_{2\text{peak}}\) and %HR\(\text{peak}\)); net metabolic cost per unit of distance (C); vertical metabolic cost \((C_{\text{vert}})\); mechanical efficiency of locomotion \((\text{Eff}_{\text{mech}})\); Pulse oxygen saturation (SpO\(_2\)) at both the start and the end of each uphill.

| Uphill | Altitude at the top (masl) | Time from the start (h) | \(\dot{V}O_{2\text{mean}}\) (%\(\dot{V}O_{2\text{peak}}\)) | HR\(\text{mean}\) (%HR\(\text{peak}\)) | C (J·kg\(^{-1}\)·m\(^{-1}\)) | \(C_{\text{vert}}\) (J·kg\(^{-1}\)·m\(^{-1}\)) | Eff\(_{\text{mech}}\) (%) | SpO\(_2\) start (%) | SpO\(_2\) end (%) |
|--------|--------------------------|-------------------------|---------------------------------|----------------|----------------|------------------|----------------|-----------------|----------------|
| 1      | 2,825                    | 7                       | 55.5                            | 84.0           | 11.3           | 37.4             | 26.2           | 94              | 83             |
| 2      | 3,279                    | 25                      | 66.7                            | 69.2           | 13.4           | 69.3             | 14.1           | 91              | 77             |
| 3      | 2,132                    | 57                      | 50.0                            | 62.7           | 11.1           | 79.6             | 12.3           | 93              | 91             |
| 4      | 2,266                    | 74                      | 56.9                            | 61.5           | 13.7           | 55.5             | 17.7           | 92              | 91             |
| 5      | 1,666                    | 103                     | 52.5                            | 60.9           | 8.9            | 59.0             | 16.6           | 96              | 94             |
| 6      | 2,459                    | 120                     | 60.6                            | 69.8           | 9.8            | 46.4             | 21.6           | 92              | 88             |
|        |                          |                         | 57.3 ± 6.0                      | 68.0 ± 8.7     | 11.4 ± 1.9     | 57.9 ± 15.2      | 18.1 ± 5.1     | 93 ± 1.8        | 87.3 ± 6.3     |

Mean ± SD of the six uphill sections is also reported.
state, should be associated with a drift upwards of the exercise intensity and a rise in the energy cost. However, an intriguing finding of the present study was that the mean exercise intensity, expressed as %$\dot{V}O_{2peak}$ and %$HR_{peak}$, was similar during the six uphill sections (Table 1). Further, C, $C_{vert}$, as well as $E_{eff}_{mech}$, did not increase throughout the MUM, with the lowest values occurred in the first but also in the last two uphills (Table 1).

CONCLUSION

We presented the case of a 50-years-old ultra-marathon athlete with the aim to provide insights into the energy requirements as well as the physiological adaptations during an extreme MUM race. Despite this is a case study and, thus, the generalizability of our findings to all the MUM participants should be done with caution, the present report could be considered a step forward in the analysis of this kind of topic considering the difficulty to apply these measures on the field (Vernillo et al., 2016c). The results indicate that, despite the distance performed during the MUM (i.e., 330 km with $+24,000$ m D+) the participant did not experience a metabolic fatigue state perhaps due to the prolonged and repetitive locomotion gesture, thereby reflecting a generic improvement in the mechanical efficiency of locomotion (Tam et al., 2016; Vernillo et al., 2016c). These data likely suggest that incorporating long-lasting uphill locomotion training, and hence predisposition to sustaining such loading, is mandatory in the training programs of mountain ultra-marathon athletes to optimize the training process governing this performance.

AUTHOR CONTRIBUTIONS

Conceived and designed the experiments: AS, PT, FD, GM, GV and FS. Performed experiments: AS, PT, EL, FD. Analyzed data: AS, AF, GM and GV. Interpreted results of research: AS, AF, PT, EL, AL, GM, GV and FS. Drafted manuscript and prepared tables/figures: AS, AF, EL, BP, GV and FS. Edited, critically revised paper and approved final version of manuscript: AS, AF, PT, EL, AL, FD, BP, GM, GV and FS. All authors have agreed to be accountable for all aspects of the work related to its accuracy and integrity.

ACKNOWLEDGMENTS

The authors would like to express their sincere thanks to the participant involved in this case study. The authors would also like to extend their gratitude to Aurelio Marguerettaz, the Regione Autonoma della Valle d’Aosta, the Tor des Géants® Organizing Committee and the Courmayeur Trailers for their outstanding support. The authors dedicate this study to the memory of Yuang Yang, who passed away on 8 September 2013, during the 2013 Tor des Géants®.
REFERENCES

Ardigò, L. P., and Capelli, C. (2012). Energy expenditure during the LANY Footrace 2011 - a case study. Appl. Physiol. Nutr. Metab. 37, 1247–1250. doi: 10.1139/h2012-108

Degache, F., Morin, J. B., Oehen, L., Guex, K., Giardini, G., Schena, F., et al. (2015). Running Mechanics During the World’s Most Challenging Mountain Ultra-Marathon. Int. J. Sports Physiol. Perform. 11, 608–614. doi: 10.1123/ijspp.2015-0238

Giovanelli, N., Ortiz, A. L., Henninger, K., and Kram, R. (2015). Energetics of vertical kilometer foot races; is steeper cheaper? J. Appl. Physiol. 120, 370–375. doi: 10.1152/japplphysiol.00546

Hill, R. J., and Davies, P. S. (2001). Energy expenditure during 2 wk of an ultra-endurance run around Australia. Med. Sci. Sports Exerc. 33, 148–151. doi: 10.1097/00005768-200101000-00022

Millet, G. P., and Millet, G. Y. (2012). Ultramarathon an outstanding model for the study of adaptive responses to extreme load and stress. BMC Med. 10:77. doi: 10.1186/1741-7015-10-77

Millet, G. Y., Hoffman, M. D., and Morin, J. B. (2012). Sacrificing economy to improve running performance—a reality in the ultramarathon? J. Appl. Physiol. 113, 507–509. doi: 10.1152/japplphysiol.00016.2012

Millet, G. Y., Tomazin, K., Verges, S., Vincent, C., Bonnefoy, R., Boisson, R. C., et al. (2011). Neuromuscular consequences of an extreme mountain ultramarathon. PLoS ONE 6:e17059. doi: 10.1371/journal.pone.0017059

Minetti, A. E., Moia, C., Roi, G. S., Susta, D., and Ferreretti, G. (2002). Energy cost of walking and running at extreme uphill and downhill slopes. J. Appl. Physiol. 93, 1039–1046. doi: 10.1152/japplphysiol.01177.2001

Morin, J. B., Tomazin, K., Edouard, P., and Millet, G. Y. (2011). Changes in running mechanics and spring-mass behavior induced by a mountain ultramarathon race. J. Biomech. 44, 1104–1107. doi: 10.1016/j.jbiomech.2011.01.028

Saugy, J., Place, N., Millet, G. Y., Degache, F., Schena, F., and Millet, G. P. (2013). Alterations of neuromuscular function after the world’s most challenging mountain ultra-marathon. PLoS ONE 8:e65596. doi: 10.1371/journal.pone.0065596

Tam, E., Bruseghini, P., Calabria, E., Dal Sacco, L., Doria, C., Grassi, B., et al. (2016). Gokyo Khumbu/Ama Dablam Trek 2012: effects of physical training and high-altitude exposure on oxidative metabolism, muscle composition, and metabolic cost of walking in women. Eur. J. Appl. Physiol. 116, 129–144. doi: 10.1007/s00421-015-3256-z

Vernillo, G., Giandolini, M., Edwards, W. B., Morin, J. B., Samozino, P., Horvais, N., et al. (2016a). Biomechanics and Physiology of Uphill and Downhill Running. Sports Med. 47, 615–629. doi: 10.1007/s40279-016-0605-y

Vernillo, G., Savoldelli, A., La Torre, A., Skafidas, S., Bortolan, L., and Schena, F. (2016b). Injury and illness rates during ultratrail running. Int. J. Sports Med. 37, 565–569. doi: 10.1055/s-0035-1569347

Vernillo, G., Savoldelli, A., Skafidas, S., Zignoli, A., La Torre, A., Pellegrini, B., et al. (2016c). An extreme mountain ultra-marathon decreases the cost of uphill walking and running. Front. Physiol. 7:530. doi: 10.3389/fphys.2016.00530

Vernillo, G., Savoldelli, A., Zignoli, A., Skafidas, S., Fornasiero, A., La Torre, A., et al. (2015). Energy cost and kinematics of level, uphill and downhill running; fatigue-induced changes after a mountain ultramarathon. J. Sports Sci. 33, 1998–2005. doi: 10.1080/02640414.2015.1022870

Vernillo, G., Savoldelli, A., Zignoli, A., Trabucchi, P., Pellegrini, B., Millet, G. P., et al. (2014). Influence of the world’s most challenging mountain ultramarathon on energy cost and running mechanics. Eur. J. Appl. Physiol. 114, 929–939. doi: 10.1007/s00421-014-2824-y

Conflict of Interest Statement: The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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