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Practical markers of the transition from aerobic to anaerobic metabolism during exercise: rationale and a case for affect-based exercise prescription

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Abstract

Background. The high rates of dropout from exercise programs may be attributed in part to the poor ability of most individuals to accurately self-monitor and self-regulate their exercise intensity. The point of transition from aerobic to anaerobic metabolism may be an appropriate level of exercise training intensity as it appears to be effective and safe for a variety of populations. Possible practical markers of this event were compared.

Methods. Two samples of 30 young and healthy volunteers each participated in incremental treadmill tests until volitional exhaustion. The ventilatory threshold, a noninvasive estimate of the aerobic–anaerobic transition, was identified from gas exchange data. Heart rate, self-ratings of affective valence (pleasure–displeasure), perceived activation, and perceived exertion were recorded every minute.

Results. In both samples, heart rate, perceived activation, and perceived exertion rose continuously, whereas the ratings of affective valence showed a pattern of quadratic decline, initiated once the ventilatory threshold was exceeded.

Conclusions. Exercise intensity that exceeds the point of transition from aerobic to anaerobic metabolism is accompanied by a quadratic decline in affective valence. This marker may be useful in aiding exercisers to recognize the transition to anaerobic metabolism and, thus, more effectively self-monitor and self-regulate the intensity of their efforts.

Keywords: Exercise intensity; Affective valence; Aerobic–anaerobic transition; Exercise prescription

Introduction

Approximately 40% of adults in the United States report no regular physical activity [86], two-thirds do not meet the current physical activity recommendations of 30 min of daily moderate activity [46], only 15% participate in activities of sufficient intensity, duration, and frequency to improve or maintain cardiorespiratory fitness [85], and 50% of those who start an exercise program drop out during the first 6–12 months [24]. According to the 1998–1999 Progress Review of the Healthy People 2000 program, over the past 15 years, "the proportion of the population reporting physical activity has remained essentially unchanged, and progress is very limited" (Ref. [87], p. 29). For these reasons, the promotion of physical activity has been characterized a national public health priority [85,86] and "the new imperative for public health" [78].

Exercise intensity is a crucial component of exercise prescription that may be related to exercise adherence in at least two ways. First, exercise intensity may be related to how enjoyable or tolerable participants perceive the exercise to be. Higher exercise intensities have been shown to be associated with reduced pleasure or increased displeasure during the activity [29] and with reduced exercise adherence [32,52,73]. Although direct evidence is still lacking, these findings are presumably causally related, because people generally tend to do what makes them feel good and avoid what makes them feel bad [31]. Second, exercise intensity can determine the extent to which exercise participation will lead to the accrual of health and fitness benefits. Individuals who begin an exercise program typically have high expectations of such benefits, which, if not met within a relatively short period of time, can lead to disappointment and dropout [23]. This is important, given that (a) low-intensity activities may not lead to significant

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fitness gains [98] and (b) although low-intensity activities have been shown to provide some health benefits, some authors have questioned whether activities performed below certain levels of intensity can lower the risk of certain diseases [53,63].

Despite the importance of exercise intensity, relatively little is currently known about the processes of self-monitoring and self-regulation of exercise intensity, particularly among formerly sedentary individuals going through the critical early stages of exercise involvement. The available studies indicate that, without prior practice, most people cannot accurately estimate and regulate the intensity of their exercise efforts [25,49–51]. Underestimation of the appropriate intensity (i.e., perceiving that the intensity is lower than it actually is) may lead to overexertion, injury, or discomfort, possibly resulting in the avoidance of activity. Overestimation (i.e., perceiving that the intensity is higher than it actually is) may lead to an intensity that is lower than what is recommended for a given purpose and, thus, prevent or delay the accrual of noticeable health and fitness benefits, causing frustration and, again, possibly dropout. Nevertheless, research also suggests that self-regulation of exercise intensity can be improved with appropriate interventions and practice [30].

The first step in designing such interventions is specifying the level of exercise intensity that strikes the optimal balance between effectiveness and enjoyment or safety and identifying markers that exercisers could be taught to recognize, preferably without the benefit of instrumentation. Currently, the American College of Sports Medicine [3] recommends an intensity corresponding to between 55% and 90% of maximum heart rate or between 40% and 85% of oxygen uptake reserve or heart rate reserve for the development and maintenance of cardiorespiratory fitness. For the accrual of health benefits, the Centers for Disease Control and Prevention and the American College of Sports Medicine [68], the Surgeon General [85], and the National Institutes of Health [65] recommend an intensity that is generally described as "moderate". These recommendations emphasize the importance of individual goals and preferences in deciding upon the exact level of intensity to be used within these broad margins, but do not provide additional details or specific instructions.

Several authors have suggested that the transition from an intensity that can be maintained through aerobic metabolism to an intensity that requires supplementation by anaerobic means, commonly operationalized as a threshold in blood lactate accumulation or gas exchange, may be a more appropriate point of reference compared to general percentages of maximal capacity (e.g., Refs. [2,26,22,39]). This argument is based on evidence that this level of intensity offers both an adequate rate of accumulation of fitness and health benefits and a relatively low likelihood of adverse consequences. Yet, implementing this proposition is made difficult by the fact that determining this level of intensity requires expensive instrumentation (lactate or expired gas analysis), making its large-scale application impractical [95].

The present study was designed as the first comparative evaluation of possible markers of the aerobic–anaerobic transition that do not require instrumentation and could be used as the basis of exercise intensity self-monitoring and self-regulation interventions on a large scale in the field. Four variables were examined, one physiological (heart rate), two perceptual (perceived exertion and perceived activation), and one affective (affective valence or pleasure–displeasure).

First, heart rate was examined because it continues to be the primary method for self-monitoring exercise intensity recommended by the American College of Sports Medicine [3]. Furthermore, it has been suggested that heart rate may be a useful noninvasive index of the transition from aerobic to anaerobic metabolism because of a possible deflection point in the relationship between heart rate and work rate that may occur at the level of the aerobic–anaerobic transition [16,17].

Second, perceived exertion was examined because it has been recommended by the American College of Sports Medicine [3] as an adjunct method for self-monitoring of exercise intensity. Furthermore, although ratings of perceived exertion are linearly related to work rate across the entire range of exercise intensity, several studies have shown that the accumulation of lactic acid [8,55,72] and the increase in ventilation [12,71,72] that accompany the aerobic–anaerobic transition are related to perceptions of exertion. Furthermore, the lactate and ventilatory (gas exchange) thresholds have been shown to correspond to stable ratings of exertion, regardless of differences in gender, training, or exercise modality [22,42,43,69,75].

Third, perceived activation was examined as it was considered a global index of somatic arousal, conceptually distinct from perceived exertion. The transition from aerobic to anaerobic metabolism is associated with exponential changes in several perceptible peripheral physiological functions, including ventilation [44,93] and muscle activation [64,77]. It was hypothesized that these changes may translate to an analogous, nonlinear intensification of the interoceptive afferent signals that reach conscious awareness.

Fourth, affective valence was examined on the basis of observations from neuroscience that negative affect is the primary means by which critical disruptions in homeostasis and energy regulation enter consciousness [20,67]. Furthermore, neuroanatomical and neurophysiological evidence suggests that interoceptive cues, such as afferents from baroreceptors, chemoreceptors, mechanoreceptors, and interoceptors in the viscera and muscles, reach areas of the brain linked to affective responses [19]. Therefore, it was hypothesized that the transition from aerobic to anaerobic metabolism would be accompanied by a surge of displeasure.

The changes in these four variables were examined in two incremental treadmill protocols performed until volitional exhaustion. Heart rate, perceived exertion, perceived activation, and affective valence were recorded every minute. Following the identification of the ventilatory threshold, which was considered an estimate of the aerobic–anaerobic transition, the responses below and above the threshold were compared and trend analyses were performed to identify whether and when any distinct patterns, such as departures from linearity, occurred.

Methods

Participants

Two groups of 30 young and healthy volunteers participated in the study. Group A included 13 women (mean age $\pm$ SD = 22.8 $\pm$ 3.0 years; mean weight $\pm$ SD = 63.7 $\pm$ 9.8 kg; mean V_{O_2}max $\pm$ SD = 46.9 $\pm$ 4.1 ml kg^{-1} min^{-1}) and 17 men (mean age $\pm$ SD = 24.4 $\pm$ 4.1 years; mean weight $\pm$ SD = 78.1 $\pm$ 7.1 kg; mean V_{O_2}max $\pm$ SD = 51.5 $\pm$ 7.0 ml kg^{-1} min^{-1}). Group B included 14 women (mean age $\pm$ SD = 21.2 $\pm$ 2.0 years; mean weight $\pm$ SD = 60.6 $\pm$ 6.6 kg; mean V_{O_2}max $\pm$ SD = 47.7 $\pm$ 7.6 ml kg^{-1} min^{-1}) and 16 men (mean age $\pm$ SD = 21.50 $\pm$ 2.45 years; mean weight $\pm$ SD = 78.5 $\pm$ 9.2 kg; mean V_{O_2}max $\pm$ SD = 56.6 $\pm$ 7.3 ml kg^{-1} min^{-1}). Before their involvement in the study, all participants read and signed an informed consent form approved by the university's Institutional Review Board. Furthermore, they all certified that they (a) had a physical examination during the previous year that revealed no contraindications to vigorous physical activity, (b) had no history of cardiovascular, respiratory, musculoskeletal, metabolic, or mental conditions, (c) were not suffering from any injuries or other ailments, and (d) were not taking any medication. In addition, all participants completed the Physical Activity Readiness Questionnaire [14]. All responses were negative.

Measures

The heart rate was assessed with a heart rate monitor (Polar Electro Oy, Finland) consisting of a stretchable chest band and a wrist-mounted receiver. Validation studies have shown correlations with electrocardiographically measured heart rate typically in the 0.94–0.99 range and deviations from 1 to 12 beats min^{-1} [54,74,84,92]. The collected heart rate values were expressed as percentages of the highest heart rate achieved during the test (%HR_{peak}).

Perceived exertion was assessed by the Rating of Perceived Exertion (RPE; Ref. [7]). The RPE is a 15-point single-item scale ranging from 6 to 20, with anchors ranging from "Very, very light" to "Very, very hard". Correlations between RPE and heart rate across the stages of a graded exercise test have been found to range between 0.85 and 0.94 [66].

Perceived activation was assessed by the Felt Arousal Scale (FAS; Ref. [81]). The FAS is a 6-point, single-item rating scale ranging from 1 to 6, with anchors at 1 ("Low Arousal") and 6 ("High Arousal").

Affective valence (positivity–negativity or pleasure–displeasure) was assessed by the Feeling Scale (FS; Ref. [40]). The FS is an 11-point, single-item, bipolar rating scale commonly used for the assessment of affective responses during exercise. The scale ranges from -5 to $+5$. Anchors are provided at zero ("Neutral") and at all odd integers, ranging from "Very Good" ($+5$) to "Very Bad" (-5).

Procedures

Both groups participated in graded treadmill tests until volitional exhaustion, but the two protocols differed in certain respects. The purpose of using different protocols was to help in determining whether any emergent patterns in the four variables of interest were protocol-specific. The main difference among the protocols was that one had longer stages and larger work increments from stage to stage compared with the other. Specifically, for Group A, there was a 3-min warm-up, 2-min stages of running, and alternating increases either in speed by 1.6 km h^{-1} or in grade by 2% at every stage (starting with an increase in speed). For Group B, there was a 5-min warm-up, 1-min stages of running, and alternating increases either in speed by 0.8 km h^{-1} or in grade by 1% at every stage (starting with an increase in speed). Furthermore, each group was tested in a different laboratory (room with no windows for Group A versus windows with natural light for Group B), with a different face mask design (noseclip and snorkel for Group A versus unobstructed mouth and nose for Group B), and a different metabolic analysis system (albeit equipped with the same models of O_2 and CO_2 analyzers and calibrated with the same method and the same standard gases).

Upon arrival to the laboratory, each participant was greeted, given an overview of the procedures to be followed, and asked to read and sign the informed consent form. This was followed by the fitting of a heart rate monitor. Once the integrity of the signal from the monitor was established, the participants were asked to complete a pre-exercise battery of questionnaires that included the FS and FAS. Next, the participants were shown to the treadmill, were presented with a description of the exercise protocol, and were fitted with a face mask. For both groups, the face masks were equipped with the same ultra-low-resistance one-way valves (Hans Rudolph, Kansas City, MO).

The O_2 and CO_2 analyzers (models N-22M and P-61B, respectively; Ametek Applied Electrochemistry, Sunnyvale, CA) were calibrated before each test. The participants were asked to sit for a period of 2 min before the beginning of the test while their expired gases were being analyzed to ensure the proper functioning of all the components of the metabolic analysis system. This was followed by a 3-min walk at 4.8 km h^{-1} (0% grade) for Group A or a 5-min walk at the same speed and grade for Group B. Once the warm-up was completed, the speed of the treadmill was increased to 8 km h^{-1} (0% grade) for both groups. Beyond this point, the workload was increased every 2 min by alternating between increases in speed by 1.6 km h^{-1} and increases in grade by 2% for Group A and every 1 min by alternating between increases in speed by 0.8 km h^{-1} and increases in grade by 1% for Group B. Speed was increased first. This procedure was continued until each participant reached the point of volitional exhaustion. This was verified by at least two of the standard criteria for reaching maximal oxygen uptake, namely (a) reaching a peak or plateau in oxygen consumption (changes of less than 2 ml kg^{-1} min^{-1}); (b) attaining a respiratory exchange ratio equal to or higher than 1.1; and (c) reaching or exceeding age-predicted maximal heart rate (i.e., 220 age).

From the beginning of the incremental phase (8 km h^{-1}; 0% grade) and until the point of volitional exhaustion, the participants gave self-ratings on the RPE, FS, and FAS (in that order) every minute by pointing out their selections on a poster-size version of the scales that was placed in front of them whenever responses were required. Metabolic analysis and heart rate data were kept out of the field of vision of the participant.

Data reduction and analysis

Given that the duration of the graded treadmill protocol varied among individuals, exercise intensity was standardized using the following time points which were considered to reflect metabolically comparable conditions across all participants: (a) the beginning of exercise, (b) the ventilatory threshold (VT), and (c) the end of exercise. The method described by Davis et al. [21] was used for the determination of VT. This method involves plotting the ventilatory equivalents for O_2(V_E/V_{O_2}) and CO_2(V_E/V_{CO_2}) across work rates and identifying the point at which there is a systematic increase in V_E/V_{O_2} without a corresponding increase in V_E/V_{CO_2}. This technique has been shown to have superior accuracy compared with other methods on the basis of ventilatory indices [13]. Following the identification of the VT, the RPE, FS, FAS, and heart rate data collected at the following eight time points during exercise were retained: the first 2 min (Min 1, Min 2), the minute before VT (VT-1), the minute of the VT (VT), 2 min following VT (VT + 1, VT + 2), and the last 2 min (End-1, End). Nonlinear trends were examined for $\%HR_{peak}$, RPE, FAS, and FS. Whenever the sphericity assumption was violated, the conservative Greenhouse–Geisser formula was used to adjust the degrees of freedom and the adjusted values are reported.

Results

An initial manipulation check of the percentages of V_{O_2}max across the two treadmill protocols showed that the effect of time was significant for both Group A [F (2.6, 72.5) = 229.1, $P < 0.001$] and Group B [F (2.5, 72.5) = 512.0, $P < 0.001$]. Follow-up analyses showed that, for both protocols, the relative intensity gradually increased across the eight successive time points (for all pairwise comparisons, $P < 0.004$).

For Group A (see Figs. 1a–1d), the average duration of exercise until the point of volitional exhaustion was 11.3 min (SD = 2.3 min). The average terminal RPE was 17.8 (SD = 1.9; between "Very hard" and "Very, very hard"). The VT was determined to be at 78.2% of V_{O_2}max (SD = 6.7%), with a range from 64.4% to 92.8%.

The main effect of time in repeated measures analyses of variance was significant for all dependent variables, $\%HR_{peak}$ [F(2.2, 40.0) = 241.8, $P < 0.001$], RPE [F(2.5, 69.4) = 154.9, $P < 0.001$], FAS [F(2.3, 63.6) = 31.0, $P < 0.001$], and FS [F(2.5, 68.6) = 44.9, $P < 0.001$]. Trend analyses showed that linear trends were significant for all variables, but quadratic trends were significant only for $\%HR_{peak}$ [F(1, 18) = 38.2, $P < 0.001$] and FS [F(1, 28) = 35.8, $P < 0.001$]. For heart rate, however, all the nonlinear trends up to the seventh-order were also significant.

Follow-up analyses examined the quadratic trends in sets of three consecutive data points at a time to identify where the departures from linearity occurred. For heart rate, the quadratic trend was significant for several three-point segments: (a) from Min 1 to VT-1 ($P < 0.001$), (b) from Min 2 to VT ($P < 0.001$), (c) from VT + 1 to End-1 ($P < 0.01$), and (d) VT + 2 to End ($P < 0.01$). In contrast, for FS, the quadratic trend was significant only from VT to VT + 2 ($P < 0.05$).

For Group B (see Figs. 1e–1h), the average duration of exercise until the point of volitional exhaustion was 12.1 min (SD = 3.0 min). The average terminal RPE was 18.4 (SD = 1.6; also between "Very hard" and "Very, very hard"). The VT was determined to be at 77.2% of V_{O_2}max (SD = 5.0%), with a range from 65.9% to 88.0%.

The main effect of time in repeated measures analyses of variance was significant for all dependent variables, $\%HR_{peak}$ [F(2.0, 55.6) = 261.0, $P < 0.001$], RPE [F(2.5, 73.2) = 191.9, $P < 0.001$], FAS [F(2.6, 75.4) = 56.7, $P < 0.001$], and FS [F(2.1, 60.5) = 68.8, $P < 0.001$]. Trend analyses showed that the linear trends were significant for all variables, but the quadratic trends were significant only for $\%HR_{peak}$ [F(1, 28) = 81.3, $P < 0.001$] and FS [F(1, 29) = 22.8, $P < 0.001$]. However, for heart rate, the cubic [F(1, 29) = 7.73, $P < 0.01$] and the fifth-order trends [F(1, 29) = 7.73, $P < 0.01$] were also significant. The quadratic trend was significant for several three-point segments: (a) from Min 1 to VT-1 ($P < 0.05$), (b) from the Min 2 to VT ($P < 0.001$), (c) from VT + 1 to End-1 ($P < 0.05$), and (d) from VT + 2 to End ($P < 0.001$). In contrast, for FS, the quadratic trend was again significant only from the VT to VT + 2 ($P < 0.01$).

The complete results of pairwise comparisons for the FS data are shown in Table 1. The protocol differences between Groups A and B did appear to have an effect on FS ratings.

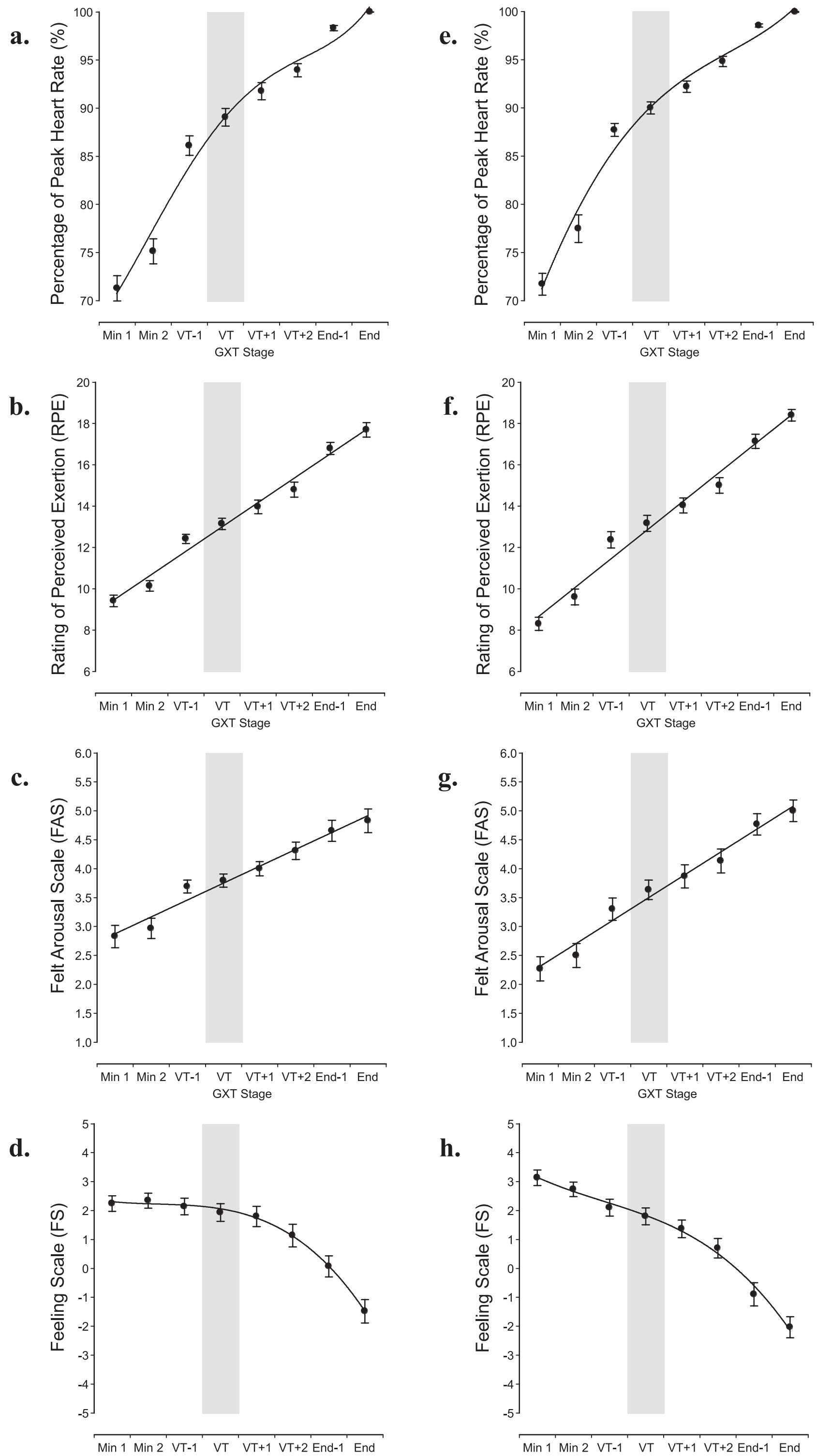

Fig. 1. The responses of heart rate, expressed as $\%HR_{peak}$ (panels a and e), ratings of perceived exertion, assessed by the RPE (panels b and f), perceived activation, assessed by the FAS (panels c and g), and affective valence, assessed by the FS (panels d and h), for Groups A and B, respectively.

After a 5-min warm-up walk, as opposed to a 2-min one, Group B started from a higher level (3.1) compared with Group A (2.2). In Group A, the change from Min 1 to VT was not significant. In contrast, in Group B, there was a significant decline from Min 1 to VT, although none of the minute-to-minute changes were significant. On the other hand, once the VT was exceeded, the pattern was similar in both groups. Although the changes from VT to VT + 1

Table 1
Results of pairwise comparisons among the eight data points in Group A (below the diagonal) and Group B (above the diagonal)

	Min 1	Min 2	VT-1	VT	VT + 1	VT + 2	End-1	End
Min 1	–	0.280	0.668*	0.854*	1.108*	1.444*	2.131*	2.918*
Min 2	– 0.070	–	0.422	0.616*	0.881*	1.238*	1.959*	2.757*
VT-1	0.068	0.135	–	0.186	0.443*	0.806*	1.546*	2.269*
VT	0.199	0.266	0.129	–	0.259	0.628*	1.382*	2.089*
VT + 1	0.263	0.324	0.196	0.077	–	0.376*	1.147*	1.827*
VT + 2	0.602	0.661*	0.532*	0.415*	0.322*	–	0.779*	1.406*
End-1	0.896*	0.961*	0.812*	0.684*	0.567*	0.218*	–	0.532*
End	1.991*	2.058*	1.887*	1.751*	1.581*	1.203*	1.037*	–

The asterisks indicate a statistically significant difference after a Bonferroni correction. The values represent effect sizes, $d = (M_i - M_j)/\mathrm{SD}_{\mathrm{pooled}}$.

were not significant in either group, each minute-to-minute decline thereafter was significant.

Discussion

The purpose of this study was to compare the patterns of responses in heart rate, perceived exertion, perceived activation, and affective valence across the stages of graded treadmill tests performed until volitional exhaustion. Of particular interest was the behavior of these markers in relation to the VT, which was used as an index of the transition from aerobic to anaerobic metabolism. The main finding was that, of the four variables examined, affective valence showed a consistently distinct pattern of change after the VT compared with before. In contrast, the heart rate exhibited a sigmoid response and perceived exertion and perceived activation showed linear responses. Importantly, these patterns were reliable across both treadmill protocols, suggesting that they are not protocol specific.

A fundamental assumption of the present study and the basis of the rationale for seeking practical markers of the aerobic–anaerobic transition was that this level of exercise intensity can be a useful reference point for individualized exercise prescriptions. This proposition is based on research evidence showing that (a) exercise performed at or just below the level of aerobic–anaerobic transition confers similar benefits compared to exercise of higher intensity among previously sedentary individuals, (b) when the intensity corresponds to the individually determined aerobic–anaerobic transition, exercise can be more effective in improving indices of fitness or health compared with prescriptions based on percentages of maximal capacity, (c) exercise intensity that exceeds the level of the aerobic–anaerobic transition may produce adverse effects compared to lower-intensity exercise, particularly in certain vulnerable populations, and (d) exercise performed at an intensity equal to or just below the level of the aerobic–anaerobic transition can be continued for a long time, whereas an intensity that significantly exceeds this level precludes the maintenance of a physiological steady state, leads to fatigue, and creates the need to discontinue the activity. Given that this evidence is of central importance to substantiating the rationale of the present study but has not been reviewed in a comprehensive manner elsewhere in the literature, it is summarized below.

First, exercise training performed at or just below the ventilatory or lactate thresholds (used as indices of the aerobic–anaerobic transition) has been shown to confer similar benefits compared to exercise above the thresholds among previously sedentary individuals [56]. In young men (average age: approximately 22 years), exercise at 80% of the lactate threshold or at 25% or 50% of the difference between the lactate threshold and the maximal aerobic capacity (but for durations designed to keep total work equal among the groups) for 5 weeks led to similar improvements in oxygen uptake, ventilation, heart rate, lactate, epinephrine, and norepinephrine responses to submaximal exercise [15]. In adult women (average age: approximately 31 years), exercise at the lactate threshold and at approximately 50% of the difference between lactate threshold and maximal aerobic capacity led to similar increases in oxygen consumption and walking or running velocity at the lactate threshold during the first 4 months of training [96]. In elderly individuals (average age: approximately 68 years), exercise at 72% and 121% of the lactate threshold for 8 weeks led to similar improvements in maximal aerobic capacity, lactate threshold, and submaximal heart rate and ventilation [5]. Finally, in a large sample (N = 432) of adults (average age: approximately 34), exercise below, at, and above the VT for 20 weeks had a similar beneficial effect on maximal aerobic capacity, although improvement in oxygen uptake at the VT was larger among those exercising above the VT compared with those exercising below and at the VT [36].

Second, when exercise prescription is based on the individually determined VT, exercise is more effective in improving indices of fitness or health compared to traditional prescriptions on the basis of heart rate reserve. In elderly individuals (average age: approximately 64 years), exercise at the VT for 12 weeks led to an improvement in maximal oxygen uptake whereas exercise at 50% of heart rate reserve did not. Furthermore, submaximal ventilation and heart rate were decreased to a larger extent following exercise at the VT compared to exercise at 50% of heart rate reserve [33]. In the same age group, exercise at the VT for 12 weeks not only led to significant improvements in maximal oxygen uptake (20%) and VT (26%), but was also associated with relatively high adherence and attendance (74% and 97%, respectively; [2]). Likewise, in patients suffering from chronic airway limitation, 4 weeks of exercise at the VT led to an increase in symptom-limited oxygen uptake and maximal oxygen pulse, whereas exercise at 50% of heart rate reserve did not significantly change these parameters. Furthermore, exercise training at the VT led to a larger increase in the VT, and lower ventilation, carbon dioxide production, and lactate accumulation at that level compared to exercise at 50% of heart rate reserve [90]. Of particular importance for individuals interested in weight loss is the finding that, in adult women (average age: approximately 29), the VT may coincide with the maximal rate of fat oxidation [4], although whether this relationship is causal or simply coincidental remains to be established.

Third, exercise at an intensity that exceeds the lactate threshold or VT has been shown to produce certain negative effects compared to exercise performed below or at these thresholds. For example, in previously sedentary men (average age: approximately 22 years), exercise at an intensity that induced blood lactate accumulation higher than 4 mmol l^{-1} for 9 weeks led to negative changes in the lipoprotein profile (i.e., decreases in HDL and increases in the LDL/HDL ratio), whereas exercise at a lower intensity led to a desired pattern of changes. Furthermore, blood lactate concentration during training was found to have a significant positive correlation with increases in the LDL/HDL ratio [1]. In asthmatic children, exercise at the VT for 12 weeks improved maximal aerobic capacity and the VT, whereas higher-intensity exercise led to a reduction in the VT and, thus, earlier onset of breathlessness [91]. Exercise above the lactate and VT has also been shown to be associated with abnormalities in the left ventricular function in both healthy untrained individuals [9,83] and heart disease patients [48]. It is also important to point out that, in addition to these physiological effects, there is evidence that the VT may be the turning point, below which exercise may be enjoyable but above which exercise may be experienced as aversive, at least by most people. Although cycle ergometry below the VT (75% of the oxygen uptake at VT) has been shown to improve affect, a bout at the VT has been found to have the opposite effect [6]. It is possible that negative affective responses to exercise bouts may, over time, lead to an aversion and avoidance of regular exercise participation, but this hypothesis has yet to be tested.

Fourth, although exercise performed within the aerobic range of intensity can be continued for a long period of time, exercise that significantly exceeds the point of transition from aerobic to anaerobic metabolism precludes the maintenance of a physiological steady state, induces fatigue, and creates the need to stop the activity, thus limiting the amount of time one can remain active. Exercise that requires a substantial anaerobic component depends on metabolic resources that are very limited (i.e., the adenosine triphosphate and creatine phosphate pool in the muscles and anaerobic glycolysis) compared to those available to aerobic metabolism (i.e., muscle and liver glycogen, free fatty acids from adipose tissue, and body proteins). Entering the anaerobic range is accompanied by a rapid accumulation of lactate and hydrogen ions dissociated from lactic acid. These, in turn, have been linked to several processes that contribute to fatigue, including the accelerated breakdown of creatine phosphate [59], the inhibition of glycolysis and glycogenolysis [79], the inhibition of lipolysis [11], and the interference with the calcium triggering of muscle contractions [34]. In addition, lactic acidosis stimulates the release of catecholamines [37] and, thus, the lactate threshold has been found to occur near a catecholamine threshold [88,97]. In turn, catecholamines have widespread effects that further push the organism toward its functional limits, including a breakpoint in the relationship between double product (the product of heart rate and systolic blood pressure) and work rate [70,82]. Moreover, to compensate for metabolic acidosis above the point of transition to anaerobic metabolism, there is an increase in the frequency and depth of ventilation [44,93]. Finally, the transition to anaerobic metabolism is accompanied by the recruitment of low-efficiency fast-twitch muscle fibers [64,77], thus increasing the oxygen cost of work and disrupting coordination patterns.

Having established the importance and the value of aerobic–anaerobic transition for exercise prescription, it is important to recognize that this point may vary widely from individual to individual, even among individuals of similar maximal aerobic capacity. Although in trained individuals, the transition "may not be observed until the subject exercises to a level that is 10–20 times the resting metabolic rate," in untrained individuals, this threshold "might be surpassed at about four times the resting metabolic rate," and, in cardiac patients, "it might be evident at less than twice the resting metabolic rate" (Ref. [94], p. VI-29). Even in the two samples examined in the present study, despite the young age, good health, and physically active status of the participants, the VT ranged from 64.4% to 92.8% and from 65.9% to 88.0% of maximal aerobic capacity, respectively. This means that the aerobic–anaerobic transition may occur in most cases somewhere within, in a few cases of highly trained individuals above, and perhaps in some cases of elderly or severely detrained individuals below the boundaries of the current exercise intensity recommendations for the development and maintenance of cardiorespiratory fitness [3]. Thus, although several authors have argued that, instead of prescribing exercise by referring to general percentages of maximal capacity, it would make more sense to tailor exercise prescriptions to individuals from the aerobic–anaerobic transition [2,26,33,39], this proves difficult to implement in field settings. The challenge lies in identifying markers of the aerobic–anaerobic transition that can be determined without the use of expensive laboratory equipment, can be easily understood by exercise participants, and can be applied on a large scale in field settings.

As noted earlier, self-ratings of affective valence (pleasure–displeasure) seem to hold a great deal of promise as practical markers of the aerobic–anaerobic transition. Consistent with the hypothesis that the intensification of interoceptive afferent signals associated with the transition to anaerobic metabolism would lead to a surge of displeasure, in two samples and two treadmill protocols, we detected quadratic declines in affective valence following the VT. Although the generalizability of this finding is limited by the characteristics of the samples, the fact that the quadratic decline occurred at the same point regardless of the differences between conditions and exercise protocols in the two groups is important and may have implications for exercise intensity prescription.

There was one noteworthy difference among the patterns of affective valence responses between the two protocols. Group B started the incremental phase of the treadmill test with a higher average affective valence rating compared to Group A (3.1 versus 2.2). This difference can be attributed to the duration of the warm-up walk. In Group A, the 2-min warm-up did not lead to an improvement in FS ratings compared to the pre-exercise assessment (2.1). On the contrary, in Group B, the 5-min warm-up led to a larger, albeit also nonsignificant, improvement compared to pre-exercise (2.5). Significant improvements in affective valence in responses to short walks have been identified previously [28]. In the present studies, the warm-up walk in Group B led to a small improvement in valence, which, in turn, led to a higher FS at the onset of the activity and a somewhat different pattern of ratings below the VT. Although the two groups did not differ at the point of the VT (1.9 versus 1.8 for Groups A and B, respectively), there was a significant decline (from 3.1 to 1.8) below the VT in Group B, but no significant change (from 2.2 to 1.9) in Group A. Despite this difference below the VT, the quadratic pattern of decline above the VT was similar in the two groups. It should be noted, however, that the ratings of affective valence did not become negative (i.e., the respondents endorsing ratings lower than zero) until 1 min before they stopped the test due to volitional exhaustion. This may be related to the fact that the average baseline response for healthy college-age respondents is not 0 (“neutral”) but closer to 3 (“good”). What was observed during the 3-min segment from VT to VT + 2 was a significant (quadratic) decline, meaning that the participants reported feeling significantly worse than they did before.

The other variables (%HR_{peak}, RPE, and FAS) did not produce distinct patterns above compared to below the VT. Nevertheless, it is noteworthy that the average RPE values at the VT (13.1 and 13.2, for Groups A and B, respectively) compare favorably with values reported in some previous studies. This is despite the fact that previous studies used cycle ergometer rather than treadmill tests and, presumably due to differences in the fitness level of the participants, the VT in most previous studies occurred at lower levels than those observed in the present study. Hill et al. [43] reported average RPEs at VT from 13.1 to 14.7 in college-age men and women. Purvis and Cureton [69] reported averages of 13.1 and 14.2 in adult men and women. On the other hand, Mahon et al. [57] reported an average of 11.5 for adults and 13.6 for children. Ratings in the 13–14 range have also been reported for the lactate threshold in some cases [22], although in others, the reported range is 10–11 [42,80]. A rating of “13” corresponds to effort described as “somewhat hard”. It is noteworthy that (a) this level is the first on the RPE scale that is accompanied by the word “hard” in the anchor, whereas the previous anchor [11] is “light”, and (b) perceived exertion and affective valence seem to develop their strongest relationship near the VT. In the present study, the correlation coefficients between RPE and FS grew increasingly stronger from VT to VT + 2 in both groups (from −0.263 to −0.503 and from −0.573 to −0.685, in Groups A and B, respectively) and these coefficients were stronger compared to those observed both before and after this time period. Thus, although the pattern of RPE responses above the VT was no different from the pattern below the VT, it seems that the level of RPE (i.e., the change from “light” to “somewhat hard”) could be used as a possible marker of the aerobic–anaerobic transition in field settings. Yet, it should be noted that, although some studies have shown that the lactate threshold and VT correspond to stable ratings of exertion that are unaffected by gender, training, or exercise modality [22,42,43,69,75], other studies have shown substantial variability in the relationship between ratings of perceived exertion and lactate as a function of age [57,58], training status [41], overtraining [35], exercise modes [99], and exercise protocols [62].

The heart rate data did not support the proposition that heart rate can serve as a noninvasive marker of the aerobic–anaerobic transition [16,17]. This finding is in agreement with most previously published studies (e.g., Refs. [10,45,89]). Several studies have found that the transition from aerobic to anaerobic metabolism may correspond to substantially different percentages of maximal heart rate or heart rate reserve in different individuals [18,27,47,61]. Dwyer and Bybee [27] pointed out that, by not providing information about the aerobic–anaerobic balance, monitoring exercise intensity by heart rate may have important implications for exercise adherence: “...compliance to a voluntary training program may be influenced by indiscriminately prescribed exercise that requires an individual to exercise considerably above his [sic] anaerobic threshold and to experience the subjective discomforts associated with exercise at that level” (p. 75).

Among possible markers that were not examined in the present study, from findings that the ventilatory frequency is increased substantially beyond the point of the aerobic–anaerobic transition [44,93], some authors have proposed using perceptible indices of ventilatory frequency, such as the point at which one begins to “hear his or her breathing” or is “just capable of talking,” as ways of monitoring exercise intensity [38,60]. Reportedly, these indices may estimate the VT with an accuracy of approximately ±15%. However, other authors have shown that a nonlinear increase in ventilatory frequency significantly overestimates the VT [76].

The findings of the present study suggest that, for practitioners interested in prescribing exercise intensity on the basis of the individual transition from aerobic to anaerobic metabolism, the surge of displeasure that appears to accompany this intensity could be valuable as a practical marker. In addition to monitoring when perceived effort turns from "light" to "somewhat hard," exercisers could also monitor when they begin to feel substantially worse than they felt before, and regulate their pace accordingly. An important caveat that both researchers and practitioners should take into account is the fact that the samples in the present studies consisted of young, healthy, and mostly physically active and fit participants. It remains an open question whether the same pattern of findings will emerge if sedentary middle-aged or older adults are studied or if participants suffer from diseases, particularly exercise-limiting ones. Preliminary data from an ongoing study involving middle-aged women who had been sedentary for at least 12 months indicate that, in some cases, the fear of unfamiliar exertion-related symptoms and the onset of muscular and skeletal symptoms (e.g., aches and pains in the leg muscles, joint pain) may prompt a decline in affective valence and even a termination of exercise before the occurrence of the VT. Clearly, more research on this important topic is warranted. Specifically, future studies should examine (a) whether the declines in affective valence coincident with the VT also occur in other groups of participants, such as in previously physically inactive or elderly individuals, (b) whether similar declines occur reliably with other popular modes of exercise, such as cycling or swimming, (c) whether novice exercisers can be trained to reproduce the exercise intensity that corresponds to the aerobic–anaerobic transition using ratings of affective valence, and (d) what influence various physiological and psychological individual differences have on ratings of affective valence at the point of the aerobic–anaerobic transition. Ultimately, future research should address whether self-monitoring and self-regulating exercise intensity based on ratings of affective valence can lead to improved rates of enjoyment and adherence over the long haul.

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