

Motor imagery priming reduces vertical ratio during exhaustive treadmill running

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Abstract

Purpose

Motor imagery (MI) is a strategy widely used to enhance motor performance and optimize motor control also in sport domain. However, its acute effects on running biomechanics remain unclear. This study investigated whether a brief MI intervention could induce immediate changes in running technique during a time-to-exhaustion (TTE) test.

Methods

Twenty-six physically active participants completed a TTE test at the velocity associated with the second ventilatory threshold after completing either a guided MI protocol or a control reading task. Running biomechanics were assessed using wearable sensors.

Results

Compared with controls, participants in the MI group showed lower vertical ratio (VR) values, while cadence, step length, ground contact time, vertical oscillation and TTE did not differ between groups. These findings suggest that a brief MI intervention can acutely influence running mechanics during exhaustive running.

Conclusion

The reduction in VR may reflect a more economical running pattern and highlight the potential of MI as a neural priming strategy for optimizing movement efficiency.

Introduction

Motor imagery (MI) is defined as the mental simulation of movement without physical execution, and engages neural networks largely overlapped with those involved in actual movement, thus contributing to motor planning and action preparation [1-3]. Consequently, MI practice has been used in sport to enhance motor learning and performance across different motor tasks [4-6].

Beyond its role in motor learning, MI may transiently optimize the neural state preceding movement by facilitating motor command preparation, thereby acting as a form of neural priming. While this has been shown in neurological conditions [7], its potential to induce immediate, acute changes in the sports domain remains largely unknown. Indeed, a limited number of studies have investigated the acute effects of a single MI session in athletes, and these investigations have primarily focused on sport-specific performance outcomes, such as basketball free-throw accuracy [8], or on performance and neuromuscular responses during explosive tasks such as drop jumps [9]. However, whether a single MI session can acutely modify the organization of movement during a complex cyclic task such as running remains poorly understood, particularly from a biomechanical perspective.

In the context of locomotion, both real and imagined gait share overlapping neural substrates, suggesting that MI can influence locomotor control [10]. One common form of locomotion is running. Running performance is strongly influenced by biomechanical factors associated with movement efficiency. Variables such as stride length, ground contact time, and vertical oscillation have been consistently linked to the energetic cost of running, with lower vertical displacement and more efficient spatiotemporal patterns generally associated with improved performance [11–13]. Interventions targeting biomechanical adjustments, such as modifying cadence or reducing vertical oscillation, have been shown to influence movement patterns during running [14]. However, these approaches typically rely on physical practice combined with external forms of feedback, including visual, auditory, or verbal cues [15], and it remains unclear whether similar biomechanical adaptations can be elicited through purely cognitive strategies such as MI.

Therefore, the aim of the present study was to investigate the acute effects of a MI intervention on running biomechanics during a time-to-exhaustion (TTE) test performed on a treadmill. We hypothesized that participants exposed to a single MI session would exhibit more favourable biomechanical parameters, known to be associated with improved running economy [16], than those in the control condition.

Methods

Subjects

Twenty-six students (13 men and 13 women) enrolled in the Master's Degree Program in Sports Sciences at the University of Genoa volunteered to participate in this study (mean age: 24.04 ± 4.10 years; mean height: 1.72 ± 0.08 m; mean body mass: 67.42 ± 11.11 kg). Participants were randomly assigned to the motor imagery group (MI) (mean age: 23.23 ± 1.17 years; mean height: 1.71 ± 0.09 m; mean body mass: 65.23 ± 9.40 kg; 8 men and 5 women) or the control group (CONTR) (mean age: 24.85 ± 5.68 years; mean height: 1.72 ± 0.08 m; mean body mass: 69.92 ± 12.59 kg; 5 men and 8 women). A post hoc sensitivity analysis was performed using GPower (v3.1.9.7) for the primary ANCOVA model (two groups, one covariate, $\alpha = 0.05$, power = 0.80). With a total sample size of 26 participants, the study was sufficiently powered to detect large effects (minimum detectable effect size: $f = 0.57$). All participants were physically active and met the World Health Organization (WHO) recommendations for physical activity through regular recreational exercise. However, none participated in competitive sports or structured running training programs, although all were familiar with treadmill running through recreational gym use. Participants were free from musculoskeletal injuries at the time of testing. All participants were informed about the experimental procedures and provided written informed consent before participation. The study protocol was approved by the Ethics Committee of the University of Genoa (Comitato Etico per la Ricerca di Ateneo, CERA; approval no. 2025/23) and was conducted in accordance with the Declaration of Helsinki.

Procedures

Participants were randomly assigned to either a motor imagery group (MI) or a control group (CONTR). They attended the laboratory on two separate occasions, and they were instructed to refrain from strenuous physical exercise for 72 hours prior to the first experimental session and to avoid any strenuous activity throughout the experimental period. During the first visit, they completed an incremental cardiopulmonary exercise test (CPET) to determine the running velocity corresponding to the second ventilatory threshold (vVT2). Approximately 24 hours later, participants returned to perform a constant-speed time-to-exhaustion (TTE) test at vVT2. Prior to the TTE test, participants completed either the MI intervention or the control reading task. Immediately afterward, they performed the running until-exhaustion test. No verbal encouragement was provided during either the CPET or the TTE test, to avoid any potential confounding on the MI intervention. MI ability was assessed at baseline using the Movement Imagery Questionnaire-Revised (MIQ-R) [17], which evaluates both kinesthetic and visual imagery abilities. The questionnaire was administered prior to the experimental procedures to characterize the imagery abilities of the participants and verify baseline comparability between groups.

Cardiopulmonary Exercise Test (CPET)

Participants completed an incremental cardiopulmonary exercise test on a motorized treadmill (Emotion Runner, MTC Climb 2000) to determine the velocity corresponding to the second ventilatory threshold (vVT2). The protocol consisted of 3-minute stages with speed increments of 2 km/h, starting at 6 km/h, and continued until volitional exhaustion [18].

Pulmonary gas exchange was continuously collected breath-by-breath during the CPET using a wearable metabolic cart (Cosmed K5, Rome, Italy) and a mask (Hans Rudolph, INC. Shawnee, KS, USA) with a dead space of 30 mL. The turbine was calibrated with a 3-L syringe (Cosmed, Rome, Italy). Gas analyzers were calibrated with ambient air and gas mixture (20.0% O₂ and 4.0% CO₂). The second ventilatory threshold was determined using the ventilatory equivalents method, based on the increase in VE/VO₂ without a concomitant increase in VE/VCO₂. The velocity corresponding to VT2 was subsequently used to set the exercise intensity during the TTE test.

Motor imagery intervention

Prior to the TTE test, participants assigned to the MI group performed a guided MI protocol while standing on the treadmill with their eyes closed. The imagery task followed principles of the PETTLEP model (in particular the physical, environment, task, and timing components) and emphasized kinesthetic imagery of running technique. The protocol consisted of two phases. In the first phase (warm-up imagery), participants were required to imagine running at a comfortable pace for approximately 30 seconds, focusing on the sensation of foot contact with the treadmill and the forward propulsion generated during each step. In the second phase (intense running imagery), participants imagined running at a higher intensity similar to a sustained hard effort, focusing on longer stride length, reduced vertical oscillation, and maintaining foot contact with the treadmill for as long as possible during each step. Participants were encouraged to focus on internal sensations associated with movement, including breathing, muscular effort, and the rhythm of running. The duration of the intense

running imagery phase was 1 minute. Reporting of the MI intervention followed the Guidelines for Reporting Action Simulation Studies (GRASS), with further details provided in the supplementary material (Online Resource 1, Table S1).

Control task

Participants assigned to the CONTR group stood on the treadmill in the same position as participants in the MI group and were instructed to read a short scientific summary describing the influence of running biomechanics (e.g., cadence and vertical oscillation) on running efficiency. The reading material was placed on the treadmill console and required a similar duration as the MI intervention.

Time-to-exhaustion test

Immediately after the MI intervention or control task, participants performed a constant-speed running test at the velocity corresponding to the vVT2 previously determined during the CPET. The test was performed on the same treadmill used during the incremental test and continued until volitional exhaustion. Time to exhaustion (TTE) was obtained from the Garmin Connect platform, which was also used to record the biomechanical variables. Heart rate was continuously monitored, and rating of perceived exertion (RPE) (by CR10 Borg scale) was immediately assessed after the exercise to exhaustion. Participants terminated the TTE tests and CPET with Borg CR10 ratings of 7.92 ± 1.02 and 7.85 ± 0.73 , respectively, exceeding the level (CR10 = 7) recommended by Borg [19] for valid assessment of working capacity in healthy individuals.

Biomechanical analysis

Running biomechanics were recorded using a wearable inertial sensor (Garmin Running Dynamics Pod, Garmin Ltd., USA) positioned on the posterior center of the shorts, close to the participant's center of mass, according to the manufacturer's recommendations. Participants also wore a Garmin Forerunner 955 watch on the left wrist during both tests to record running kinematic parameters. The following spatiotemporal variables were collected: cadence (CAD, steps·min⁻¹), step length (SL, m), ground contact time (GCT, ms), vertical oscillation (VO, cm), and vertical ratio (VR, %), calculated as the ratio between vertical oscillation and step length, expressed as a percentage [20,21].

Statistical Analyses

Statistical analyses were performed using IBM SPSS Statistics (v.21) and GraphPad Prism (v.8.4). MIQ-R kinesthetic, visual, and total scores were analyzed using mixed-design ANOVAs, with Group (MI vs. CONTR) as the between-subjects factor and Time (PRE vs. POST) as the within-subjects factor.

Initially, group differences across the set of spatiotemporal variables (CAD, SL, GCT, and VO) were examined using a multivariate generalized linear model (GLM) with running speed as a covariate. The corresponding univariate tests were subsequently inspected to identify which variables contributed to the observed effects.

To further investigate biomechanical efficiency, we evaluated the determinants of VR with a hierarchical linear regression, with speed entered in the first step and group allocation in the second. Additionally, an Analysis of Covariance (ANCOVA) was performed using individual VR values as the dependent variable, running speed during the TTE as the covariate, and group allocation as the fixed factor. The analysis was used to assess whether the relationship between VR and running speed differed between groups (i.e., differences in regression slopes) and, where appropriate, to compare adjusted group means (differences in intercepts).

Time to exhaustion was compared using univariate ANOVA. Statistical significance was set at $p < 0.05$. In the text data are reported as mean $\pm$ standard deviation.

Results

Twenty-six participants completed all experimental procedures. MIQ-R scores did not differ between groups and did not change over time, with no significant Group $\times$ Time interactions for kinesthetic, visual, or total scores (all $p > 0.05$). Baseline MIQ-R scores were not significantly different between groups. The MI group presented mean kinesthetic, visual, and total imagery scores of 11.00 ± 3.74 , 7.85 ± 2.88 , and 18.85 ± 5.97 , respectively, whereas the CONTR group presented scores of 11.62 ± 3.99 , 9.62 ± 4.01 , and 21.23 ± 6.23 , respectively.

No significant baseline differences between groups were observed for physiological or biomechanical variables obtained during the CPET (Online Resource 1, Table S2). Descriptive statistics for the biomechanical variables are presented in Table 1.

The multivariate GLM revealed no significant overall effect of Group on the combined set of biomechanical variables during the TTE test ($F(5,19) = 1.212$, $p = 0.342$, partial $\eta^2 = 0.242$). However, the results of the univariate analysis revealed a significant Group effect for VR ($F(1,23) = 5.239$, $p = 0.032$, partial $\eta^2 = 0.186$) (Fig. 1A). Participants in the MI group exhibited significantly lower VR values ($7.32 \pm 1.18\%$) compared to the CONTR group ($8.68 \pm 1.77\%$).

Table 1
Descriptive statistics of performance and spatiotemporal variables during the time-to-exhaustion test (TTE)

Variable	Group	
	MI	CONTR
Velocity (km/h)	11.38 ± 2.10	10.86 ± 1.80
Time to Exhaustion (min)	14.50 ± 6.19	13.92 ± 4.38
Cadence (steps/min)	165.62 ± 10.40	163.00 ± 9.26
Step Length (m)	1.33 ± 0.07	1.31 ± 0.07
Vertical Oscillation (cm)	9.92 ± 1.56	11.14 ± 2.34
Vertical Ratio (%)	7.32 ± 1.18	8.68 ± 1.77
Ground Contact Time (ms)	240.08 ± 17.96	243.23 ± 29.10
Note: Values are presented as mean ± SD		

Hierarchical regression analysis further confirmed that group allocation significantly predicted VR during the TTE ($R^2=0.184$, $p = 0.029$). When running speed was added to the model, it did not significantly improve the fit ($\Delta R^2=0.002$, $p = 0.820$), indicating that the observed technical adjustment was independent of running intensity. This was corroborated by the results of the ANCOVA showing no significant difference between slopes values of the regression lines of the two groups ($F(1,22) = 0.006$, $p = 0.9408$), but a significant difference in intercepts ($F(1,23) = 5.239$, $p = 0.0316$), indicating a consistent lower VR value in the MI group compared to CONTR group across the range of running speeds (Fig. 1B). Time to exhaustion did not differ significantly between groups (MI: 14.50 ± 6.20 min; CONTR: 13.92 ± 4.38 min, $p > 0.05$).

Discussion

The present study investigated whether a brief motor imagery intervention performed immediately before running could acutely influence running biomechanics during a treadmill TTE test. Our findings suggest that MI intervention administered before running may induce acute changes in running biomechanics, as indicated by lower VR values during the TTE test. Notably, this reduction was systematic and independent of running velocity, as evidenced by the identical slopes and significantly different elevations of the regression lines.

These findings may reflect a neural priming effect. Priming has been described as a form of nonconscious memory that enhances the processing of perceptual representations without requiring explicit recall [22]. In the motor domain, this concept is consistent with motor priming frameworks suggesting that prior activation of motor networks may facilitate subsequent movement execution by altering the neural state of the system [7, 23]. Recent evidence involving neurological patients indicates

that MI acted as a priming stimulus modulating corticospinal excitability and preparing the nervous system for action [7], consistent with the principle of functional equivalence between imagined and executed actions [1]. Within this framework, the reduction in VR observed in the present study during treadmill running may reflect enhanced accessibility to the sensorimotor representation of the movement, which was voluntarily simulated during the preceding MI, thereby leading to immediate adjustments in the subsequent movement execution.

An important aspect of the present findings is that the observed differences emerged specifically in VR, rather than in isolated biomechanical variables such as VO or SL alone. VR represents the relationship between vertical displacement and forward progression and may therefore provide a more integrative representation of running pattern than individual spatiotemporal parameters considered separately [12, 13]. In particular, given that VR reflects the relationship between vertical displacement and forward progression during running, lower values are generally associated with a more economical movement pattern [12]. Therefore, although no significant global effect was observed across the full set of biomechanical variables, the present findings suggest that MI may influence specific coordinative aspects of running mechanics with potential implications for movement efficiency. The comparison of regression lines further strengthened this interpretation by demonstrating identical slopes but consistently lower intercepts values in the MI group across the speed spectrum. This suggests that the imagery intervention did not simply alter individual biomechanical parameters at a specific intensity but may have influenced the coordination between vertical and horizontal components of running mechanics in a systematic manner. In this context, VR may be particularly sensitive to subtle adjustments in movement organization induced by MI.

The specificity of the imagery instructions may also help explain the observed findings. The MI script explicitly emphasized technical elements related to running mechanics, including reducing VO, increasing SL, maintaining prolonged GCT, and minimizing unnecessary vertical displacement. Interestingly, the variable that differed between groups was precisely the parameter integrating these components, namely VR. This specificity strengthens the plausibility that the observed effects were directly related to the sensorimotor content of the imagery intervention rather than reflecting nonspecific cognitive or attentional effects. Such findings are consistent with the PETTLEP framework, which proposes that greater correspondence between imagined and executed actions enhances the effectiveness of MI interventions [24].

An important aspect of the present design is that participants in the control condition were also exposed to biomechanical information related to running technique, including concepts associated with CAD and VO. Therefore, the observed differences cannot be attributed solely to the acquisition of declarative knowledge regarding how to run more efficiently. Instead, the findings suggest that the internally generated representations elicited by MI may have played a central role in the observed technical adjustments. Although action-related language may partially engage movement-related processes, explicit MI appears to recruit cortical networks more strongly than silent reading alone [25]. Furthermore, MI involves sensorimotor simulation processes in a manner more closely related to actual movement

execution [1]. This distinction may help explain why only the MI group exhibited lower VR values despite both groups receiving conceptually similar biomechanical information.

Conclusion

In conclusion, a brief MI intervention performed immediately before running was associated with lower VR values during a TTE test, suggesting acute changes in movement organization and running biomechanics. Although no significant effects were observed in the other spatiotemporal parameters or in endurance performance, the consistent reduction in VR across different running speeds suggests that MI promoted a more efficient control of vertical displacement relative to forward progression, potentially reflecting subtle neuromuscular adaptations and improved movement coordination. These findings highlight the potential of MI as a strategy for pre-exercise preparation capable of acutely modulating running technique during demanding exercise conditions. It should be noted that the present study was conducted in physically active university students rather than trained endurance runners. Future studies should confirm these findings in more specialized athletic populations. Furthermore, the present study investigated only the acute effects of a single MI session, but it opens the door to future studies examining repeated exposure to imagery interventions aimed at inducing longer-lasting biomechanical adaptations.

Statements and Declarations

Funding

No funding was received for this study.

Competing interests

The authors declare that they have no relevant financial or non-financial interests to disclose.

Ethics approval

The study protocol was approved by the Ethics Committee of the University of Genoa (Comitato Etico per la Ricerca di Ateneo, CERA; approval no. 2025/23) and was conducted in accordance with the Declaration of Helsinki.

Informed consent

Written informed consent was obtained from all participants prior to participation.

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Figures

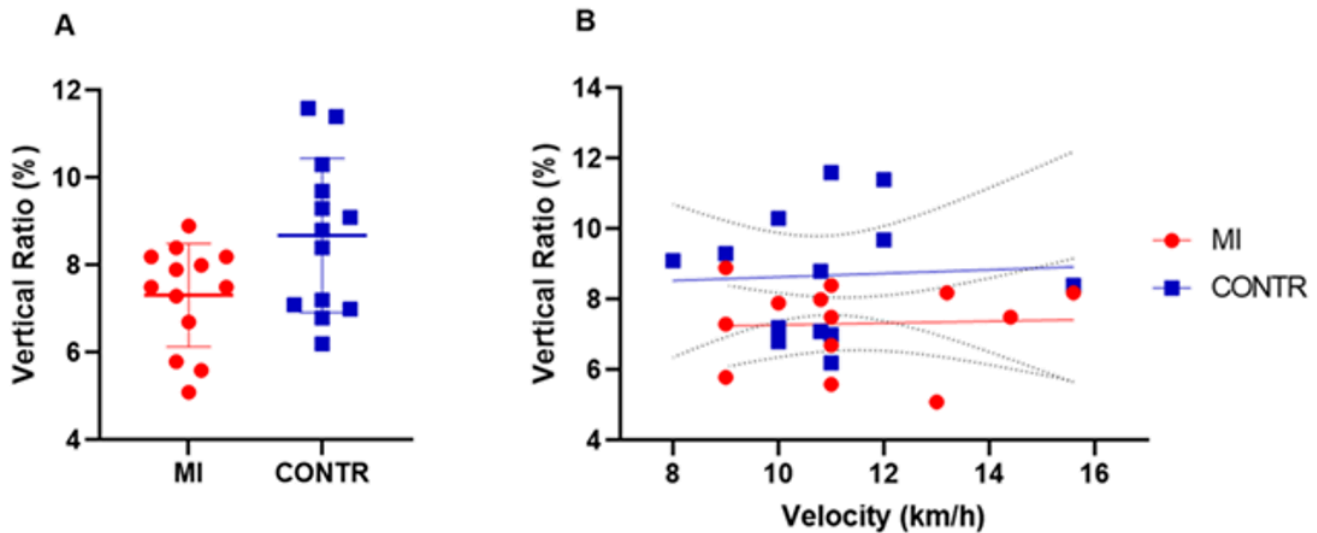


Figure 1

Effects of motor imagery priming on vertical ratio during a time-to-exhaustion running test. Panel A shows individual vertical ratio (VR) values for the motor imagery (MI) and control (CONTR) groups. Horizontal bars represent mean values. Error bars indicate standard deviations. Panel B shows the relationship between running speed and VR during the time-to-exhaustion test. Each data point represents an individual participant. Solid lines depict the linear regression for each group (MI, circles; CONTR, squares), while dotted lines represent the corresponding 95% confidence intervals.

Supplementary Files

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