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ORIGINAL INVESTIGATION

# The Relationship Between Training Load and Acute Performance Decrements Following Different Types of Training Sessions in Well-Trained Runners

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*Purpose:* This study investigated the relationship between training-load (TL) metrics and the acute performance decrement (APD) measured immediately after 4 training sessions performed by well-trained runners. *Methods:* On a treadmill, 12 well-trained runners (10 men and 2 women) performed an incremental test, a baseline time-to-exhaustion (TTE) test at maximal aerobic speed, and 4 randomized training sessions followed by a TTE test to measure APD. The training sessions were matched for external load (60 arbitrary units) but differed in the time spent in the 3 intensity domains. The TL metrics used were based on training impulse, heart-rate variability, ratings of perceived exertion, and the NASA Task Load Index (NASA-TLX) rating scale. *Results:* TTE was significantly shorter after all the training sessions compared with baseline ($P < .001$). While APD was higher (+16%, $P = .035$) for long-duration high-intensity training ($HIT_{long}$) compared with low-intensity training (LIT), most TL metrics showed higher values ($P < .001$) in LIT than in $HIT_{long}$. Conversely, NASA-TLX values were higher ($P < .001$) in $HIT_{long}$ than in LIT and were significantly associated with APD values ($P < .001$, $\beta = 0.54$). Physiological parameters showed that less time was spent above 90% of $\dot{V}O_2max$ during LIT compared with the other training sessions ($P < .01$), while average respiratory frequency and mean respiratory exchange ratio were higher during $HIT_{long}$ compared to LIT ($P < .01$). *Conclusion:* APD was observed after the 4 running training sessions, and it was not associated with most of the TL metrics. Only NASA-TLX was associated with APD, suggesting that this TL metric could be leveraged for training monitoring.

*Keywords:* running, fatigue, TRIMP, heart-rate variability

The quantification of training load (TL) is expected to reflect the stress that a specific training session induces on the human body,[1] combining intensity and duration in a way that is proposed to represent a "dose" of training.[2] Recent studies have shown that internal TL, defined as an athlete's psychophysiological response to external TL,[3] provides better results in determining the effects of training on endurance performance and physiological parameters (eg, maximal oxygen uptake [$\dot{V}O_2max$] and ventilatory thresholds) compared to external TL.[4] However, the validity of currently used metrics of internal TL has recently been challenged.[2]

According to classic training principles, the TL imposed on the athlete results in a corresponding acute performance decrement (APD),[5] which can be quantified for instance through the decrease in time to exhaustion (TTE) or in time-trial performance (TT).[2] Hence, irrespective of the different factors inducing fatigue (eg, central or peripheral fatigue),[6] the APD concept is based on the premise that effective metrics of internal TL should be closely associated with the extent of APD.[2,5,7] However, Kesisoglou et al[5,7] showed that most internal TL metrics calculated for maximal and submaximal training sessions performed by cyclists and runners did not reflect the APD measured as a 5-minute TT or 1500-m TT. Likewise, Vermeire et al[8] showed that commonly used TL metrics based on heart rate (HR) were dissociated from APD. A common problem observed in these studies is the overestimation of the TL of prolonged low-intensity continuous sessions and the consequent underestimation of the TL of short high-intensity sessions. This is evident in all the metrics computed by multiplying intensity and duration (eg, training impulse based on HR), thus obtaining a training volume rather than a TL/dose.[9] The results of studies assessing the validity of TL metrics using the APD concept have been reinforced by those investigating the durability (ie, the athlete's ability to maintain performance after accumulated loads)[10] supporting the notion that the decrease in power output observed in short-term tests (ie, 1- to 3-min efforts) is associated with the amount of prior accumulated high-intensity exercise rather than low-intensity training.[11,12]

Despite the growing interest in the concepts of APD and durability, most studies have focused on cycling, while running has been studied to a lesser extent. In the few available studies on running,[7] the training sessions were not designed to reproduce sessions commonly used in training practice, thus limiting ecological validity. Furthermore, no comprehensive physiological assessment was made by Kesisoglou et al[7] while a detailed description of the time

spent in different intensity domains may improve the understanding of the physiological factors associated with APD. Hence, further studies are required to shed some light on the APD that occurs after ecological running training sessions and on the related physiological responses.

Given the limitations described for currently used methods of internal TL,[2,5,7] it is important to assess if other metrics may better reflect the stress imposed on the athlete. Recent studies have shown that the heart rate variability (HRV) index ($TL_{HRV}$) using the root mean square value of the successive differences between the beat intervals (RMSSD) could be a promising noninvasive method for monitoring TL in endurance sports.[13] This indicator appears to be sensitive to quantify the early recovery of the autonomic nervous system after an acute stress response associated with typical training sessions of well-trained runners.[14] Besides, previous studies have observed that the National Aeronautics and Space Administration Task Load Index (NASA-TLX) may resemble the APD response.[5,7,8] Considering the multifactorial nature of postexercise fatigue,[6] an advantage of the use of the NASA-TLX scale is the opportunity to measure different dimensions of perceived workload (ie, mental demand, physical demand, temporal demand, frustration, effort and performance) and to compute an overall score by averaging the values of the 6 dimensions.[15] However, to our knowledge, there are no studies in well-trained runners comparing different internal TL metrics (eg, $TL_{HRV}$, training impulse with HR [HR TRIMPs], $TL_{RPE}$ and NASA-TLX) with APD after different training sessions commonly performed by endurance athletes, including an investigation of the possible underlying physiological factors for APD.

The present study was designed to assess the acute effects of 4 training sessions commonly used by well-trained runners on subsequent APD, and to investigate the relationship between different internal TL metrics and APD. To this end, we matched the training sessions for the same external TL as previously performed by Vermeire et al[8] and modulated intensity and duration providing different combinations of time spent in the 3-intensity domains. Furthermore, several cardiorespiratory variables were measured to identify physiological parameters that are associated with APD.

# Material and Methods

## Participants

Twelve well-trained runners (10 males and 2 females; mean age 26.8 [6.9] y; mean body mass 63.3 [7.7] kg, mean height 1.74 [0.07] m) were recruited for this study at the School of Sport Science of the University of Udine. Participants had at least 3 years of experience competing in events ranging from 800 m to half marathon. They trained 5 to 7 hours per week, and their personal best time for 10,000 m was on average 35.1 (3.4) minutes. Participants gave written informed consent to participate in this study. Research procedures were conducted following the Declaration of Helsinki. The study was approved by the ethics committee and the local Institutional Review Board of the University of Udine (IRB 57/2022).

## Experimental Design

The study adopted a cross-over design. Each participant visited the laboratory 6 times, separated by at least 48 hours, in a 3-week period (Figure 1). All tests were performed under supervision, on a treadmill (Skillrun, Technogym), in a room with constant temperature and humidity (18°–19°, 50%–60% relative humidity). The first visit consisted of an incremental test to determine maximal oxygen consumption ($\dot{V}O_2max$), the respiratory compensation point (RCP),

and the gas-exchange threshold (GET). Each participant then rested for 5 minutes in a quiet room before completing a familiarization trial of the TTE protocol, including equipment and questionnaire completion. The second visit was a baseline TTE test conducted at maximal aerobic speed (MAS). During visits 3 to 6, participants completed the 4 randomized training sessions followed by a TTE test at MAS. All training sessions were completed at the same time of the day with participants fully rested and hydrated, having consumed a light meal 3 hours before and having refrained from alcohol and caffeine consumption and vigorous exercise for 24 hours previously. The participants were not familiarized with the training sessions, as they were used to run regularly on the treadmill during the winter season, with training sessions similar to those proposed in our study.

## Measurements

### Incremental Test

To determine $\dot{V}O_2max$, maximal heart rate ($HR_{max}$), and ventilatory thresholds, participants carried out an incremental test at the laboratory of Sport Science in Udine. The incremental test started at 10 km·h$^{-1}$ at 1% fixed slope. The duration of each step was 1 minute, and the speed was increased by 0.5 km·h$^{-1}$ every minute until volitional exhaustion. Oxygen consumption ($\dot{V}O_2$), carbon dioxide production ($\dot{V}CO_2$), ventilatory parameters, and HR were measured during this test using a wearable metabolic unit (K5, Cosmed) and a chest strap (Polar H10, Polar), respectively. Before every test, we calibrated the gas analyzers and flow meter as suggested by the manufacturer. The GET was determined by the first inflection point of minute ventilation ($\dot{V}_E$), the first "breakpoint" in $\dot{V}_E·\dot{V}O_2^{-1}$ and the V-slope method.[16,17] RCP was determined by a second inflection point in $\dot{V}_E$, a second "breakpoint" in $\dot{V}_E·\dot{V}O_2^{-1}$, an "inflection point" in $\dot{V}_E·\dot{V}CO_2^{-1}$ after isocapnic buffering and the V-slope method.[16,17] GET and RCP were assessed by 2 independent and trained researchers. If they disagreed, a third independent researcher was consulted.

$\dot{V}O_2max$ was calculated as the higher average 30-second $\dot{V}O_2$ according to previously established criteria[18]: (1) plateau in $\dot{V}O_2$ (ie, increase < 150 mL·min$^{-1}$), (2) respiratory exchange ratio (RER) > 1.1, and (3) ≥90% of theoretical $HR_{max}$. One minute after the end of the test, we collected mixed venous blood at the earlobe and measured the blood lactate concentration (BLC; Lactate Scout 4, EKF Diagnostic). The MAS was recorded as the velocity at the last completed stage.[19]

### TTE Tests

Participants performed 5 TTE tests with an intensity corresponding to the MAS derived from the incremental test. The first baseline TTE was performed after a standardized warm-up. This warm-up consisted of 15 minutes of low-intensity running (ie, 90% GET), followed by three 15-second sprints at 110% of MAS, interspersed with 90 seconds of rest and dynamic stretching, and concluded with 5 minutes of rest in a standing position.[20] The other 4 TTE tests were performed after completing the 4 training sessions, each performed in separate days. All TTE tests were run on a treadmill (Skillrun, Technogym). $\dot{V}O_2$, $\dot{V}CO_2$, and ventilatory variables were measured breath by breath using a portable metabolic unit and then averaged at 5-second intervals, while HR was measured with a chest strap during each TTE. At the end of each TTE test, the BLC was measured by capillary blood from the earlobe (BLC; Lactate Scout 4, EKF Diagnostic). Five minutes after the end of each TTE test, rating of perceived exertion (RPE) was assessed using the CR-10 scale.[21] Participants were encouraged to complete the TTE test covering the
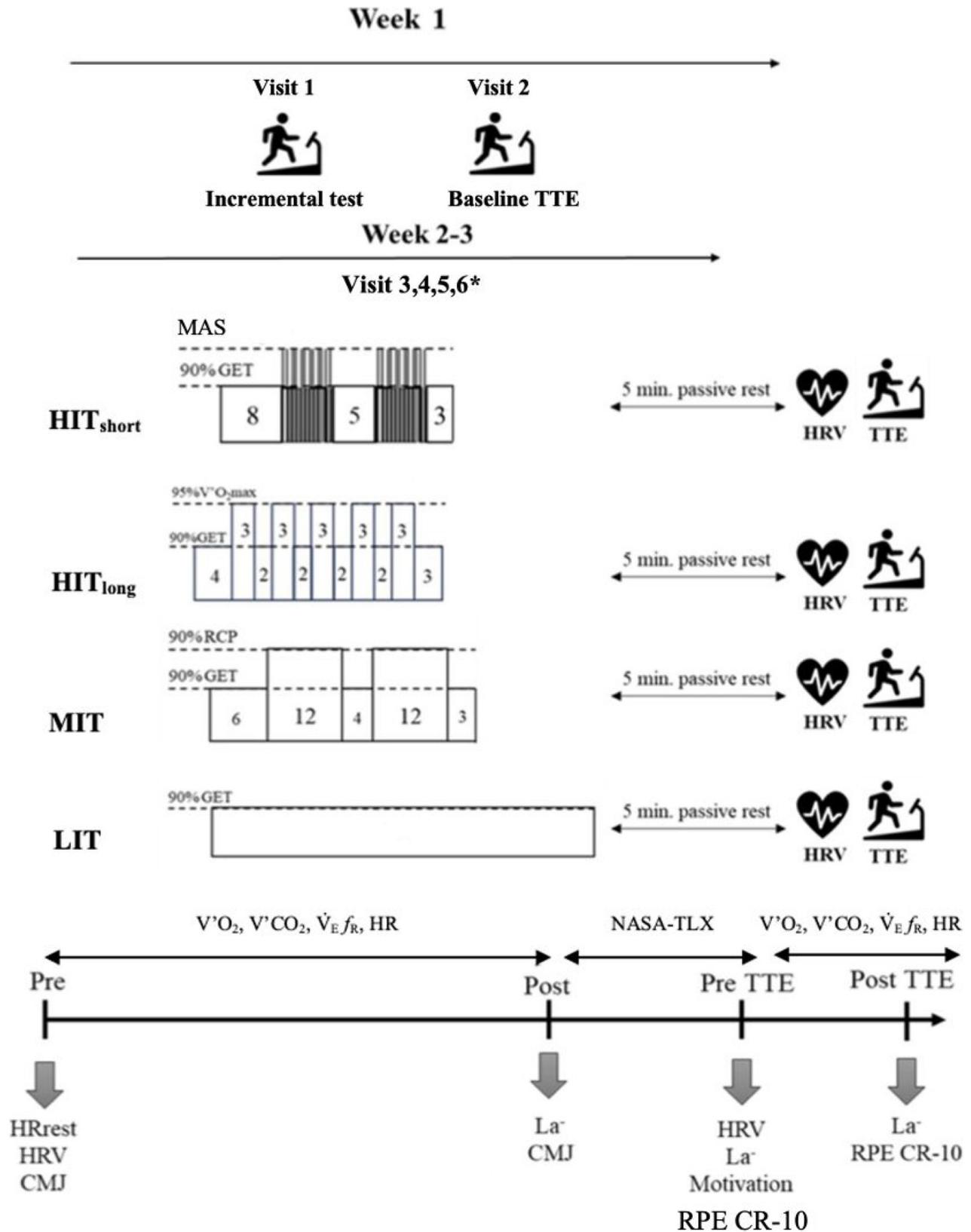
**Figure 1** — Schematic representation of the study design. CMJ indicates countermovement jump; $f_R$, respiratory frequency; 90% GET, speed corresponding to 90% of gas-exchange threshold; $HIT_{long}$, long-duration high-intensity training; $HIT_{short}$, short-duration high-intensity training; HR, heart rate; $HR_{rest}$, HR in resting condition; HRV, HR variability; $La^-$, lactate; LIT, low-intensity training; MAS, maximal aerobic speed; MIT, medium-intensity training; NASA-TLX, NASA Task Load Index rating scale; 90% RCP, speed corresponding to 90% of respiratory compensation point; RPE CR-10, rating of perceived exertion using the CR-10 Borg scale; TTE, time to exhaustion; $\dot{V}CO_2$, carbon dioxide production; $\dot{V}_E$, minute ventilation; $\dot{V}O_2$, oxygen consumption; 100% $\dot{V}O_2max$, speed corresponding to maximal $\dot{V}O_2$; 95% $\dot{V}O_2max$, speed corresponding to 95% of maximal $\dot{V}O_2$. *The training sessions were randomized for visits 3, 4, 5, and 6.

longer distance possible. During all the TTE tests, the participants did not receive any feedback.

## Training Sessions

All athletes took part in 4 different training sessions performed in random order (Figure 1). All training sessions were equalized for the same external TL based on Lucia TRIMP (luTRIMP$_{speed}$) of 60 arbitrary units calculated with the speed in the 3 physiological intensity domains: zone 1 for intensities below GET; zone 2 for intensities between GET and RCP; and zone 3 for intensities above RCP.[22] We chose luTRIMP$_{speed}$ to match the training sessions because it is a practical method to prescribe exercise and define a priori the time spent in the 3 different intensity domains. Hence, we managed to propose training sessions commonly used by well-trained runners while setting the time spent in the different intensity domains and equalizing the sessions for the same external load. Each session was preceded by a warm-up and cooldown at the same intensity (eg, 90% of GET).

The 4 training sessions were

- Low-intensity training (LIT): 60 minutes of training at a speed equivalent to 90% of the GET.
- Medium-intensity training (MIT): 2 blocks of 12 minutes at a speed equivalent to 90% of RCP, separated by 4 minutes of recovery at 90% of GET. The warm-up and cooldown lasted 6 and 3 minutes, respectively. The total duration was 37 minutes.
- Long-duration high-intensity training (HIT$_{long}$): 5 steps of 3 minutes each at 95% of $\dot{V}O_2$max, separated by 2-minute recovery at 90% of GET. The training was preceded by a 4-minute warm-up phase, which ended with a 3-minute cooldown phase, both performed at an intensity of 90% of GET. The entire training session lasted 30 minutes.
- Short-duration high-intensity training (HIT$_{short}$): 2 blocks of 11 minutes each, alternating 30 seconds of high intensity at MAS and 30 seconds of recovery at 90% of the GET. An active recovery of 5 minutes at 90% of GET was adopted between the 2 blocks. The training was preceded by an 8-minute warm-up, which ended with a 3-minute cooldown, both performed at an intensity of 90% of GET. The entire session lasted 38 minutes.

The cooldown was standardized in all 3 training intervals so that there was the same period between the end of the cooldown and the 5 minutes of passive recovery before the TTE test. Prior to each training session, participants rested for 1 minute in a seated position in a quiet room before starting the recording to reduce the influence of movement on HRV.[23] We then measured resting HR and HRV for 1 minute using the root mean square of successive differences between normal heart beats (RMSSD) with the HRV4training app (https:///www.hrv4training.com) connected to the chest strap (Polar H10, Polar Electro Oy), following the instructions of Plews et al.[23] In addition, jump height was measured during countermovement Jump (OptoGait, Microgate Srl).[24] At the end of each training session, we collected mixed venous blood from the earlobe and measured BLC, and then the countermovement jump was performed. Each athlete then underwent 5 minutes of passive recovery in a seated position. During these 5 minutes, the NASA-TLX questionnaire was administered to obtain the total score in 6 different subcategories (see "Data Analysis" for more details), as suggested by Kesisoglou et al.[5] At the end of the 5 minutes, each participant was tested to measure RMSSD values as described above and the RPE value of the entire session using the Borg CR-10 scale modified by Foster et al.[21] We

calculated the $\Delta$ jump height before and after each training session to indirectly assess neuromuscular fatigue.[25] Before each TTE test, each participant was asked to rate their motivation to perform the test on a scale from 0 to 9, where 0 represents "not at all" and 9 represents "very motivated."[26] The APD was defined as the percentage change in the TTE compared with their best baseline TTE.[5] During the 4 training sessions, $\dot{V}O_2$, $\dot{V}CO_2$, ventilatory parameters, and HR were measured using a portable metabolic unit and a chest strap, as described above. Energy expenditure (EE) of each exercise bout was calculated from expired gases.[27]

## Data Analysis

For TL quantification we selected different internal TL methods. The Bannister TRIMP (bTRIMP) was calculated using exercise duration, average HR, and an intensity factor (IF) with the following equation[28]:

$$bTRIMP = \text{Duration training (minutes)} \times \Delta \text{ HR} \times y,$$

where $\Delta$ HR = (HR$_{mean}$ − resting HR)/(HR$_{max}$ − resting HR), $y$ is a sex-dependent exponential intensity weighting factor based on lactate responses of $0.64e^{1.92x}$ for males and $0.84e^{1.67x}$ for females.[29]

The Edwards TRIMP (eTRIMP) was calculated by multiplying the time spent in 5 predefined zones (zone 1, 50%–59% HR$_{max}$, IF = 1; zone 2, 60%–69% HR$_{max}$, IF = 2; zone 3, 70%–79% HR$_{max}$, IF = 3; zone 4, 80%–89% HR$_{max}$, IF = 4; zone 5, 90%–100% HR$_{max}$, IF = 5) by the respective IF and then summing to calculate the total score.[30] Modified eTRIMP (eTRIMPmod) was calculated by multiplying the time spent in 5 different zones,[30] calculated using the HR at the ventilatory thresholds and $\dot{V}O_2$max according to Watts et al[31] by the respective IF and then summed to obtain the total score. luTRIMP based on HR was calculated using 3 physiological HR zones: zone 1 (IF = 1) below GET, zone 2 (IF = 2) between GET and RCP, and zone 3 (IF = 3) above RCP.[22] The time in each zone is multiplied by the respective IF and then summed to obtain an overall value.[22]

TL$_{HRV}$ was calculated based on the method defined by Saboul et al,[13] and modified for our study.

The specific formula was:

$$TL_{HRV} = \ln\left(T \times \text{Pre-5} - \text{Post-5}\right),$$

where $T$ = duration of the exercise, Pre-5 = RMSSD (in milliseconds) 5 minutes before training, and Post-5 = RMSSD (in milliseconds) 5 minutes after training.

RPE was assessed 5 minutes after the exercise session using the modified CR-10 scale and multiplied by the exercise duration in minutes to quantify the TL$_{RPE}$.[21]

The NASA-TLX rating scale was completed immediately after each training session, as suggested by Kesisoglou et al.[5] It is composed of 6 subscales, assessing mental demand, physical demand, temporal demand, frustration, effort, and performance. The mental demand (How mentally demanding was the task?) assesses the mental and perceptual demand required to complete a task. The physical demand (How physically demanding was the task?) assesses the physical activity required to complete the task. The temporal demand (How hectic or rushed was the pace of the task?) assesses the time pressure the performer was under and whether the pace of the task was perceived as slow or fast. The performance subscale (How successful were you in completing the task?) requires the test subjects to assess how successful they were in completing the task set by the experimenter. The effort subscale (How hard did you try to achieve your level of performance?) assesses the mental and physical resources

required to complete a task. Finally, the frustration subscale (How insecure, discouraged, irritated, stressed and annoyed were you?) assesses the negative feelings/emotions that the performer experienced during the task. After completing a task, the performer is asked to give a score from low to high on a 20-point scale (except for the performance subscale that starts with good to poor) for each of the different subscales. Participants' scores for each of the 6 subcategories were multiplied by 5 to obtain a score in cents, then the average of the scores for each item was taken to obtain a total score.[15]

## Statistical Analysis

Data were analyzed using GraphPad Prism (version 10.2.0) and STATA (version 18). Statistical significance was set at $P < .05$. The Shapiro–Wilk test was used to assess the normality of the data. The results obtained are expressed as the means and SD for normally distributed data, while in the case of a nonnormal distribution, the data were expressed as median and interquartile range. Analysis of variance for repeated measures was used to assess differences within TL methods for the different training sessions and to check for differences between the different TTEs and physiological parameters. A Greenhouse–Geisser correction was used for violations of the sphericity assumption, which was verified by Mauchly test. The Friedman test was used to assess differences in nonnormally distributed physiological parameters. Linear mixed models with a univariable and multivariable analysis were used to analyze the association of APD with TL metrics and physiological parameters measured during the 4 training sessions and estimating the regression coefficient $\beta$. These analyses allow for the evaluation of the relationship between APD, TL metrics and the physiological parameters considering the different exercise conditions. Finally, effect size (ES) was calculated using Cohen $d$ considering the differences in TTE parameters, TL metrics, and physiological characteristics between the 4 training sessions. ES < 0.20 was considered negligible, <0.50 small, between 0.50 and 0.79 medium, and equal or above 0.80 large.[32]

## Results

### Incremental Test

The $\dot{V}O_2$max and MAS from the incremental test were 4.17 (0.72) L·min$^{-1}$ (65.6 [6.1] mL·kg$^{-1}$·min$^{-1}$) and 18.3 (1.3) km·h$^{-1}$, whereas HR$_{max}$ and [La]$_{peak}$ were 187.3 (12.1) beats·min$^{-1}$ and 8.61 (1.20) mmol·L$^{-1}$, respectively (Table 1).

### Time to Exhaustion

The TTE was different under the different conditions ($P < .001$). The TTE after exercise was shorter after LIT (−72.8 [57.9] s, $P = .003$, ES 1.05 *large*), MIT (−107.8 [84.5] s, $P < .001$, ES 1.40 large), HIT$_{long}$ (−119.1 [61.1] s, $P < .001$, ES 1.78 large), and HIT$_{short}$ (−105.1 [50.0] s, $P < .001$, ES 1.78 *large*) compared with the baseline TTE. [La]$_{post}$ of the TTE test was lower after MIT compared to HIT$_{short}$ (−1.48 [1.37] mmol·L$^{-1}$, $P = .048$, ES 0.60 *large*). No further significant differences were observed between the parameters of the TTE test (Table 2). An APD was observed after all experimental training sessions ($P = .041$). Bonferroni post hoc testing found a significant difference ($P = .031$, ES 0.83 *large*) in APD between HIT$_{long}$ (36.0% [18.7%]) and LIT (21.5% [15.7%]).

**Table 1    Anthropometrical and Physiological Parameters of the Participants, Mean (SD)**

|  | All (N = 12) |
| --- | --- |
| Age, y | 26.8 (6.9) |
| Body mass, kg | 63.3 (7.7) |
| Height, m | 1.74 (0.07) |
| BMI, kg·m$^{-2}$ | 20.8 (1.4) |
| Maximal $\dot{V}O_2$ |  |
| $\dot{V}O_2$, mL·min$^{-1}$ | 4172.6 (718.1) |
| $\dot{V}O_2$, mL·kg$^{-1}$·min$^{-1}$ | 65.6 (6.1) |
| HR$_{max}$, beats·min$^{-1}$ | 187.3 (12.1) |
| RER max | 1.15 (0.05) |
| [La]$_{end}$, mmol·L$^{-1}$ | 8.61 (1.20) |
| Speed, km·h$^{-1}$ | 18.3 (1.3) |
| Respiratory compensation point |  |
| $\dot{V}O_2$, mL·min$^{-1}$ | 3711.2 (639.7) |
| $\dot{V}O_2$, mL·kg$^{-1}$·min$^{-1}$ | 58.4 (5.2) |
| $\dot{V}O_2$, %max | 89.2 (4.7) |
| HR, beats·min$^{-1}$ | 181.7 (12.2) |
| HR, %max | 97.0 (1.5) |
| RER | 1.06 (0.05) |
| Speed, km·h$^{-1}$ | 16.6 (1.1) |
| Gas-exchange threshold |  |
| $\dot{V}O_2$, mL·min$^{-1}$ | 3207.8 (477.1) |
| $\dot{V}O_2$, mL·kg$^{-1}$·min$^{-1}$ | 50.7 (4.4) |
| $\dot{V}O_2$, %max | 77.6 (7.2) |
| HR, beats·min$^{-1}$ | 171.1 (13.5) |
| HR, %max | 87.8 (6.9) |
| RER | 0.98 (0.04) |
| Speed, km·h$^{-1}$ | 14.5 (1.02) |

Abbreviations: BMI, body mass index; HR, heart rate; HR$_{max}$, maximal HR; RER, respiratory exchange ratio; $\dot{V}O_2$, oxygen consumption.

### Training Sessions

For all TL metrics, we found that there were significant differences among the 4 training sessions ($P < .001$; Figure 2). For bTRIMP and eTRIMP, LIT showed higher values of TL compared to MIT, HIT$_{long}$, and HIT$_{short}$ ($P < .001$), while HIT$_{long}$ showed lower values ($P < .001$) compared with MIT and HIT$_{short}$ (Figure 2B and 2C). For eTRIMPmod, LIT showed higher values of TL compared to HIT$_{long}$ ($P = .034$, ES 0.74 *medium*) (Figure 2D). HIT$_{long}$ showed the lowest value for luTRIMP compared to LIT ($P = .023$, ES 1.20 *large*), MIT ($P = .002$, ES 1.11 *large*), and HIT$_{short}$ ($P = .025$, ES 0.73 *medium*) (Figure 2E). TL$_{RPE}$ was lower for HIT$_{long}$ than for LIT ($P = .030$, ES 0.93 *large*) and HIT$_{short}$ ($P = .013$, ES 1.43 *large*) (Figure 2F). TL$_{HRV}$ showed similar TL values between training sessions (Figure 2G). NASA-TLX was lower for LIT than for MIT ($P = .004$, ES 1.31 *large*), HIT$_{long}$ ($P < .001$, ES 1.57 *large*), and HIT$_{short}$ ($P = .001$, ES 1.65 *large*) (Figure 2H).

### Physiological Characteristics

From a physiological point of view, we observed that $\dot{V}O_2$ total and EE were higher ($P < .001$) during LIT than during the other training

**Table 2    Physiological, Perceptual, and Mechanical Parameters of the Baseline TTE Test and the TTE Test Following Each Training Session, Mean (SD)**

| | Baseline | LIT | MIT | HIT$_{long}$ | HIT$_{short}$ | P |
|---|---|---|---|---|---|---|
| Time, s | 351.8 (54.8) | 279.1 (76.9)* | 244.0 (92.1)* | 225.4 (84.4)* | 246.8 (57.8)* | <.001 |
| Distance, m | 1765.2 (325.6) | 1406.1 (435.8)* | 1229.6 (488.3)* | 1137.7 (450.2)* | 1239.2 (331.3)* | <.001 |
| $\dot{V}O_2$peak, mL·min$^{-1}$ | 4316.3 (678.1) | 4032.8 (722.0) | 4051.4 (792.5) | 4114.6 (732.1) | 4143.9 (739.8) | .096 |
| HR$_{peak}$, beats·min$^{-1}$ | 186.7 (11.7) | 185.3 (10.9) | 184.7 (12.2) | 184.7 (11.9) | 186.1 (12.6) | .110 |
| [La$^-$]$_{post}$, mmol·L$^{-1}$ | 9.98 (2.20) | 8.28 (1.88) | 7.82 (2.35) | 9.79 (2.43) | 9.30 (2.86)£ | .038 |
| RPE, n | 9.45 (0.69) | 9.00 (1.48) | 9.09 (1.04) | 9.00 (1.41) | 8.91 (1.14) | .246 |
| Motivation, n | 7.22 (1.48) | 7.00 (1.54) | 6.36 (1.63) | 6.10 (1.66) | 6.70 (2.16) | .252 |

Abbreviations: HIT$_{long}$, long-duration high-intensity training; HIT$_{short}$, short-duration high-intensity training; HR$_{peak}$, peak heart rate; [La$^-$]$_{post}$, lactate levels post exercise; LIT, low-intensity training; MIT, medium-intensity training; RPE, rating of perceived exertion; TTE, time to exhaustion; $\dot{V}O_2$peak; peak oxygen uptake.
*Different versus baseline, $P < .05$. £Different versus MIT, $P < .05$.

sessions (Table 3). The relative proportion of $\dot{V}O_2$ spent in zone 3 was lower in LIT than in MIT ($P = .002$), HIT$_{long}$ ($P < .001$), and HIT$_{short}$ ($P = .003$) (Table 3). At the same time, the time spent above 90% of $\dot{V}O_2$max was lower in LIT than in MIT ($P < .001$), HIT$_{long}$ ($P < .001$), and HIT$_{short}$ ($P = .039$) (Table 3). LIT showed lower HR$_{mean}$ values during training compared with MIT ($P = .029$, ES 0.63 *medium*), HIT$_{long}$ ($P = .005$, ES 0.65 *medium*), and HIT$_{short}$ ($P = .030$, ES 0.55 *medium*) (Table 3). HIT$_{long}$ induced a higher maximal [La$^-$]$_{post}$ after exercise compared to LIT ($P = .003$) and MIT ($P = .017$) (Table 3). The mean respiratory frequency ($f_R$) expressed as a percentage of respiratory frequency reserve (%$f_R$R) during exercise was lower in LIT compared with MIT ($P < .001$, ES 0.76 *medium*), HIT$_{long}$ ($P < .001$, ES 0.89 *large*), and HIT$_{short}$ ($P = .006$, ES 0.56 *medium*) (Table 3). The mean RER during exercise was lower in LIT than in HIT$_{long}$ ($P < .001$, ES 1.72 *large*) and HIT$_{short}$ ($P = .004$, ES 1.46 *large*) (Table 3). During the recovery phase, the $\Delta$ RMSSD (%pre) was higher for LIT than for HIT$_{long}$ ($P = .014$, ES 0.33 *small*) and HIT$_{short}$ ($P = .006$, ES 0.43 *small*) (Table 3). A complete overview of the psychophysiological data recorded during the different training sessions can be found in Table 3.

## Associations

Univariable analysis showed that APD (in percentage) was positively associated with NASA-TLX ($P < .001$, $\beta = 0.54$) but not with the other TL metrics (Table 4). The univariable analysis of APD (in percentage) showed that it was positively associated with mean respiratory frequency ($f_R$) expressed as a percentage of respiratory frequency reserve (%$f_R$R; $P = .001$, $\beta = 1.59$; Table 5) and RER ($P = .001$, $\beta = 178.9$; Table 5). The multivariable analysis showed that $f_R$ mean (%$f_R$R; $P = .024$, $\beta = 0.93$; Table 5) and RER ($P \le .001$, $\beta = 124.1$; Table 5) have the greatest influence on the APD (in percentage) variations over all the different training sessions.

## Discussion

The main findings of the present study were that in a group of well-trained runners: (1) significantly larger APD was observed after HIT$_{long}$ compared with LIT; (2) among the different TL indices, only NASA-TLX resembled the response observed for APD; and (3) APD was related to mean $f_R$ and RER measured during exercise.

The first finding was that the magnitude of APD was greater for HIT$_{long}$ compared with LIT (ie, 36% and 21.5% on average, respectively, $P < .001$) despite a substantially lower exercise duration (30 min vs 60 min). Conversely, no significant differences in APD were observed between HIT$_{long}$, HIT$_{short}$, and MIT. These results indicate that exercise intensity may play an important role in determining APD, as the physiological responses we measured suggest. Indeed, LIT showed the lowest values of time spent in zone 3 (%), T90% $\dot{V}O_2$max, and $\dot{V}_{Emean}$. Besides, [La$^-$]$_{post}$ and RER were higher during HIT$_{long}$ compared with LIT. In addition, we observed higher levels of cardiovascular responses during HIT$_{long}$ than LIT through higher mean values of $O_2$ pulse (ie, an indirect marker of stroke volume) during activity. Furthermore, we observed lower values of $\Delta$ RMSSD (% pre) in the acute postexercise recovery phase after long and short interval training compared to LIT and MIT. As suggested by Seiler et al,[14] a higher exercise intensity (ie, above RCP as for the HIT$_{long}$) may induce a greater strain on the sympathetic nervous system working to ensure a high $O_2$ supply to the working muscle, as well as higher rates of glycogenolysis and glycolysis during the activity.[33]

The fact that exercise intensity is an important determinant of APD is consistent with findings from previous studies. Indeed, Kesisoglou et al[5] found that 5- and 20-minute maximal TTs induced a higher APD in recreational cyclists than 20- and 40-minute sessions at submaximal intensities. Kesisoglou et al[7] also found a significantly larger APD in well-trained runners after a maximal 10-minute interval training session (ie, RPE 10) compared with a continuous 25-minute training session at a submaximal intensity (ie, RPE 6). Vermeire et al[8] found a greater APD after high-intensity exercises than high-volume, low-intensity exercise commonly performed by recreational cyclists. Thus, our results and findings from previous studies suggest that training above the CP or RCP exacerbates the occurrence of fatigue compared with cycling or running below this threshold, probably because of a larger proportion of type II fibers activated, higher glycogen utilization (eg, as suggested by higher mean RER values in our study), and higher peripheral fatigue.[6,34]

The second finding was that different internal TL methods lead to different TL responses compared with APD (Figure 3). We observed that, in contrast to APD, HR TRIMPs, TL$_{RPE}$, and TL$_{HRV}$ assigned higher TL values for LIT and MIT compared to HIT$_{long}$ and HIT$_{short}$. We observed that these metrics are more influenced by training duration than intensity. Our results agree with those of Kesisoglou et al,[5] who showed that most internal TL metrics
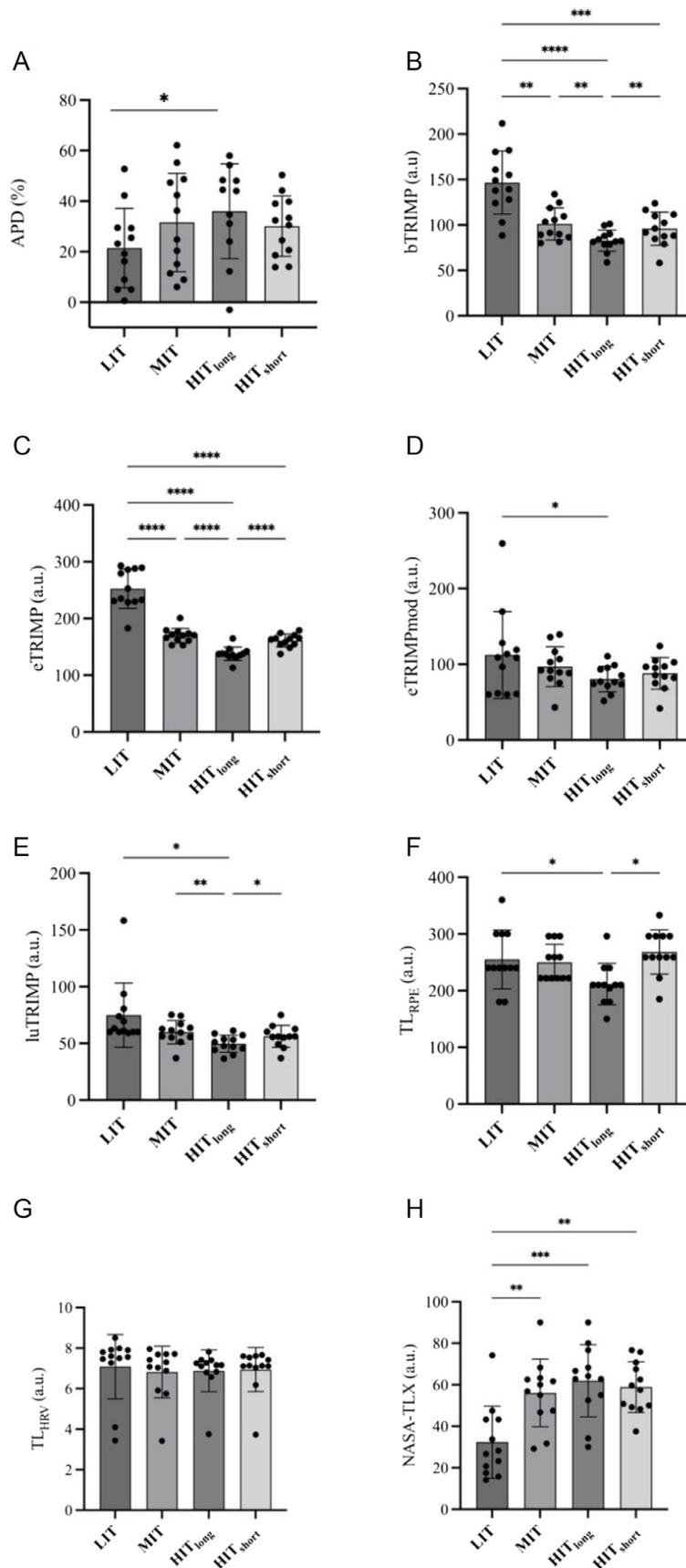
**Figure 2** — Training-load metrics for the training. APD indicates acute performance decrement; a.u., arbitrary units; bTRIMP, Bannister TRIMP; eTRIMP, Edwards TRIMP; eTRIMPmod, Edwards TRIMP modified; $HIT_{long}$, long-duration high-intensity training; $HIT_{short}$, short-duration high-intensity training; LIT, low-intensity training; luTRIMP, Lucia TRIMP; MIT, medium-intensity training; NASA-TLX, NASA Task Load Index rating scale; $TL_{HRV}$, training load with heart-rate variability; $TL_{RPE}$, training load with rating of perceived exertion; TRIMP, training impulse. $^*P < .05$. $^{**}P < .01$. $^{***}P < .001$. $^{****}P < .0001$.

**Table 3 Physiological Parameters Measured During Each Training Session or During the Recovery Phase**

| | LIT | MIT | HIT$_{long}$ | HIT$_{short}$ | *P* |
|---|---|---|---|---|---|
| $\dot{V}O_2$mean, mL·min$^{-1}$ | 3029.5 (437.4) | 3426.6 (488.8)* | 3557.0 (455.1)* | 3361.7 (553.7)* | <.001 |
| $\dot{V}O_2$total, L | 179.5 (26.1) | 124.7 (18.7)* | 104.1 (16.8)*£† | 121.2 (21.3)*& | <.001 |
| % $\dot{V}O_2$mean/$\dot{V}O_2$max | 73.3 (4.9) | 83.0 (6.4)* | 84.0 (7.0)* | 81.0 (4.2)* | <.001 |
| $\dot{V}O_2$ zone 1, % | 73.9 (37.3) | 31.8 (15.2)* | 32.1 (19.5)* | 40.0 (21.3)* | <.001 |
| $\dot{V}O_2$ zone 2, % | 23.4 (30.2) | 41.0 (14.8) | 30.2 (13.6) | 39.1 (15.9) | .227 |
| $\dot{V}O_2$ zone 3, % | **0.0 (48.0)** | **23.0 (82.8)*** | **28.0 (78.8)*** | **12.6 (66.0)*** | <.001 |
| T90% $\dot{V}O_2$max, s | **0.0 (220.0)** | **570.0 (1325.0)*** | **648.0 (1110.0)*** | **345.0 (1185.0)*** | <.001 |
| [La$^-$]$_{post}$, mmol·L$^{-1}$ | **1.1 (1.5)** | **4.0 (5.4)*** | **5.6 (9.2)*£** | **4.2 (6.8)*** | <.001 |
| HR$_{mean}$, beats·min$^{-1}$ | 158.5 (12.9) | 167.2 (14.8)* | 167.3 (13.9)* | 165.8 (13.3)* | <.002 |
| $\dot{V}_{Emean}$, L·min$^{-1}$ | 82.1 (10.0) | 103.0 (15.5)* | 108.2 (16.3)* | 99.8 (16.6)*& | <.001 |
| $f_R$ mean, %$f_R$R | 67.0 (10.7) | 74.7 (9.5)* | 75.1 (7.2)* | 72.6 (9.2)* | <.001 |
| $V_{Tmean}$, L | 1.83 (0.26) | 2.09 (0.32)* | 2.19 (0.30)* | 2.08 (0.31)* | <.001 |
| O$_2$pulse, mL·beats·min$^{-1}$ | 19.8 (3.2) | 20.5 (3.9) | 21.3 (3.4)* | 20.9 (3.5) | .006 |
| Δ RMSSD, % pre | 28.4 (25.3) | 17.6 (14.1) | 13.6 (7.8)* | 12.2 (9.6)* | .004 |
| RER | 0.92 (0.04) | 0.96 (0.04) | 0.99 (0.05)* | 0.97 (0.04)* | .004 |
| Energy expenditure, kcal | 908.4 (132.8) | 719.6 (84.3)* | 666.1 (95.8)* | 734.4 (151.1)* | <.001 |
| RPE, n | 4.25 (0.87) | 6.75 (0.87)* | 6.91 (0.94)* | 7.25 (1.01)* | <.001 |
| Δ CMJ, cm | **0.0 (17.5)** | **1.1 (12.9)** | **0.5 (8.2)** | **−0.3 (9.5)** | .592 |

Abbreviations: Δ CMJ, differences between countermovement-jump height calculated before and after exercise; $f_R$ mean, mean respiratory frequency during exercise expressed in percentage to respiratory frequency reserve; HIT$_{long}$, long-duration high-intensity training; HIT$_{short}$, short-duration high-intensity training; HR$_{mean}$, mean heart rate during exercise; [La$^-$]$_{post}$, lactate levels 1 minute postexercise; O$_2$pulse, mean oxygen pulse during exercise; LIT, low-intensity training; MIT, medium-intensity training; RER, respiratory exchange ratio; Δ RMSSD (% pre), differences between root-mean-square of successive differences in heartbeats calculated before and after exercise and expressed as a percentage of pre values; $\dot{V}_{Emean}$, mean minute ventilation during exercise; $\dot{V}O_2$mean, mean oxygen consumption; $\dot{V}O_2$total, total oxygen consumption during exercise; % $\dot{V}O_2$mean/$\dot{V}O_2$max, percentage of mean oxygen consumption related to maximal oxygen consumption; $\dot{V}O_2$ zone 1, percentage of time spent under the oxygen consumption corresponding with gas-exchange threshold; $\dot{V}O_2$ zone 2, percentage of time spent at oxygen consumption between ventilatory thresholds; $\dot{V}O_2$ zone 3, percentage of time at oxygen consumption between respiratory-compensation point and $\dot{V}O_2$max; T90% $\dot{V}O_2$max, time elapsed equal or above 90% of $\dot{V}O_2$max; $V_{Tmean}$, mean tidal volume during exercise. Note: All values are presented as mean (SD) or as median and interquartile range (bold).
*Different versus LIT, $P < .05$. £Different versus MIT, $P < .05$. &Different versus HIT$_{long}$, $P < .05$. †Different versus HIT$_{short}$, $P < .05$.

**Table 4 Univariable Analysis Between the APD and the Training-Load Metrics**

| APD,[a] % | Univariable analysis | | |
|---|---|---|---|
| | β | 95% CI | *P* |
| bTRIMP, a.u. | 0.16 | −0.06 to 0.38 | .146 |
| eTRIMP, a.u. | 0.19 | −0.06 to 0.44 | .135 |
| eTRIMPmod, a.u. | 0.10 | −0.04 to 0.23 | .169 |
| luTRIMP, a.u. | 0.17 | −0.10 to 0.44 | .217 |
| TL$_{RPE}$, a.u. | 0.07 | −0.03 to 0.18 | .190 |
| TL$_{HRV}$, a.u. | 0.47 | −6.51 to 7.44 | .895 |
| NASA-TLX, a.u. | 0.54 | 0.34 to 0.73 | **<.001** |

Abbreviations: APD, acute performance decrement; a.u., arbitrary units; bTRIMP, Bannister TRIMP; eTRIMP, Edwards TRIMP; eTRIMPmod, Edwards TRIMP modified; luTRIMP, Lucia TRIMP; NASA-TLX, NASA Task Load Index rating scale; TL$_{HRV}$, training load with heart-rate variability; TL$_{RPE}$, training load with rating of perceived exertion; TRIMP, training impulse. Note: Bold text indicates a statistically significant correlation.
[a]Analysis adjusted for the training modes.

(sRPE, bTRIMP, luTRIMP) overestimated TL of 20- and 40-minute sessions at submaximal intensities compared to 5 and 20 minutes at maximal effort. A similar trend was observed in Kesisoglou et al,[7] where bTRIMP, individualized TRIMP, eTRIMP, and TL$_{RPE}$ showed higher values during 25 minutes of continuous or intermittent submaximal exercise compared to maximal continuous or intermittent 10-minute sessions. Finally, Vermeire et al[8] found that after 4 training sessions commonly used by recreational cyclists, all internal TL methods based on HR showed a higher TL for LIT compared to HIT$_{long}$ and HIT$_{short}$ training, thus showing a dissociation from the APD response.

Several factors may partially explain the contradictory results between APD and most internal TL metrics. First, the way exercise duration is incorporated as a multiplier in TL metrics could be a contributing factor. Most TL metrics, including TL$_{RPE}$ and TL$_{HRV}$, quantify TL by multiplying exercise intensity by duration, as originally proposed by Banister et al.[28] This notion is supported by a recent study demonstrating that exercise duration is the primary determinant of the TL score when calculated in this way.[9] Second, metrics based on HR are influenced by the fact that HR may not represent effectively the exercise intensity, especially during high-intensity intermittent exercise. Indeed, during short-term high-intensity training sessions in the severe domain, HR is delayed at the onset and offset of the work bouts.[7,35] HR may not effectively represent exercise intensity even during moderate exercise when it shows a slow component at the beginning of exercise[36] or a cardiac drift in the absence of fatigue.[37] The combination of these methodological and physiological factors may partially explain the lower validity of HR-based TRIMPs, which overestimate TL during prolonged low-intensity exercise and underestimate TL during high-intensity exercise.

Interestingly, we observed that the NASA-TLX showed a similar response to APD, which is in line with previous studies.[5,7] Indeed, Kesisoglou et al[5,7] found that NASA-TLX was the only metric that broadly resembled the APD response in running and

**Table 5** Univariable and Multivariable Analysis Between the APD and Physiological Parameters Measured During Exercise

| APD,[a] % | Univariable analysis | | | Multivariable analysis | | |
|---|---|---|---|---|---|---|
| | $\beta$ | 95% CI | *P* | $\beta$ | 95% CI | *P* |
| $\dot{V}O_2$total, L | −0.05 | −0.37 to 0.26 | .733 | | | |
| $\dot{V}O_2$mean, mL·min$^{-1}$ | −0.01 | −0.01 to 0.01 | .869 | | | |
| $T_{lim}$90% $\dot{V}O_2$max, s | | −0.01 to 0.02 | .488 | | | |
| $\dot{V}O_2$ zone 1, % | −0.10 | −0.33 to 0.13 | .399 | | | |
| $\dot{V}O_2$ zone 2, % | 0.13 | −0.08 to 0.34 | .236 | | | |
| $\dot{V}O_2$ zone 3, % | −0.08 | −0.35 to 0.19 | .579 | | | |
| $V_{Tmean}$, L | −4.98 | −28.38 to 18.41 | .676 | | | |
| $f_R$ mean, %$f_R$R | 1.59 | 0.66 to 2.52 | **.001** | 0.93 | 0.48 to 1.39 | **<.001** |
| $[La^-]_{post}$, mmol·L$^{-1}$ | 1.40 | −0.96 to 3.76 | .246 | | | |
| Energy expenditure, kcal | 0.01 | −0.04 to 0.05 | .751 | | | |
| $O_2$pulse, mL·beats·min$^{-1}$ | −0.29 | −0.97 to 0.38 | .396 | | | |
| Respiratory-exchange ratio | 178.96 | 62.53 to 295.36 | **.003** | 124.13 | 16.65 to 231.62 | **.024** |
| RPE, n | 2.20 | −2.34 to 6.75 | .342 | | | |

Abbreviations: APD, acute performance decrement; $f_R$ mean, mean respiratory frequency during exercise expressed in percentage to respiratory frequency reserve; $[La^-]_{post}$, lactate levels 1 minute postexercise; $O_2$pulse, mean oxygen pulse during exercise; RPE, rating of perceived exertion of the whole exercise; $\dot{V}O_2$max, maximal oxygen uptake; $\dot{V}O_2$mean, mean oxygen consumption; $\dot{V}O_2$total, total oxygen consumption during exercise; $\dot{V}O_2$ zone 1, percentage of time spent under the oxygen consumption corresponding with gas-exchange threshold; $\dot{V}O_2$ zone 2, percentage of time spent at oxygen consumption between ventilatory thresholds; $\dot{V}O_2$ zone 3, percentage of time at oxygen consumption between respiratory-compensation point and $\dot{V}O_2$max; $T_{lim}$90% $\dot{V}O_2$max, time elapsed above 90% of $\dot{V}O_2$max; $V_{Tmean}$, mean tidal volume during exercise. Note: Bold text indicates a statistically significant correlation.
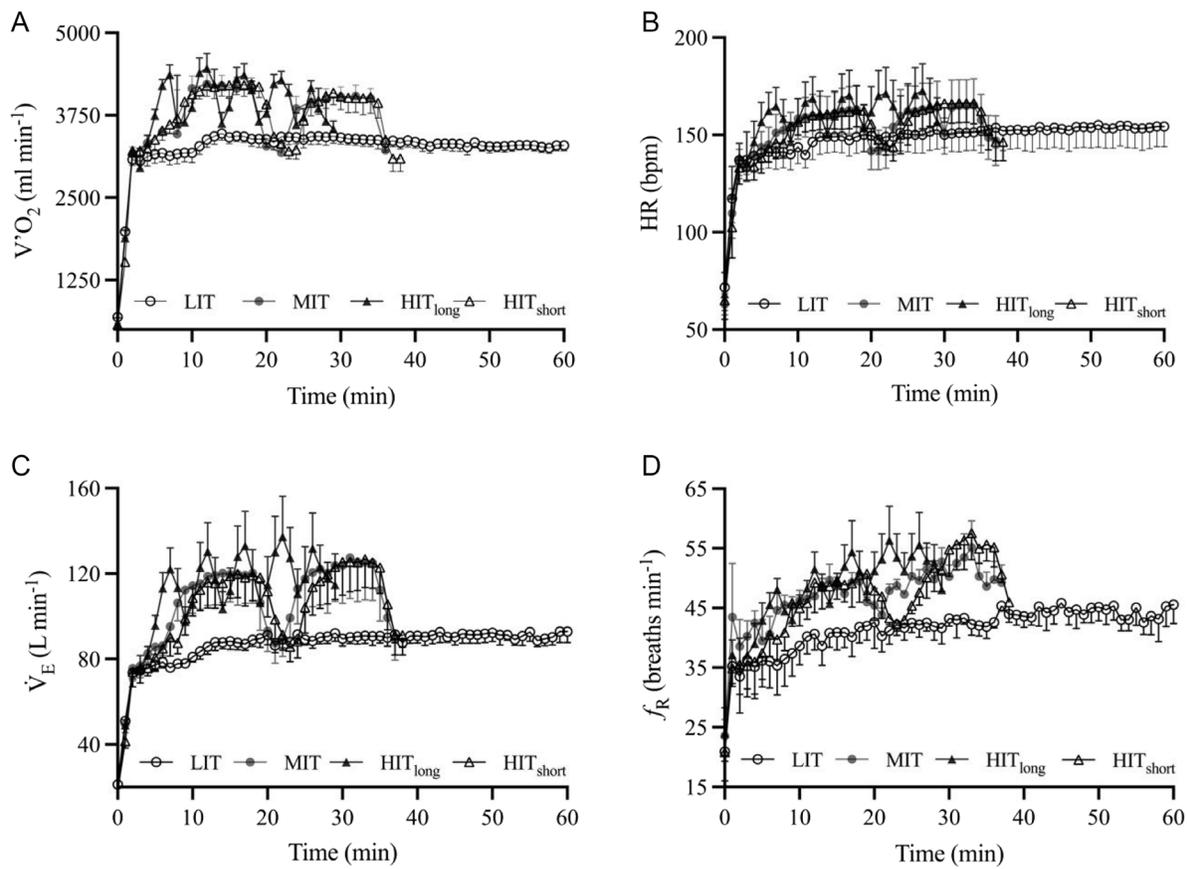[a]Analysis adjusted for the training modes.



**Figure 3** — Overview of the main physiological variables registered during the different training sessions. bpm indicates beats per minute; $f_R$, respiratory frequency; HIT$_{long}$, long-duration high-intensity training; HIT$_{short}$, short-duration high-intensity training; HR, heart rate; LIT, low-intensity training; MIT, medium-intensity training; $\dot{V}CO_2$, carbon dioxide production; $\dot{V}_E$, minute ventilation; $\dot{V}O_2$, oxygen consumption.

cycling sessions differing in intensity and duration. However, the extent of the association between APD and NASA-TLX was not quantified in the previous studies.[5,7] Conversely, we performed a univariable analysis relating the different TL metrics with APD and found that APD was significantly associated with NASA-TLX but not with the other TL metrics (Table 4). These findings corroborate and extend previous observations.[5,7] Given the multifactorial nature of postexercise fatigue and APD, the fact that NASA-TLX aggregates the scores of 6 different dimensions (ie, mental demand, physical demand, temporal demand, performance, effort and frustration) may partially explain the association found with APD. Another relevant factor is that duration is not used as a multiplier when the NASA-TLX is computed. Collectively, the present and previous findings encourage the use of the NASA-TLX in training monitoring.

From a physiological point of view, through a univariable analysis considering the different training modes, we found that APD (%) showed a positive relationship with $f_R$ mean (%$f_R$R) and RER during the different training sessions. The association between breathing variables and APD is in line with previous observations,[2] and can be explained by the fact that $f_R$ is a valid marker of physical effort,[38] which appears to be an important component of APD.[2] The fact that intensity substantially contributes to APD is further suggested by the positive association found between APD and RER, which appears to be a more sensitive indicator of performance deterioration than HR or $\dot{V}O_2$.

## Limitations

Our study has some limitations. First, of the 12 participants recruited, only 2 were females. Therefore, they cannot be considered a representative sample of female runners. Second, although our study design replicated typical exercise sessions among well-trained runners, further research is needed to determine how the APD magnitude varies across different combinations of volume and intensity of exercise. Third, although we have attempted to determine the physiological variables associated with APD, more detailed measures of central and peripheral fatigue would be useful to improve the understanding of the mechanisms underlying APD. This would also highlight the limitations of currently used internal TL metrics and aid in the development of new approaches.

## Practical Applications

We found that most of the TL methods used in our study such as HR-based TRIMPs, $TL_{HVR}$, and $TL_{RPE}$ contrast with APD as they use exercise duration as a multiplier in their formulas. In addition, the results of this study confirm that exercise intensity is one of the most important determinants of APD. Given the association between APD and $f_R$, further research should investigate the usefulness and development of new internal TL methods based on $f_R$ during exercise. From a practical perspective, coaches and athletes who use TL metrics to evaluate training sessions of different durations could try to use the NASA-TLX. Future studies are needed to evaluate the usefulness of the NASA-TLX scale in different training sessions and over longer periods of time.

## Conclusions

In summary, high-intensity training elicited the greatest acute performance decrement compared with high-volume, low-intensity training. This finding was supported by physiological parameters measured during both training sessions and recovery. Furthermore, we found that the currently used internal training-load metrics overestimate the stress imposed by longer running training sessions below the gas-exchange threshold compared to shorter training sessions above the respiratory compensation point. Nevertheless, only the NASA Task Load Index values are consistent with acute performance decrement.

## Acknowledgments

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