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Energetic and neuromuscular impact of running on even or uneven surfaces in standardized laboratory conditions

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ABSTRACT

Purpose: We examine the energetic and neuromuscular effects of running on even (E-T) and uneven terrains (UE-T) by creating smooth and rough conditions on a standardized circuit.

Methods: Ten adults (age 32.1 ± 7.6 years, body mass 62.2 ± 7 kg, height 167.5 ± 4.2 cm) ran on an 'iterative-8-shaped' path. For UE-T, solid hemispheres were fixed to a perforated mat, while for E-T, visible marks guided foot placement. Participants performed two 6-min trials on both terrains in a counterbalanced order, maintaining consistent running patterns and low-intensity speed with a metronome to guide step frequency. This ensured consistency in the timing and positioning of foot placement between the two conditions. Cardio-metabolic parameters were measured continuously, and muscle activation was recorded from six leg muscles using surface EMG.

Results: The analysis showed significantly higher cardio-metabolic responses in UE-T compared to E-T, with increases in oxygen cost (+18 %), energy cost (+23 %), respiratory frequency (+7%), ventilation (+19 %), heart rate (+10 %), and RPE (+50 %) (all $p < 0.05$). Electromyographic activation of the tibialis anterior (+22 %) and peroneus longus (+10 %) also increased in UE-T.

Conclusions: These findings indicate that running on uneven terrain demands more energy and greater activation of ankle stabilizers, as required in off-road and trail running.

1. Introduction

It is in general known that greater metabolic energy expenditure is required when running on natural surfaces compared to running on smooth and hard terrains (Jensen et al., 1999; Pinnington and Dawson, 2001; Zamparo et al., 1992). Specifically, running outdoors on natural surfaces can affect running biomechanics, as runner adapt their running style to minimize the energy cost of running. (Lieberman et al., 2015; Snyder and Farley, 2011).

Trail running is a perfect example of a sport where athletes compete on uneven terrain, with participation growing considerably in recent years, nearly doubling between 2009 and 2017 in the US alone (Scheer et al., 2020). It is defined as a foot race conducted in natural environments, such as mountains, deserts, forests, or coastal areas, traversing diverse terrains like dirt roads, forest trails, single tracks, and beach sand. Paved or asphalt roads account for no more than 20–25 % of the total course (Scheer et al., 2020). Trail running has been shown to significantly increase mediolateral foot acceleration compared to treadmill running, particularly during the foot–ground contact phase, as quantified by the range of acceleration in the mediolateral axis across each step (Nicot et al., 2022). These variations in surface and track slope during off-road running require athletes to make continuous adjustments to their running speed, which in turn increases the variability of heart rate responses (Creagh et al., 1998).

The CV of biomechanical parameters like muscle activation and stride kinematics further highlights differences between even and off-road conditions. Biomechanical alterations, as evidenced by EMG muscle activation analysis, have been explored in previous studies investigating muscular changes resulting from surface perturbations during walking or running (Müller et al., 2010; Skroce et al., 2023; Voloshina and Ferris, 2015). An increased mean value and variability of muscle activation have been noted in thigh muscles when running on uneven

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terrain (Voloshina and Ferris, 2015). Additionally, augmented variability in EMG activity has been observed in lower leg muscles such as the *peroneus longus*, *tibialis anterior*, *soleus*, and *lateral gastrocnemius* in comparison to running on even surfaces (Skroce et al., 2023; Voloshina and Ferris, 2015).

Given the difficulties in reproducing the outdoor conditions and constraints when studying off-road running, researchers have sought to mimic real outdoor settings in different ways under controlled laboratory setups (Dhawale and Venkadesan, 2023; Gantz and Derrick, 2018; Schrøder Jakobsen et al., 2022; Voloshina and Ferris, 2015); by utilizing modified treadmills with wooden blocks of different dimensions (from 1.27 to of 3.81 cm of height) attached to the treadmill belt (Voloshina and Ferris, 2015) or by using indoor pathways made with fiberglass and epoxy that texturally resembled weathered rock (Dhawale and Venkadesan, 2023). These setups presented intrinsic limits when the research aim is to compare running in outdoor conditions with running on an even surface. As an example, the athletes could choose their preferred running pattern in terms of step positioning (ground contact), thus introducing possible biases in the data analysis: a great inter-individual EMG variability could emerge when running on the previously mentioned setups. In such situations, it is difficult to understand whether EMG differences between even and uneven conditions are due to different foot positioning, different running surfaces or both. Furthermore, in treadmill setups, the reduced visibility of the uneven elements could limit athletes from effectively controlling their foot trajectory approaching ground contact. Finally indoor pathways were often presented as linear and short, forcing athletes to 180° changes of direction, thus impeding continuous running at a constant speed.

Thus, this study aimed to analyze the effect of surface when running on even or uneven terrain, by comparing the energetic and neuromuscular demands of running with the same pattern on standardized smooth and rough terrain. The experimental design was conceived to maintain the same movement speed and the same foot positioning in the two conditions. We hypothesized that: *i)* an increased activation of lower leg muscles rather than thigh muscles is required when running on uneven than on even terrains when the same step sequence is guaranteed; *ii)* a higher metabolic effort should be observed in uneven running conditions, due to the increased muscle involvement during foot stabilization; *iii)* elevated requirements of foot stabilization could lead to augmented muscle activation variability in uneven terrain.

2. Methods

2.1. Experimental setup

To explore the energetic and neuromuscular effects of running on even (E-T) versus uneven (UE-T) terrains, we conducted a controlled study using a standardized circuit featuring both smooth and rough conditions. Ten adult participants were asked to run on an ‘iterative-8-shaped’ path. For the UE-T condition, we created a rough surface by attaching solid hemispheres of different sizes to a perforated foam mat. In contrast, the E-T condition involved a smooth surface with visible markers to guide foot placement. Each participant ran two 6-minute trials on both terrains, with a 10-minute rest between trials, in a counterbalanced sequence. They ran at a self-selected, low-intensity speed while maintaining a consistent running pattern, with a metronome used to keep their step frequency and foot placement timing consistent across both terrain types, reducing the variability that would have been introduced if foot positioning during the stance phase had been different and inconsistent between the two conditions.

2.2. Subjects

Ten physically active adults, 5 males and 5 women, volunteered to participate in this study (mean ± standard deviation, age: 32.1 ± 7.6 years; height: 167.5 ± 4.2 cm; body mass: 62.2 ± 7 kg). Participants were moderately active in running activity, with familiarity in walking and running on off-road terrain, and none of them had any history of injuries affecting their ability to walk or run. Before taking part in the study, participants provided informed written consent and the study protocol was approved by the ethical committee of the University of Verona and it was conducted according to the ethical standards of the Helsinki Declaration.

2.3. Procedures

Subjects performed two 6-min run trials on an “iterative-8-shaped” path (length = 30.5 m) (Fig. 1) in a laboratory environment, with a 10-min rest in between. Two different running conditions were created on a perforated semi-rigid foam mat with a thickness of 5 cm. To mimic the uneven running terrain (UE-T), solid hemispheres with non-slip surfaces and of different dimensions (small ∅: 240 mm, medium ∅: 340 mm, and large ∅: 400 mm) created for this purpose (Powerstone, Key Stone, Folgaria, Italy) were fixed to the foam mat using proper fixing devices. The average distance between the hemispheres was 0.86 ± 0.10 m, which was fixed for all subjects and corresponded to 52 % of the subjects’ average height. The hemispheres of different sizes were randomly alternated on the path, ensuring that within a complete lap, participants performed an equal number of steps on stones of different sizes with each leg.

To replicate a comparable even terrain (E-T), visible tape was used to mark areas on the foam mat, matching the circumference of the hemispheres in the UE-T condition. Participants were instructed to place their feet consistently on the upper part of the hemispheres in the UE-T condition, while in the E-T condition, foot placement was required within the tape-marked areas. Subjects always started their runs from the same point (the yellow stone in Fig. 1) and were instructed to begin with the same leg for all trials, ensuring consistency in step pattern and minimizing unnatural movements, even during turns.

Before data collection, a 15-minute warm-up session was conducted to allow participants to familiarize themselves with the running conditions. During this warm-up, performed on the UE-T condition, participants ran at a self-selected low-intensity pace. A metronome was synchronized to their self-selected step frequency during the final minutes of the warm-up, which was then used in both experimental conditions to ensure the same step frequency and running speed.

For all trials, electromyographic analysis was conducted on the dominant leg, which was determined prior to testing. Subjects ran in their own pair of running shoes, primarily road running shoes, as the surfaces in the experiments were mostly smooth.

Bipolar electrodes (24x24mm; CDE-C, OTBioelettronica, Torino, Italy) were placed on the dominant leg, on the muscle belly of *vastus lateralis (VLa)*, *biceps femoris (BFe), tibialis anterior (TAn), peroneus longus (PLo), soleus (Sol)* and *gastrocnemius medialis (GMe),* with an inter-electrode distance of 2 cm, accordingly to the SENIAM guidelines (Hermens et al., 1999) to minimize cross talks and geometrical artifacts also during dynamic contractions (Rainoldi et al., 2000). Before this procedure, the interested skin zones were hair-shaved, slightly abraded, and cleaned with alcohol to reduce impedance. Moreover, the athletes were prepared for the cardio-metabolic measurements with a facial mask, a heart rate belt (Garmin, KS, USA) and a portable metabolimeter (K5, Cosmed, Roma, Italy), that was previously calibrated following the manufacturer’s guidelines and fixed to the athletes’ back through a specific support.

The EMG (DUE Pro, OT Bioelettronica, Torino, Italy) signals were sampled at 2048 Hz, hardware amplified (gain 1000 V/V ± 1 %), converted A/D and transmitted wirelessly via Bluetooth (Wireless G USB adapter) to a computer for the storage process (OT Biolab 2.0.6484.0EM acquisition software, OT Bioelettronica, Torino, Italy). The cardio-metabolic data were acquired in a breath-by-breath mode to measure oxygen consumption (VO_2), carbon dioxide production (VCO_2), minute ventilation (VE), respiratory frequency (Rf), respiratory exchange ratio

Fig. 1. Panel a report an in-scale representation of the running course (m). In panels b and c, uneven and even running course are presented.

(RER), and heart rate (HR).

EMG and cardio-metabolic measurements were taken continuously during the trials. At the end of each trial, the subjects were asked to evaluate the perception of their effort by using the Borg CR-100 Scale with the 0 value meaning “nothing at all” and the 100 value meaning “maximal” (Borg and Kaijser, 2006).

2.4. Data analysis

For each condition, data were collected continuously, and the final two minutes of exercise were analyzed. The EMG signals were band-pass filtered (20–450 Hz; 20 dB/oct) to remove noise and were full wave rectified. A linear envelope of the EMG signal was obtained through a 20 Hz Butterworth 4th-order low-pass digital filter, to overlap the EMG signals relative to all the running cycles over a time-normalized period and to discard eventual running cycles in which the EMG signal was out of 95 % confidence interval. For each running condition, the level of muscle involvement was considered as the averaged rectified value (ARV) of the valid running cycles (Zoppirolli et al., 2017) over the entire cycle time; the coefficient of variation (CV) of each ARV also was calculated (CV = SD/mean). All cardio-metabolic data resulted from the average of the final two minutes of exercise. Moreover, we calculated the energy cost of running (Cr = metabolic power / speed) in both running conditions (Di Prampero et al., 1993).

2.5. Statistical analysis

The data are expressed as mean ± 1SD. Statistical analyses were performed using the software *Jamovi* (v. 2.4.8.0). Normality distribution of data was checked with Shapiro-Wilk test. *Student' t*-test for repeated measures was applied to test the significance of the differences between the two running conditions for each variable considered, with a level of significance set at $p \leq 0.05$. *Choen's d* effects size was also calculated to determine the relevance of the differences, with values 0.8 representing a large effect, 0.5 indicating a medium effect, and 0.2 a small effect.

3. Results

Subjects ran both the courses with an average step frequency of 1.97 ± 0.19 Hz and an average speed of 1.71 ± 0.17 m/s.

3.1. Surface electromyography

During UE-T, an elevated EMG activation was observed in the muscles involved in ankle joint stabilization compared to E-T. Specifically, a significant difference was found in *TAn,* with mean activation increasing from 0.048 ± 0.013 mV in E-T to 0.058 ± 0.012 mV in UE-T (+22 %; p = 0.03; d = 0.82) and *PLo*, increasing from 0.055 ± 0.017 in E-T to 0.060 ± 0.015 in UE-T (+10 %; p = 0.02; d = 0.87), while *GMe* showed a 24 % increase between conditions, although this difference was not statistically significant (+24 %, p = 0.08, d = 0.62). On the contrary, no differences were found in *VLa, Sol* and *BFe* muscles ($P > 0.05$). (Fig. 2). CV analysis did not show any statistical difference in the level of muscle activation variability between the two running conditions (Table 1).

3.2. Cardiopulmonary measurements and rate of perceived exertion

During UE-T, respiratory parameters and cost of running were all significantly higher ($p < 0.05$) with respect to E-T. In specific, we measured an 18 % increase in VO_2, from 1767.94 ± 359.78 mL/min in E-T to 2085.22 ± 192.66 mL/min in UE-T (p = 0.01; d = 1) together with a 23 % increase in Cr (p = 0.02; d = 0.9), a 7 % increase in Rf (p = 0.02; d = 0.85), a 20 % increase in VE (p = 0.006; d = 1.1) and a 10 % increase in heart rate (HR), from 140.8 ± 29.9 bpm in E-T to 155 ± 27.1 bpm in UE-T (p = 0.02; d = 0.94). A significant difference between conditions for RPE was also observed, with a 50 % increase in UE-T compared to E-T running ($p < 0.001$) (Fig. 3).

4. Discussion

This study aimed to explore the energetic and neuromuscular effects of running on both even (E-T) and uneven (UE-T) terrains, using standardized smooth and rough iterative running paths with consistent characteristics in terms of step positioning, running velocity, and step frequency. This allowed us to analyze the effect of different surface conditions on energy consumption and muscle activation. By maintaining a consistency in the timing and positioning of foot placement

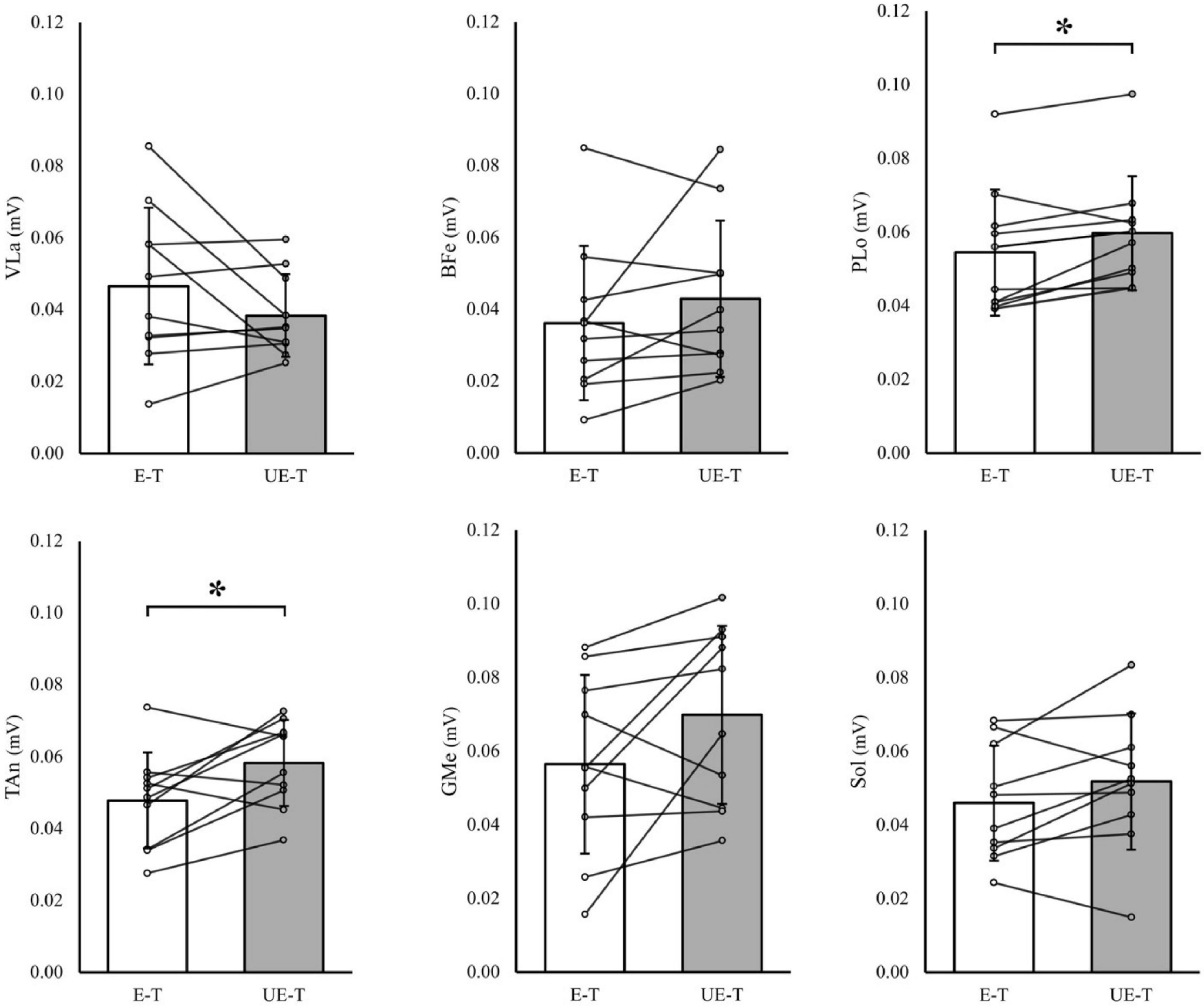

Fig. 2. EMG mean activation of muscles, in both running conditions (E-T: even terrain, UE-T: uneven terrain). Dots and lines represent individual responses. VLa: vastus lateralis, BFe: Biceps femoris, Tan: Tibialis anterior, PLo: peroneus longus, GMe: Gastrocnemius medialis, Sol: soleus. Student *t*-test results are reported: * = $p < 0.05$.

Table 1
Coefficient of variation (CV) of muscle activation in even (E-T) and uneven (UE-T) running conditions. VLa: vastus lateralis, BFe: Biceps femoris, Tan: Tibialis anterior, PLo: peroneus longus, GMe: Gastrocnemius medialis, Sol: soleus. Data are expressed as mean ± standard deviation.

CV	VLa	BFe	TAn	PLo	GMe	Sol
E-T	2.79 ± 1.46	2.21 ± 0.92	1.37 ± 0.16	1.56 ± 0.17	1.95 ± 0.28	1.66 ± 0.21
UE-T	2.34 ± 1.40	2.31 ± 1.13	1.44 ± 0.13	1.55 ± 0.18	1.92 ± 0.12	1.70 ± 0.12

between the two conditions, we could isolate the specific impact of the uneven surface, reducing the variability that would have been introduced if foot positioning during the stance phase had been different and inconsistent between the two conditions. The major findings of this study were that: i) EMG activation of the muscles involved in the ankle joint stabilization was increased when running on uneven terrain, despite step sequence being the same as in the even terrain condition ii) cost of running and all the cardio-metabolic values were elevated in UE-T, as well as the rate of perceived exertion; iii) maintaining a comparable running pattern in the two conditions, the variability of muscle activation was not different between UE-T and E-T.

This ensured consistency in the timing and positioning of foot placement between the two conditions.

4.1. Neuromuscular impact

We found that two key muscles responsible for ankle joint stabilization exhibited increased EMG activation during running on uneven terrain compared to the even condition. Specifically, the *tibialis anterior* and *peroneus longus* showed enhanced activity by 22 % and 10 %, respectively. The *gastrocnemius medialis* also exhibited a 24 % increase in activity, although this difference did not reach statistical significance. No differences were found in the thigh muscles monitored in this study or in the other leg muscles. Furthermore, the lack of significant differences in the CV for any of the monitored muscles suggests that, overall, the magnitude and variability of muscle activity patterns remained largely stable across conditions, particularly for the larger leg muscles. Taken together, these findings suggest a greater neuromuscular involvement of the leg muscles controlling the inversion-eversion movements of the foot, and to a lesser extent flexion–extension, when maintaining the same running pattern on rough terrains compared to smooth terrains. These results aligned with the findings highlighted by Nicot et al. (Nicot et al., 2022), who reported elevated mediolateral acceleration variability when running on trail terrain, indicating an increased mechanical effort in moving or controlling the feet along the

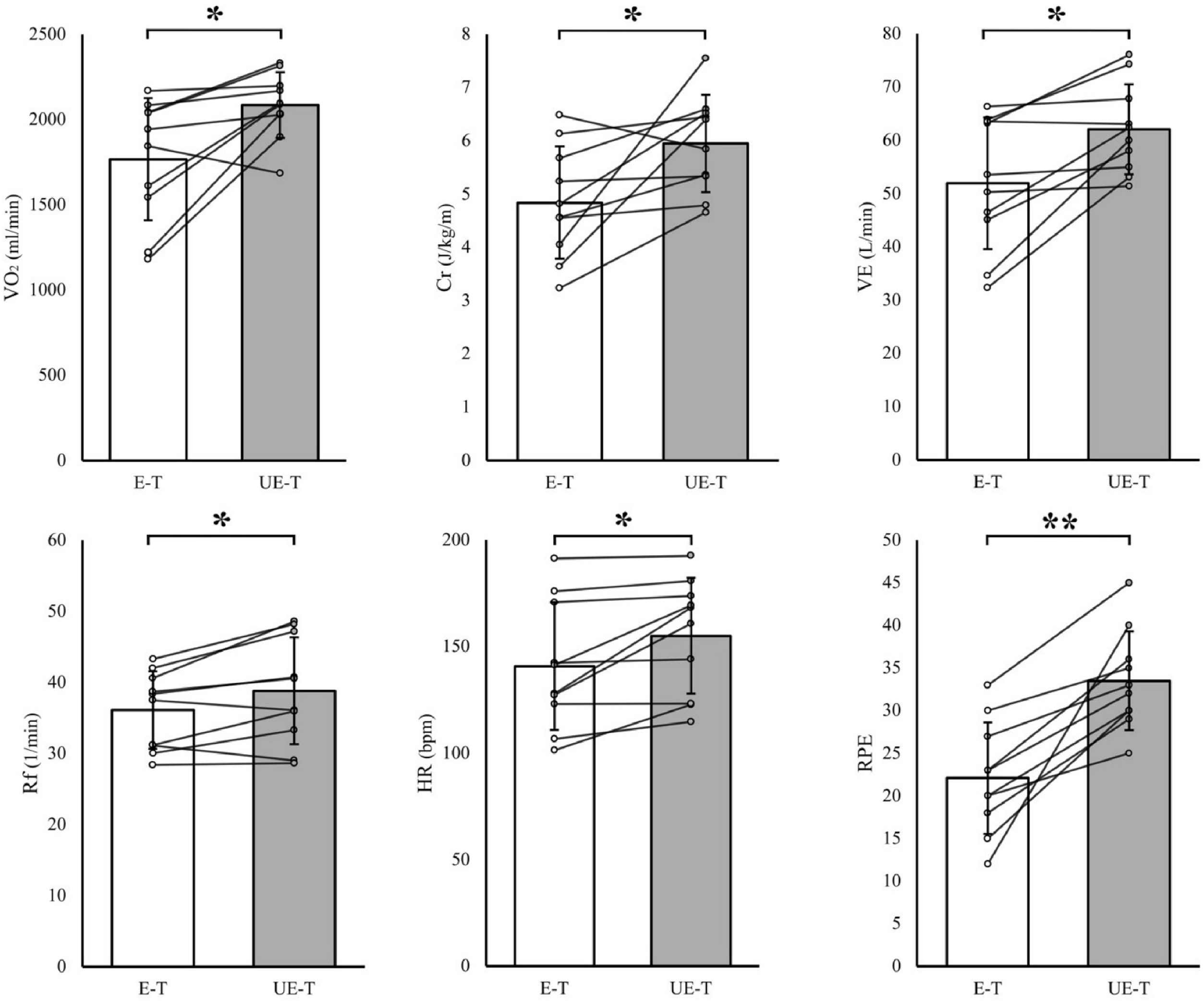

Fig. 3. Oxygen consumption (VO_2), cost of running (Cr), heart rate (HR), minute ventilation (VE), respiratory frequency (Rf) and perception of effort (RPE) are reported as mean ± standard deviation. Dots and lines represent individual responses. Student *t*-test results are reported: * = $p < 0.05$; ** = $p < 0.001$.

mediolateral direction (Nicot et al., 2022).

A different involvement of the ankle joint during running on uneven surfaces, compared to smooth surfaces, has previously been shown by different authors (Gantz and Derrick, 2018; Schrøder Jakobsen et al., 2022; Voloshina and Ferris, 2015). For instance, Gantz (2018) reported that runners on uneven terrain exhibited a reduction in inversion at foot contact, possibly as a protective mechanism to avoid ankle sprains, while also increasing knee flexion to compensate for the loss of shock attenuation. Voloshina and Ferris (2015) observed that running on uneven terrain led to slightly decreased ankle range of motion, suggesting runners adapted by landing with flatter feet, likely to reduce ankle instability. Jakobsen et al. (2022) also noted a reduction in ankle plantarflexion/dorsiflexion ROM and plantar flexor moments on unstable surfaces, which might be a protective strategy against ankle injuries. However, our EMG results are in contrast with the findings of the other studies that tried to recreate standardized laboratory setups to analyze running dynamics on irregular terrain. For example, Voloshina and Ferris did not find any significant difference in lower leg muscle activation during running on a modified uneven surface treadmill (Voloshina and Ferris, 2015), but they found increased EMG activity in thigh muscles. These differences could be explained by the fact that in our protocol we imposed a running pattern to isolate the effect of the running surface from other factors.

The CV of muscle activation did not show any differences between running conditions. These results are in contrast with previous studies that showed differences in this parameter (Schrøder Jakobsen et al., 2022; Skroce et al., 2023; Voloshina and Ferris, 2015) as well as in the CV of joint accelerations (Nicot et al., 2022). In Voloshina and Ferris (2015), all the muscles analyzed showed an increased EMG variability during uneven running, while Skroce et al. (2023) found greater EMG variability only in *tibialis anterior* and *soleus muscle* during running on a treadmill with unexpected lateral oscillations. The discrepancies with our results may be again imputable to the different experimental setups. Indeed, in the previous studies, athletes could choose their preferred running pattern in terms of foot positioning (ground contact), thus introducing possible biases during the EMG analysis. With our protocol we ensured a consistent step pattern across conditions, for the first time in the specific scientific literature, altering the characteristics of the contact surface only. We can state that, only certain lower leg muscles show increased activation, when the running surface is uneven compared to when running on smooth surfaces, and that there are no significant differences in the variability of muscle activation between the two conditions.

The integration of all these new findings together with the previous observations, indicated that a greater involvement of the muscles proximal to the ankle joint without an increased variability in muscle activation, are specific neuro-muscular features related to the influence of the running surface only (type of foot support) on movement control.

These results indicated an elevated neuro-muscular engagement to control foot support during un-even running with a fast adaptation of the central nervous system in supplying an adequate and consistent level of muscle control during foot support under uneven conditions. In this view, our neuro-muscular results can be considered as a basic step in the comprehension of neuro-muscular control during trail running.

4.2. Cardio-metabolic parameters

The collected data underscored significant differences in cardio-metabolic parameters between running on even or uneven terrains. Notably, there was an increase in respiratory frequency, oxygen consumption, heart rate, and perceived exertion during UE-T compared to E-T conditions, even if the run was performed at the same standardized velocity and at the same standardized step length and frequency. As previously discussed, the augmented need for stabilization during ground contact and the subsequent increase in EMG activation could explain the different metabolic responses observed here, as also found by other authors (Seki et al., 2020). Our results showed an approximate 18 % increase in oxygen consumption when running on uneven terrain compared to even terrain. This aligns with prior studies showing heightened physiological demands during off-road running in contrast to treadmill running at similar speeds and gradients (Jensen et al., 1999; Nicot et al., 2022). Nicot et al. reported a 10 % increase in the oxygen cost of trail running compared to treadmill running, with the energy expenditure escalating further with augmented trail technicity (Nicot et al., 2022).

In indoor settings, literature presents conflicting results. Voloshina and Ferris (Voloshina and Ferris, 2015) tested subjects on a treadmill under both even and uneven conditions, observing a 5 % increase in energy demand when running on uneven terrain. Gantz et al. found similar results with a 10 % increase in oxygen consumption while running on a modified irregular surface treadmill (Gantz and Derrick, 2018). However, Dhawale and Venkadesan (Dhawale and Venkadesan, 2023) noted a 5 % rise in metabolic power consumption when running on a custom-made path of both even and uneven surfaces, although this difference wasn’t statistically significant. The magnitude of the increase in the cost of running was greater in our study compared to the mentioned studies, but the disparities observed in the results could be attributed to the diverse setups and the different absolute intensities employed by the various research groups. As discussed above, the uneven conditions induce biomechanical and neuro-muscular alterations, thought to contribute to the increase in energy expenditure. Therefore, as the magnitude of these perturbations amplifies, the muscle activation increases leading to an augmented cost of running. In our research, we forced the same running velocity and an equal running pattern in both even and uneven running conditions. This task did not let the athlete naturally adapt to the surface for a more economical and easy running pattern, suggesting that when running with the same pattern, the effect of surface condition on running economy is even greater than what can be measured in the ecological trail environments.

Although the activation pattern of the lower leg muscles remained largely consistent between conditions, with only increased activity observed in the ankle stabilizers, this localized neuromuscular adaptation likely contributes to the increased oxygen consumption observed during uneven terrain running. However, it is likely that other factors, such as the activity of stabilizing muscles in the trunk and upper body, also play a role in the rise in metabolic cost. As this was not directly assessed in our study, further research is needed to explore the involvement of these additional muscle groups and gain a more comprehensive understanding of the physiological demands of running on uneven terrain.

This study has several limitations that should be acknowledged. Firstly, the focus was primarily on the muscles of the lower body, without a comprehensive analysis of core and upper body muscles, which may play a crucial role in stabilizing locomotion and influencing energy expenditure. Secondly, plantar forces were not measured, which could have provided valuable insights into pressure distribution and its relationship with stability. Thirdly, we analyzed only one submaximal speed for both running conditions. Additionally, the 8-shaped course used in the study, while carefully designed to emulate specific characteristics of trail running in a controlled laboratory setting, included curvilinear running and a relatively short length that may not fully replicate the dynamics of outdoor trail running. The turns, although moderate, could have influenced the participants’ biomechanics and should be considered when interpreting the results. Furthermore, even and uneven surfaces could have had different stiffness, partially influencing the data. This could be taken into consideration for future studies, where surface stiffness should also be assessed, and athletes who habitually run on uneven surfaces, such as trail runners, should be involved.

5. Conclusions

In conclusion, our protocol was designed to ensure similar gait patterns across different surface conditions by providing foot placement targets and using a metronome to standardize step lengths and step frequencies. This approach aimed to isolate the influence of the terrain on running performance, minimizing the effects of step positioning during ground contact on both even and uneven surfaces. Running on UE-T elicits elevated neuromuscular activation of the ankle’s stabilizer muscles and elevated metabolic responses compared to E-T. The findings obtained have contributed to elucidating the impact of terrain variability in trail running on physiological and neuromuscular features. This study underlines the importance of considering the unique characteristics of outdoor terrains where off-road running competitions are held, including their unevenness and variability. Understanding how surface terrain influences physiological and neuromuscular responses can aid in developing more effective injury prevention strategies and optimizing performance.

Founding

This work was founded by Key Stone (Folgaria, Italy). Key Stone (Folgaria, Italy) also provided the stones that were used in the experimental setup. However the results presented in this article do not in any way represent a bias toward Key Stone products or brand. The results of the study were presented clearly, honestly, and without fabrication, falsification or inappropriate data manipulation. The founder had no role in the study design, data collection and analysis, decision to publish or preparation of the manuscript.

CRediT authorship contribution statement

Simone Bettega: Writing – review & editing, Writing – original draft, Formal analysis. **Lorenzo Bortolan:** Writing – review & editing, Methodology, Conceptualization. **Federico Stella:** Writing – review & editing, Methodology, Investigation, Formal analysis. **Cantor Tarperi:** Writing – review & editing. **Federico Schena:** Writing – review & editing, Supervision, Resources. **Barbara Pellegrini:** Writing – review & editing, Supervision, Resources. **Chiara Zoppirolli:** Writing – review & editing, Writing – original draft, Investigation, Formal analysis, Data curation, Conceptualization.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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