Similar Running Economy With Different Running Patterns Along the Aerial-Terrestrial Continuum

Thibault Lussiana, Cyrille Gindre, Kim Hébert-Losier, Yoshimasa Sagawa, Philippe Gimenez, and Laurent Mourot

Purpose: No unique or ideal running pattern is the most economical for all runners. Classifying the global running patterns of individuals into 2 categories (aerial and terrestrial) using the Volodalen method could permit a better understanding of the relationship between running economy (RE) and biomechanics. The main purpose was to compare the RE of aerial and terrestrial runners. Methods: Two coaches classified 58 runners into aerial (n = 29) or terrestrial (n = 29) running patterns on the basis of visual observations. RE, muscle activity, kinematics, and spatiotemporal parameters of both groups were measured during a 5-min run at 12 km/h on a treadmill. Maximal oxygen uptake (VO₂max) and peak treadmill speed (PTS) were assessed during an incremental running test. Results: No differences were observed between aerial and terrestrial patterns for RE, VO₂max, and PTS. However, at 12 km/h, aerial runners exhibited earlier gastrocnemius lateralis activation in preparation for contact, less dorsiflexion at ground contact, higher coactivation indexes, and greater leg stiffness during stance phase than terrestrial runners. Terrestrial runners had more pronounced semitendinosus activation at the start and end of the running cycle, shorter flight time, greater leg compression, and a more rear-foot strike. Conclusions: Different running patterns were associated with similar RE. Aerial runners appear to rely more on elastic energy utilization with a rapid eccentric-concentric coupling time, whereas terrestrial runners appear to propel the body more forward rather than upward to limit work against gravity. Excluding runners with a mixed running pattern from analyses did not affect study interpretation.

Keywords: biomechanics, muscle activity, optimization strategies

Running economy (RE) is an important determinant of running performance. Running biomechanics influences RE, although the nature and magnitude of the relationship is debated. For instance, studies have associated both long and short contact time with enhanced RE. In contrast, other studies have found no relationship between contact time and RE. Likewise, both rear-foot and non-rear-foot strike patterns are suggested to be more economical. Gruber et al. reported no marked difference in RE on the basis of footstrike pattern, and the self-selected footstrike was the most economical. Oxygen consumption has been shown to increase linearly with the muscle electromyographic (EMG) activity of the biceps femoris during the braking phase of running, whereas an increased coactivation of agonist and antagonist muscles before and after ground contact enhances knee- and ankle-joint stiffness, which enhances force potentiation during push-off and reduces metabolic cost. Overall, although several studies have identified relationships between biomechanical factors and RE, results are contradictory and practical applications are unclear.

All considered, it is likely that no unique or ideal running pattern is the most economical for all runners. The Volodalen method (see below) allows the classification of runners through visual observation under the premise that a runner is a global and dynamic system that seeks to optimize RE. This method is very practical in nature and allows coaches, clinicians, and scientists to quickly classify, based on visual observations, the running patterns of individuals along a continuum. Overall, the method describes 2 different strategies to optimize RE: 1 that relies more on the ability to propel the body forward rather than upward, and another that relies more on the ability to store and release elastic energy. Runners who use the first strategy are called terrestrial runners; those who use the second strategy are called aerial runners. Anecdotally, coaches report the presence of both types of runners across the competition spectrum, and the aerial and terrestrial patterns are observed in both recreational and highly competitive runners.

Recently, these 2 running patterns, assessed on the basis of 5 subjectively evaluated criteria (Figure 1), were shown to demonstrate distinct objectively assessed running characteristics. More specifically, aerial runners exhibit shorter contact times, greater leg stiffness, and longer flight times than terrestrial runners, as well as larger vertical displacements of the center of mass and maximal vertical ground-reaction forces. Given the scientific literature suggesting that self-selected running patterns are the most economical and the observed presence of both aerial and terrestrial runners across the competition spectrum, we can anticipate no difference in the RE of aerial and terrestrial runners. However, this assumption has not yet been verified experimentally.

Thus, our main aim was to compare the RE of aerial and terrestrial runners. A secondary aim was to investigate the muscle activity and biomechanics of the aerial and terrestrial runners during running to objectify the biomechanical strategies used by both groups. Finally, to verify that differences between groups were not

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due solely to differences in maximal running performance levels, we aimed to compare maximal aerobic capacities between both groups. We hypothesized that aerial and terrestrial runners would demonstrate similar RE values despite distinct electromyographic and biomechanical characteristics.

Methods

Participants

Fifty-eight recreational male runners (mean ± standard deviation [SD]: age, 30 ± 8 y; height, 177 ± 5 cm; and body mass, 72 ± 9 kg) voluntarily participated in this study. Inclusion criteria were good self-reported general health, absence of lower-extremity injury for the past year, and ability to run at 12 km/h with submaximal effort. To limit confounding variables, we recruited only men. All participants were tested within a 2-month period. The university’s Institutional Review Board approved the study protocol before participant recruitment (CPP: 2014-A00336-41), which was conducted in accordance with international ethical standards and adhered to the Declaration of Helsinki of the World Medical Association.

Design

Each participant completed 1 experimental session in our laboratory. After providing written informed consent, participants ran a 5-minute warm-up on a treadmill (Training Treadmill S1830; HEF Techmachine, Andrézieux-Bouthéon, France) at 10 km/h with no inclination. During this warm-up, 2 running coaches with more than 5 years of experience using the Volodalen method focused on the global movement patterns of participants, with particular attention to 5 key elements (Figure 1). Each criterion was scored between 1 and 5 after the attainment of a consensus between coaches. The global subjective score (V score), which is the sum of each individual score, allows the classification of runners into 2 different categories: terrestrial runner (V score ≤ 15) or aerial runner (V score > 15). A score of 15 reflects the midpoint of the scale, making the use and interpretation of the V score practical and simple. The V score demonstrates adequate intra- and interrater reliability (intraclass correlation coefficient [ICC], 0.940 and 0.945; standard error of the mean [SEM], 1.28 and 1.31).

In the current study, 29 participants were classified as aerial runners (V score 19.3 ± 2.5) and the remaining 29 were classified as terrestrial runners (V score 11.5 ± 2.0). The baseline characteristics of runners were similar in the 2 groups (aerial vs terrestrial: age, 29 ± 9 vs 30 ± 9 y; height, 178 ± 6 vs 177 ± 5 cm; and body mass, 72 ± 9 vs 71 ± 8 kg; all P values > .390).

After the warm-up, participants performed a submaximal running test and a maximal incremental running test. Tests were interspersed by a 5-minute passive recovery in the seated position. All subjects were familiar with running on a treadmill as part of their usual training programs and wore their habitual running shoes (aerial vs terrestrial: mass, 317 ± 50 vs 300 ± 55 g; heel height, 22 ± 5 vs 20 ± 4 mm; and drop-off, 9 ± 4 vs 9 ± 3 mm; all P values > .249).

Submaximal Running Test

Participants ran 5 minutes on a treadmill at 12 km/h. This speed was chosen on the basis of participants’ running performance to avoid efforts above ventilatory threshold. Gas exchange was

Figure 1 — Subjective grid of the Volodalen method to assess the individual running pattern.
measured breath-by-breath using a gas analyzer (Metamax 3B; Cortex Biophysik, Leipzig, Germany) and subsequently averaged over 10-second intervals throughout the test. Before each test, the gas analyzer was calibrated according to the manufacturer’s recommendations using ambient air (O₂, 20.93%; CO₂, 0.03%) and a gas mixture of known composition (O₂, 15.00%; CO₂, 5.00%). The spirometer was calibrated using a 3-L syringe. Respiratory exchange ratios (RER), oxygen uptake (VO₂), and carbon dioxide output (VCO₂) were averaged over the last minute of the 5-minute running trial. Steady state was confirmed through visual inspection of the VO₂/VCO₂ curves. RER had to remain below 1.0 during the running trial. Steady state was confirmed through visual inspection by Morin et al13 the spring-mass characteristics of the lower extremity were estimated using a sine-wave model using tmax, tmin, leg length (L), the distance between the greater trochanter, lateral femoral condyle; and the sole of the foot-ground; and the plantar-flexion of plantar foot-ground (αplantar); and the knee angle (αknee) determined using the line connecting the lateral malleolus to the lateral femoral condyle and the lateral femoral condyle to the greater trochanter; the αankle was determined using the lines connecting the fifth metatarsal phalangeal joint to the lateral malleolus and the lateral malleolus to the lateral femoral condyle; and the αankle was determined using the line connecting the fifth metatarsal phalangeal joint relative to the plane of the treadmill. The reliability of this procedure has been analyzed previously in our laboratory with ICC and SEM values ranging from .88 to .98 and 1.1 to 1.3 for αknee, αankle, and αstrike. Strike pattern was classified as described by Altman and Davis:14 midfoot strike = –1.6 ° < αstrike < 8.0 °; rear-foot strike = αstrike > 8.0 °; forefoot strike = αstrike < –1.6 °.

EMG activity of the rectus femoris (RF), semitendinosus (ST), tibialis anterior (TA), and gastrocnemius lateralis (GL) muscles of the right leg was evaluated with preamplified single-diagonal surface electrodes (Trigno Wireless EMG; Delsys Inc, Natick, MA) with an interelectrode distance of 10 mm and a common mode rejection ratio of 92 dB. The skin preparation and electrode placements were done according to SENIAM project recommendations.15 EMG and temporal events (ie, footstrike and toe-off recorded with the Optogait) were synchronized between systems using ADInstruments system and software (Labchart 7.0, ADInstruments Ltd, Oxford, UK). Custom scripts developed in MATLAB (The MathWorks, Natick, MA) were used to process the EMG signals. First, EMG signals were filtered using a second-order Butterworth band-pass filter from 20 to 480 Hz. To generate an EMG profile, signals were then rectified and passed through a critically damped low-pass filter with a 20-Hz cutoff to create a linear envelope. To produce a representative EMG pattern, 70 consecutive running steps taken from the last minute of the 5-minute submaximal running trial were averaged for each individual16; the signals were time-normalized to the running cycle (ie, right-foot contact to right-foot contact represented 100% of a cycle).

The EMG activity of each muscle was quantified using the root-mean-square amplitude (μV) and expressed as a percentage of the peak signal (RMS, %) captured during the running trial for each individual. The time of peak activity of each muscle was determined and expressed as a percentage of the running cycle (peak, %). In addition, the mean and standard deviation (± SD) muscle activity were computed for the following subphases of the running cycle: first contact phase (0–50% of the stance phase), second contact phase (50–100% of the stance phase), first swing phase (0–80% of the swing phase), and second swing phase (80–100% of the swing phase). Coactivation indexes (CO, %) between the RF/ST and the TA/GL muscles were also computed for these 4 subphases according to the method proposed by Winter.17 More specifically, agonist and antagonist muscles that show a common area of activity define a cocontraction area, with the CO calculated as

\[ CO = 2 \times \frac{\text{common area (agonist and antagonist)}}{\text{area agonist} + \text{area antagonist}} \times 100\% \]

### Maximal Incremental Test

The maximal incremental running test was performed on the treadmill starting at 10 km/h. The treadmill speed was subsequently increased by 0.5 km/h every minute until volitional exhaustion. The participants received strong verbal encouragement to ensure
attainment of maximal values during the test. The maximal oxygen uptake (VO₂max), averaged over 30 seconds, was said to be attained when 2 or more of the following criteria were met: an increase in VO₂ less than 2.1 mL · kg⁻¹ · min⁻¹ between 2 consecutive stages, an RER greater than 1.1, and/or a heart rate (RS810; Polar Electro Oy, Kempele, Finland) of ≥ 10 beats/min of the predicted maximal heart-rate value (ie, 220 minus age). The highest velocity achieved during the test was recorded as the PTS. When the participant could not complete the last stage completely (<1 min), the PTS was calculated using fractional time supported during the last stage multiplied by the speed-increment rate.

**Statistics**

Descriptive statistics of data are presented as mean ± SD values. Because all data were normally distributed (according to the Kolmogorov-Smirnov test), parametric statistical methods were used for data analysis. Two-tailed t tests were used to examine differences between the 2 groups of runners. RE and maximal incremental test data were also compared between groups using data from extreme aerial runners (n = 14, Vscore = 21.5 ± 1.6) and terrestrial runners (n = 14, Vscore = 9.6 ± 1.5) to limit confounding from individuals with midrange Vscore values. Pearson correlation coefficients (r) and their 90% confidence intervals (CI) were calculated to assess the relation between Vscore and RE, PTS, and VO₂max. The following criteria were adopted to interpret the magnitude of the correlation: ≤.1, trivial; >.1 to .3, small; >.3 to .5, moderate; >.5 to .7, large; >.7 to .9, very large; and >.9 to 1.0, almost perfect.20 A correlation was deemed unclear when its confidence limits overlapped the thresholds for small positive and small negative correlations (ie, the chances of the correlation being positive and negative were both >5%).20 Statistical significance was accepted when the overall P value was <.05, with statistics performed in SigmaStat 12 for Windows (Systat Software Inc., San Jose, CA) and Microsoft Excel (Microsoft Corp., Redmond, WA) using Hopkins’ spreadsheet (http://www.sportsci.org).

**Results**

**RE and Performance**

RE measured at 12 km/h, PTS, and VO₂max were similar in aerial and terrestrial runners (see histograms in Figure 2; all P values >.120), as well as between extreme aerial and terrestrial runners (see circles in Figure 2; all P values >.101). The most economical aerial and terrestrial runner had quite similar RE values (aerial vs. terrestrial runner: 6.00 vs 5.94 m · mL⁻¹ · kg⁻¹ and 0.825 vs 0.834 kcal · km⁻¹ · kg⁻¹).

Correlations between Vscore and RE were trivial and unclear (r = −.08, 90% CI, [−.29–.11], P = .523; r = .097, 90% CI, [−.12, 0.28], P = .378, respectively). Correlations were small and clear between Vscore and PTS (r = −.27 [−.45, −.07], P = .035), as well as between Vscore and VO₂max (r = −.29 [−.47, −.10], P = .027).

**Kinematics and Spring Mass**

Values of t_c, t_f, f, Δz, ΔL, Fmax, k_leg, k_vert, α_knee, α_ankle, and α_strike are reported in Table 1. The aerial group exhibited significantly lower t_c and ΔL with greater t_f, Δz, Fmax, and k_leg than the terrestrial group. The aerial group also demonstrated greater α_ankle and lower α_strike than the terrestrial group.

**Electromyography**

Activation profiles of the RF, ST, TA, and GL muscles recorded during the submaximal running trial in 1 representative aerial runner and one representative terrestrial runner are presented in Figure 3. The aerial group showed an earlier peak GL activity and later peak TA activity than the terrestrial group (see Figure 4).

The muscle activity and coactivation indexes recorded during the 4 subphases of the running cycle are reported in Table 2. Compared to the aerial pattern, the terrestrial pattern exhibited higher ST-RMS in the first contact and the second flight phases, while the
Table 1  Measures Collected During the Submaximal Running (12 km/h) Trial in Aerial and Terrestrial Running Groups, Mean ± SD

<table>
<thead>
<tr>
<th>Group</th>
<th>$t_c$ (s)</th>
<th>$t_f$ (s)</th>
<th>$f$ (steps/s)</th>
<th>$\Delta z$ (m)</th>
<th>$\Delta L$ (m)</th>
<th>$F_{\text{max}}$ (kN)</th>
<th>$k_{\text{vert}}$ (kN/m)</th>
<th>$k_{\text{leg}}$ (kN/m)</th>
<th>$\alpha_{\text{knee}}$ (°)</th>
<th>$\alpha_{\text{ankle}}$ (°)</th>
<th>$\alpha_{\text{strike}}$ (°)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Aerial</td>
<td>0.268 ± 0.020</td>
<td>0.092 ± 0.021</td>
<td>2.79 ± 0.18</td>
<td>0.062 ± 0.009</td>
<td>0.131 ± 0.015</td>
<td>1.49 ± 0.25</td>
<td>24.2 ± 2.7</td>
<td>11.5 ± 2.3</td>
<td>168 ± 4</td>
<td>117 ± 10</td>
<td>9.8 ± 9.2</td>
</tr>
<tr>
<td>Terrestrial</td>
<td>0.287 ± 0.022</td>
<td>0.069 ± 0.022</td>
<td>2.83 ± 0.14</td>
<td>0.058 ± 0.007</td>
<td>0.139 ± 0.013</td>
<td>1.36 ± 0.21</td>
<td>23.6 ± 3.5</td>
<td>9.8 ± 1.6</td>
<td>167 ± 4</td>
<td>111 ± 5</td>
<td>16.9 ± 6.4</td>
</tr>
<tr>
<td>$P$</td>
<td>&lt;.001</td>
<td>&lt;.001</td>
<td>.161</td>
<td>.013</td>
<td>.016</td>
<td>.011</td>
<td>.275</td>
<td>&lt;.001</td>
<td>.236</td>
<td>.002</td>
<td>&lt;.001</td>
</tr>
</tbody>
</table>

Note: Boldface type indicates significance of $P \leq .05$.

Abbreviations: $t_c$, contact time; $t_f$, flight time; $f$, step frequency; $\Delta z$, center of mass displacement; $\Delta L$, leg spring compression; $F_{\text{max}}$, maximal vertical force; $k_{\text{vert}}$, vertical stiffness; $k_{\text{leg}}$, leg stiffness; $\alpha_{\text{knee}}$, knee angle; $\alpha_{\text{ankle}}$, plantar-flexion angle; $\alpha_{\text{strike}}$, foot-ground angle.
Figure 3 — Illustrations of mean muscle activation during the submaximal running (12 km/h) trial in one typical terrestrial runner (left) and one typical aerial runner (right), expressed as a percentage of the running cycle. Shaded areas represent ±1 SD. Dashed lines delineate toe-off events.

Figure 4 — Mean point of peak activity as a percentage of the running cycle for the rectus femoris (RF peak), semitendinosus (ST peak), tibialis anterior (TA peak), and gastrocnemius lateralis (GL peak) muscles obtained during the submaximal running (12 km/h) trial in aerial and terrestrial groups. Error bars indicate ±1 SD.
aerial pattern showed higher GL-RMS in the first contact phase. Moreover, the RF/ST-CO was greater in the aerial than in the terrestrial pattern during the 5 contact phases.

Discussion

This study demonstrates for the first time that aerial and terrestrial running patterns, determined using a subjective rating scale, exhibit similar RE despite their distinct biomechanical and electromyo-graphic characteristics. Our study adds to the scientific literature indicating that different global running patterns can lead to similar RE, reflecting results from previous work with a focus on footstrike pattern.7

The GL showed an earlier activation onset in preparation for landing and reached peak activation more quickly after ground contact in the aerial runners compared with the terrestrial runners (Figure 4); the aerial pattern demonstrated more positive ankle angles (ie, less dorsiflexion) and negative foot-ground angles (ie, less rear-foot strike) at foot strike. Landing in a more plantar-flexed position suggests an increased capacity of the passive structures to store elastic energy at the beginning of the stance phase.21 Greater activation of the plantar flexors in preparation for ground contact during the braking phase can increase the utilization of elastic energy during human locomotion,22 and preactivation increases leg stiffness23 and stretch-shortening cycle efficiency.24 Furthermore, the aerial runners demonstrated higher coactivation indexes during the stance phase than the terrestrial runners, suggesting superior knee joint stiffness, corroborating the higher leg stiffness values we observed in the aerial group. By investigating joint-angle moment curves and muscle-activity patterns at different running speeds, Kyrolainen et al8 inferred that increases in muscle stiffness around the knee and ankle joints during the early stance phase of running enhanced force potentiation during push-off and increased the mechanical efficiency of runners. Furthermore, the coupling time (ie, time between stretching and shortening of muscle tendon units during the stretch-shortening cycle) is positively related to contact time, with short coupling times believed to reflect a more efficient utilization of elastic energy during the stretch-shortening cycle.25

We propose that the aerial runners’ self-optimization strategy is to enhance force generation via a more efficient utilization of the stretch-shortening cycle and to limit the braking phase by contacting the ground close to the center of mass (Figure 5).

Aura and Komí26 highlighted that there may be substantial interindividual differences in ability to store and release elastic energy. Here, the aerial and terrestrial running patterns showed no differences in RE despite demonstrating distinct neuromuscular and biomechanical characteristics, suggesting that different biomechanical strategies can lead to a similar oxygen cost of running. Terrestrial runners contacted the ground more in front of their center of mass (based on the visual observation) and with more pronounced ankle dorsiflexion and rear-foot strike than aerial runners, which was followed by a greater leg compression during stance and longer contact time. There is evidence to suggest the existence of an inverse relationship between the energy cost of running, wherein longer contact times are associated with lower rates of energy consumption.27 In fact, a longer contact time allows force to be generated over a longer period of time.27 Thus, strategies associated with longer ground-contact times, such as rear-foot strike patterns,5 allow runners to be economical without necessarily promoting the storage and release of elastic energy through the mechanism described above. These arguments are supported by a recent study wherein habitual rear-foot strikers had shorter flight times and longer ground-contact times than habitual forefoot strikers, as well as 5.4% and 9.3% better RE at 11 and 13 km/h, respectively.5

The EMG analysis showed that the ST muscle of the terrestrial runners worked at a higher percentage of its peak recorded amplitude during the first contact and second flight phases than in the aerial runners. These results are consistent with observations by Yong et al5 of greater activity (normalized to the peak found during walking) of the lateral hamstring muscle during the terminal swing phase in natural rear-foot strikers. The hip extensor muscles are important in driving the body powerfully forward,8 given that a more horizontal resultant ground reaction force vector has been recently associated with a better RE.29 Ultimately, using energy to drive the body forward rather than upward can reduce the oxygen cost of running, because smaller vertical displacements of the center generally improves RE.30 Although it is difficult to directly compare the level of muscle activity between groups given the dynamic normalization method used in this study, we propose that terrestrial

### Table 2 Root-Mean-Square Activation Amplitude (% of Peak) During 4 Subphases of the Running Cycle for the Muscles Monitored in the Study, As Well As Coactivation Indexes for Muscles, in the Aerial and Terrestrial Running Pattern Groups, Mean ± SD

<table>
<thead>
<tr>
<th></th>
<th>First 50% of Contact Phase</th>
<th>Second 50% of Contact Phase</th>
<th>First 50% of Swing Phase</th>
<th>Second 50% of Swing Phase</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Aerial</td>
<td>Terrestrial</td>
<td>Aerial</td>
<td>Terrestrial</td>
</tr>
<tr>
<td>RF-RMS</td>
<td>45.4 ± 15.6</td>
<td>47.3 ± 12.0</td>
<td>59.2 ± 12.8</td>
<td>56.3 ± 12.7</td>
</tr>
<tr>
<td>ST-RMS</td>
<td>64.2 ± 10.7</td>
<td>68.2 ± 12.2*</td>
<td>52.3 ± 18.3</td>
<td>50.3 ± 23.9</td>
</tr>
<tr>
<td>TA-RMS</td>
<td>72.0 ± 9.2</td>
<td>72.0 ± 6.1</td>
<td>46.4 ± 17.4</td>
<td>38.9 ± 19.4</td>
</tr>
<tr>
<td>GL-RMS</td>
<td>46.7 ± 12.7</td>
<td>41.8 ± 11.7*</td>
<td>76.9 ± 4.5</td>
<td>76.3 ± 3.9</td>
</tr>
<tr>
<td>RF/ST-CO</td>
<td>61.9 ± 13.0</td>
<td>55.1 ± 8.2*</td>
<td>69.0 ± 11.6</td>
<td>59.5 ± 15.6*</td>
</tr>
<tr>
<td>TA/GL-CO</td>
<td>62.2 ± 11.5</td>
<td>58.4 ± 12.3</td>
<td>67.2 ± 16.3</td>
<td>59.8 ± 17.6</td>
</tr>
</tbody>
</table>

**Abbreviations.** RF, rectus femoris; ST, semitendinosus; TA, tibialis anterior; GL, gastrocnemius lateralis; RMS, root-mean-square; CO, coactivation indexes.

*P < .05 (significant difference between aerial and terrestrial patterns).
runners self-optimize their running pattern by propelling the body forward rather than upward and limiting the work against gravity.

The correlation coefficients between \( V \) score and RE were trivial and unclear, supporting our results of no meaningful difference in the RE of aerial and terrestrial runners. On the other hand, the small negative correlations between \( V \) score and PTS, as well as between \( V \) score and \( \text{VO}_2 \text{max} \), are suggestive of a tendency toward better performance during the maximal incremental test in our terrestrial runners compared with our aerial runners. Unfortunately, at the time of participant recruitment and data collection, we did not seek to collect data regarding the distances and types of events that our runners preferred or in which they performed better. The recreational level of our runners may limit the generalization of the current study findings.

Moreover, the assessment of RE at a unique submaximal speed (ie, 12 km/h) limits inferences to slower and faster speeds because aerial and terrestrial runners might show different RE responses to changes in running speed. For instance, given the enhanced contribution from the storage and release of elastic energy to running as speed increases, \( V \) score and \( \text{VO}_2 \text{max} \), aerial runners may be relatively more economical than terrestrial runners at faster speeds, and terrestrial runners may be relatively more economical than aerial runners at slower speeds. Another consideration here is the threshold used to classify aerial and terrestrial runners. Consistent with previous investigations, a cut-off score of 15 was chosen to classify runners to facilitate the use and interpretation of the \( V \) score, and data from all participants were included in the analysis to reflect the reality of the population and represent the entire running pattern continuum. Although excluding runners with midrange \( V \) score values did not meaningfully influence RE and PTS interpretation, further validation of the use of a 2-group classification system with a deterministic \( V \) score of 15 is needed.

**Practical Applications**

From a practical perspective, fix, bend, roll, and push summarizes the terrestrial self-optimization strategy, whereas fly, touch, and bounce summarizes the aerial one. As running pattern can vary under different conditions (eg, in a fatigued state or under psychological stress), we advise coaches to assess their athletes more than once before using the \( V \) score to inform their training prescription. In any case, through a better understanding of these biomechanical strategies and their relationships with RE at an individual level, our results could assist athletes and coaches to individualize exercise prescription, thereby improving training responses. Athletes and coaches can modify certain aspects of the running technique, favoring either the aerial or terrestrial pattern, or even both, depending on training objectives and what might benefit the athlete the most. However, a crossover intervention study assessing the effect of a training program targeting either the stretch-shortening cycle or forward propulsion on the RE of aerial and terrestrial runners is warranted. In addition, it should be mentioned that running technique is not the only factor to influence RE. Several other biomechanical and physiological factors are involved that were not evaluated in the current study.

**Conclusions**

Aerial and terrestrial runners demonstrate similar RE measures despite exhibiting distinct running biomechanics and electromyographic characteristics. Aerial runners exhibited earlier GL activation, less dorsiflexion, and higher coactivation indexes and leg stiffness than terrestrial runners. Terrestrial runners showed more pronounced recruitment of the ST in the late swing phase and early ground-contact phase, longer contact time, and greater leg compression than aerial runners. In fact, aerial runners appear to benefit from storing and release of elastic energy (ie, shorter coupling times and higher leg stiffness) to a greater extent than terrestrial runners, who appear to propel the body more forward rather than upward to minimize oxygen cost. Given that the Volodalen method classifies runners along a continuum, the current study results also include runners with a mixed running pattern who use both aerial and terrestrial strategies to varying extents (ie, more midrange \( V \) score). Excluding these mixed runners from analyses still support that aerial and terrestrial running patterns have similar RE, which is achieved
through different biomechanical and neuromuscular means. Both strategies involve a certain trade-off given that the aerial strategy encourages vertical oscillation and work against gravity, whereas the terrestrial strategy limits the energetic contribution from the stretch-shortening cycle. Whether one can benefit fully from the economical advantages of both strategies is not certain, because a trade-off between strategies appears unavoidable.

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